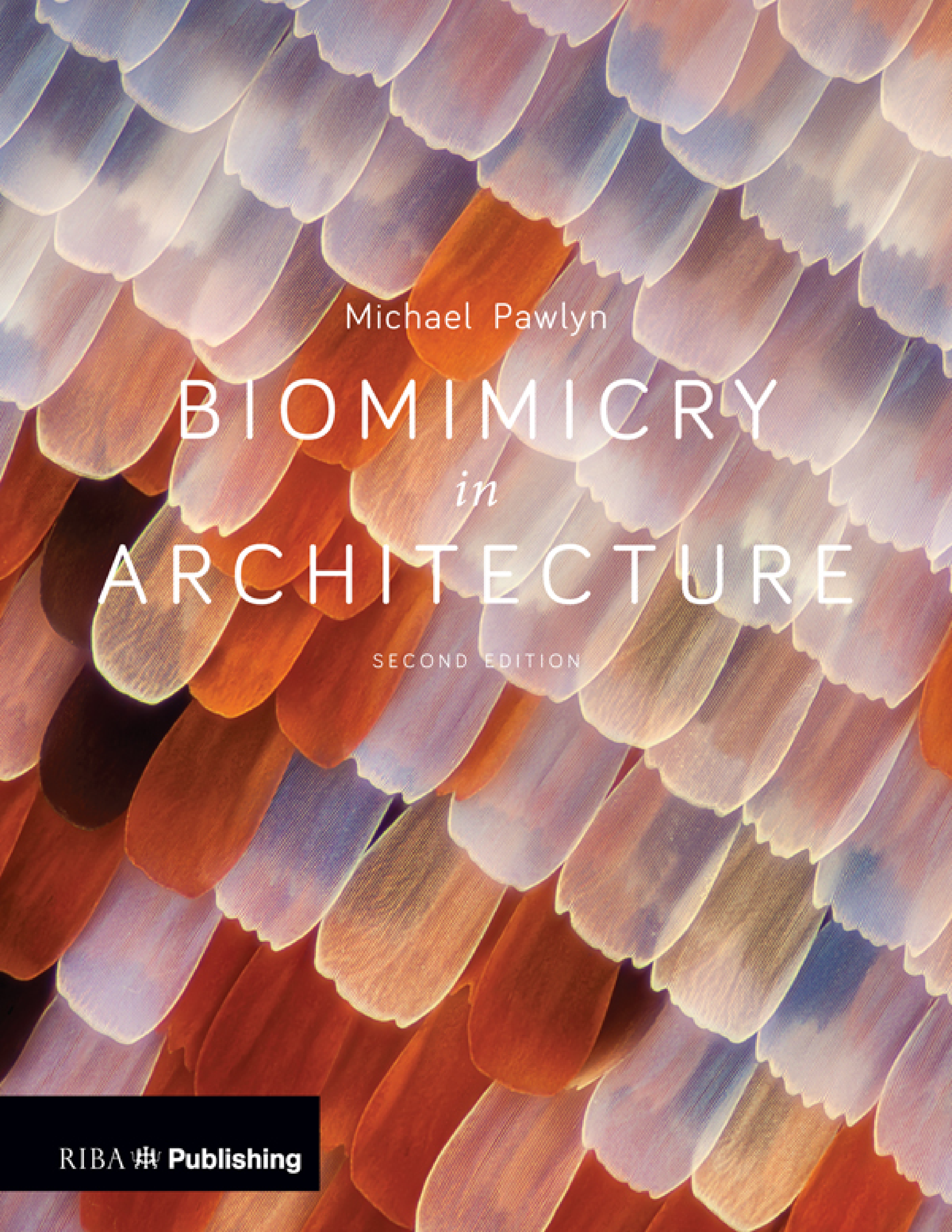

Michael Pawlyn

BIOMIMICRY *in* ARCHITECTURE

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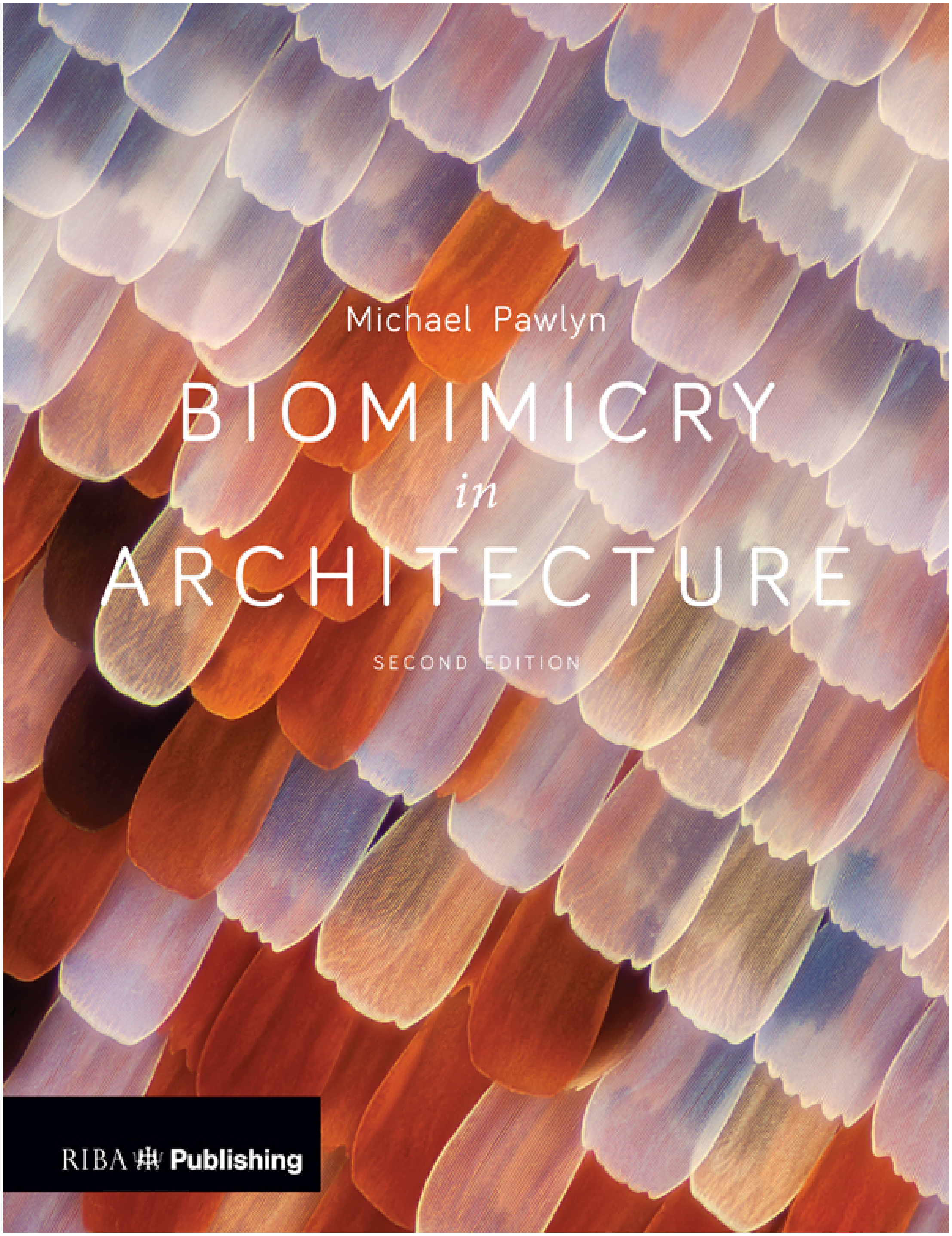

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MICHAEL PAWLYN BSc, BArch, RIBA, is an architect, the founding director of Exploration Architecture Ltd and has a well-earned reputation as a pioneer of biomimicry. Before setting up his own practice, he worked with Grimshaw for ten years and was central to the team that radically re-invented horticultural architecture for the Eden Project. He lectures widely on the subject of sustainable design and his talk on TED.com has been viewed over 1.5 million times.

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Foreword: Dame Ellen MacArthur

In this remarkable book, Michael Pawlyn makes the case for placing buildings and architecture at the heart of a bio-inspired and biomimetic future. It's more than this, however. A book of principles and action for the twenty-first century, it's an example of a new lens: a systemic way of seeing which has the potential to enable transition to a world that is regenerative, accessible to all and abundant.

Michael quotes Buckminster Fuller's ambition 'to make the world work for a hundred percent of humanity, in the shortest possible time, through spontaneous cooperation, without ecological offense or the disadvantage of anyone'. This is a bold ambition and a question of design and intention, but these alone do not describe a course of action. *Biomimicry in Architecture* is replete with examples of the manifestation of changes in the use of materials, structure, energy, function and form which take their cues from living systems to provide real benefits.

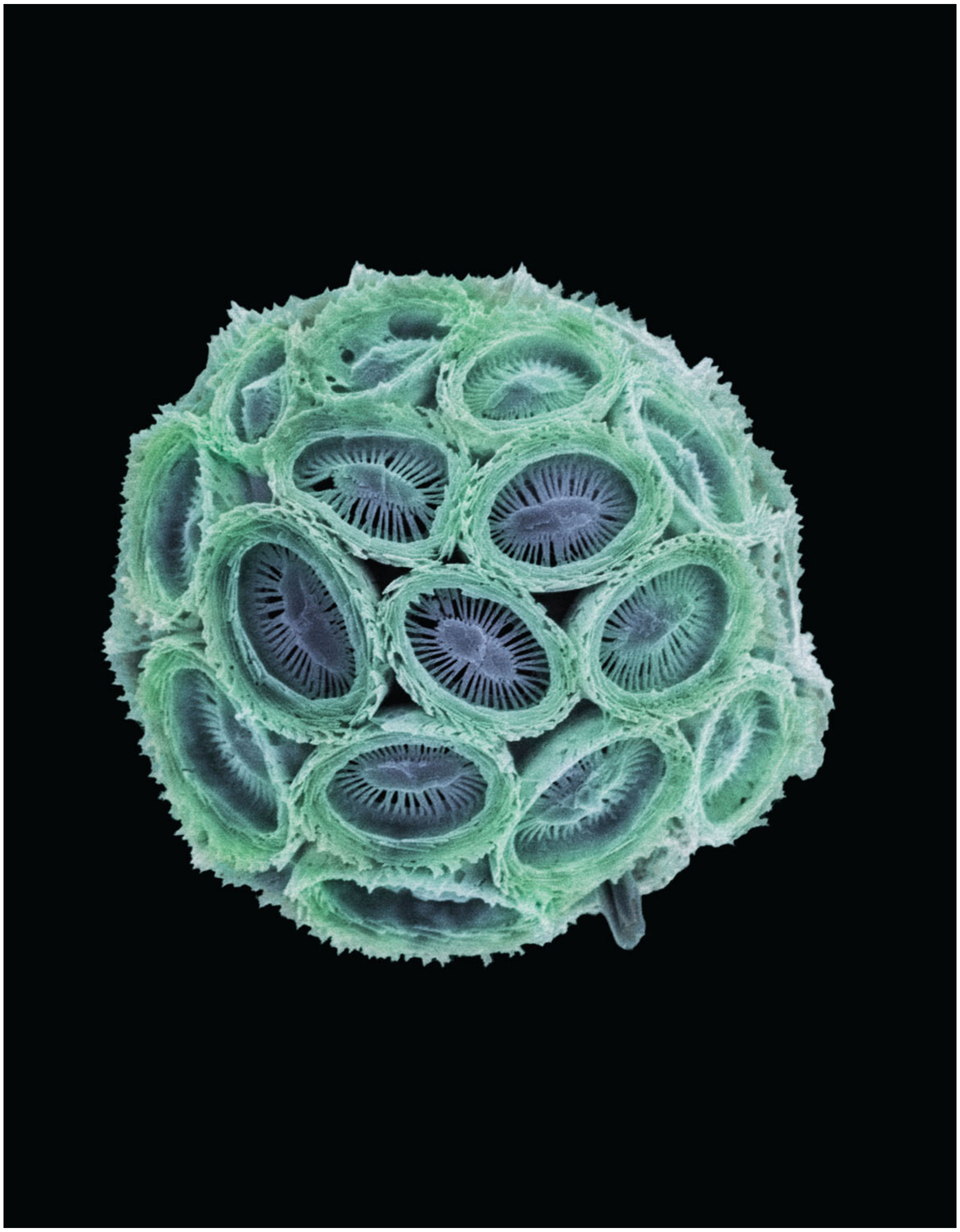
We are entering an age in which knowledge is the prime substitute for matter. Biology, to give just a few more intriguing examples from the text, also contrasts 'hierarchical structure with monolithic structure'; stresses 'environmentally influenced self-assembly' against 'externally imposed form'; and uses a 'limited subset of non-toxic elements' against our use of every element in the periodic table!

This sense of exhilaration and possibility pervades the book as the text covers more than the subjects of materials, spaces and connection. Michael puts people at its heart: 'The biological paradigm, translated into architecture, means putting people at the centre; employing their ingenuity during design, involving them in the richly rewarding act of building and the enjoyment of beauty.' In this breadth of vision he is surely an heir to the likes of such well-regarded pioneers as Christopher Alexander and Victor Papenek.

This century will surely go down as marking the transition not just of the built environment but of the entire economy. If we are to meet the needs of a population of nine billion elegantly and effectively, then we need a different operating system for our entire economy. The circular economy, an economic model which I am passionate about, is another version or expression of the same energising transition Michael identifies: from the take–make–dispose thinking of the original industrial era, an era of mechanistic thinking, to one where the opportunities increasingly lie with closed-loop, feedback-rich systems. And most importantly one where we can anticipate new forms of prosperity, while decoupling from materials and energy constraints. The new edition of *Biomimicry in Architecture* is essential reading on our journey together.

DAME ELLEN MACARTHUR

Introduction



1. Coccolithophores (marine micro-organisms) make their skeletons from calcium carbonate using elements in seawater and are thought to be part of the planet's long-term carbon cycle. In geological periods when carbon dioxide levels in the atmosphere rose, coccolithophores bloomed and, when they died, fell to the ocean floor to form layers of limestone, so transferring carbon from the atmosphere to the lithosphere. The challenge facing humanity now is that the rate of carbon dioxide increase is far in excess of anything that has previously occurred in the history of the planet and beyond a level that can be controlled by correcting mechanisms such as coccolithophores

What do we need to do to achieve true sustainability? Will incremental efficiency improvements and mitigation of negative impacts be enough? Or do we need to set more ambitious aims for the grand project of humanity? What I will argue in this book is that **biomimicry – design inspired by the way functional challenges have been solved in biology** – is one of the best sources of solutions that will allow us to create a positive future and make the shift from the industrial age to the ecological age of humankind. The latter, in my view, is not only eminently possible; we already have nearly all the solutions we need to achieve it.

If biomimicry increasingly shapes the built environment – and I feel it must – then, over the next few decades, we can create cities that are healthy for their occupants and regenerative to their hinterlands, buildings that use a fraction of the resources and are a pleasure to work or live in, and infrastructure that becomes integrated with natural systems. Thousands of years of human culture can continue to flourish only if we can learn to live in balance with the biosphere. This is not a romantic allusion to some intangible Arcadia; what I describe in this book is a route map based on scientific rigour that can be translated by the human imagination into a tangible reality.

For me, there is no better mission statement than Buckminster Fuller's: 'To make the world work for a hundred percent of humanity, in the shortest possible time, through spontaneous cooperation, without ecological offense or the disadvantage of anyone.'[1] How do we achieve this? There are, I believe, three major changes that we need to bring about: achieving radical increases in resource efficiency,[2] shifting from a fossil-fuel economy to a solar economy and transforming from a linear, wasteful way of using resources to a completely closed-loop model in which all resources are stewarded in cycles and nothing is lost as waste. Challenging goals, but if we choose to embark on these linked journeys then there is, in my opinion, no better discipline than biomimicry to help reveal many of the solutions that we need.

Biomimicry in Architecture is a book all about that rich source of solutions, and this new edition reflects the changing state of the art. Biomimicry involves learning from a source of ideas that has benefitted from a 3.8-billion-year research and development period. That source is the vast array of species that inhabit the earth and represent evolutionary success stories. Biological organisms can be seen as embodying technologies that are equivalent to those invented by humans, and in many cases have solved the same problems with a far greater economy of means. Humans have achieved some truly remarkable things, such as modern medicine and the digital revolution, but when one sees some of the extraordinary adaptations that have evolved in natural organisms, it is hard not to feel a sense of humility about how much we still have to learn.

Why is now the right moment for biomimicry? While fascination with nature undoubtedly goes back as long as human existence itself, now we can revisit the advances in biology with the massive advantages of expanding scientific knowledge, previously unimaginable digital design tools and aesthetic sensibilities that are less constrained by stylistic convention. Designers have never had such an opportunity to rethink and contribute to people's quality of life, while simultaneously restoring our relationship with our home – the home that Buckminster Fuller called 'spaceship earth'.[3]

It is true to say that biology proceeds by tinkering (to use Francois Jacob's term[4]) with what already exists, consequently producing some undeniably suboptimal solutions,[5] whereas human invention is capable of completely original creation. The great asset that biology offers is aeons of evolutionary refinement. Biomimicry is neither thesis nor antithesis. At its best, biomimicry is a synthesis of the human potential for innovation coupled with the best that biology can offer.[6] This synthesis exceeds the power of either alone.

This book describes the extent of solutions available in biomimicry, how architects are currently implementing those solutions, and the breadth of scale over which biomimicry is applicable. The book closes with a guide to working effectively with biomimicry and how to deliver the buildings and cities we need for the ecological age.

What is biomimicry?

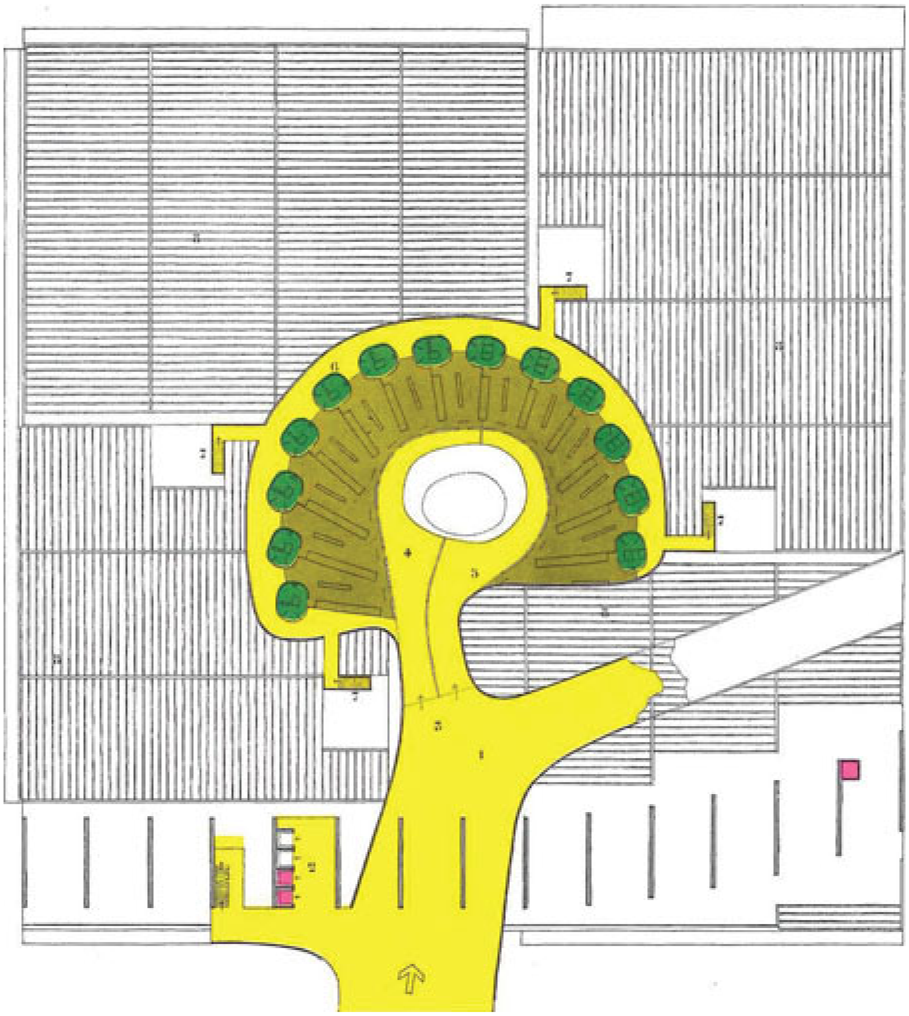
Throughout history, architects have looked to nature for inspiration for building forms and approaches to decoration: nature is used mainly as an aesthetic sourcebook. Biomimicry is concerned with functional solutions, and is not necessarily an aesthetic position. The intention of this book is to study ways of translating adaptations in biology into solutions in architecture.

The term 'biomimicry' first appeared in scientific literature in 1962,[7] and grew in usage particularly among materials scientists in the 1980s. The term 'biomimicry' was preceded by 'biomimetics', which was first used by Otto Schmitt in the 1950s, and by 'bionics', which was coined by Jack Steele in 1960.[8] There has been an enormous surge of interest during the past 15 years, driven by influential and extensively published figures like biological sciences writer Janine Benyus, Professor of Biology Steven Vogel and Professor of Biomimetics Julian Vincent. Julian Vincent defines the discipline as ‘the implementation of good design based on nature’,[9] while for Janine Benyus it is ‘the conscious emulation of nature’s genius’.[10] The only significant difference between ‘biomimetics’ and ‘biomimicry’ is that many users of the latter intend it to be specifically focused on developing sustainable solutions, whereas the former is often applied to fields of endeavour such as military technology. I will be using biomimicry and biomimetics as essentially synonymous.

Since the publication of the first edition of this book, definitions in this field have moved on considerably, including the use of ‘bio-inspired design’ or ‘biodesign’ rather than ‘biomimicry’ or ‘biomimetics’. ‘Biodesign’ emerged as a term partly in the medical world (inventing and implementing new biomedical technologies), partly in robotics, and partly as a broad definition (which formed the title of a book and an exhibition by William Myers[11]) encompassing a range of design disciplines based on biology. The point being asserted in adopting a new term is that both ‘biomimicry’ and ‘biomimetic’ imply copying, whereas ‘bio-inspired’ is intended to include the potential for developing something beyond what exists in biology. I adopt the term ‘biomimicry’ because ‘bio-inspired architecture’ suggests a very broad definition – including everything from superficial mimicking of form all the way through to a scientific understanding of function and how that can inspire innovation. I find ‘bio-inspired engineering’ less problematic because ‘engineering’ implies functional rigour. No term will perfectly capture what we are doing and, as with any negotiations, it is more important to agree on common ground that unites the disciplines – being trans-disciplinary, evidence-based, focused on function and directed towards delivering transformative change[12] – rather than battling over fine distinctions that divide them. Biomimicry and biomimetics are now widely understood as functionally based approaches. I’m not aware of anyone in the field who restricts themselves to only those solutions that exist in nature, so I am not particularly troubled by the asserted associations of ‘mimicry’. Time will tell which proves to be the most widely accepted term in an architectural design context. There are some other terms that are worth clarifying: ‘biophilia’, ‘biomorphic’, ‘bio-utilisation’ and ‘synthetic biology’. ‘Biophilia’ was a term popularised by the biologist E. O. Wilson[13] and refers to a hypothesis that there is an instinctive bond between human beings and other living organisms. ‘Biomorphic’ is generally understood to mean design based on biological forms. ‘Bio-utilisation’ refers to the direct use of nature for beneficial purposes, such as incorporating planting in and around buildings to produce evaporative cooling. We will see later in Chapter 3 that this approach has a major role to play in biomimetic systems thinking. ‘Synthetic biology’ refers to the design and fabrication of living components and systems that do not already exist in the natural world and the redesign and fabrication of existing living systems. The key distinction between biomimicry and synthetic biology is that the former is not currently trying to create living components.

This image is not available due to rights permissions

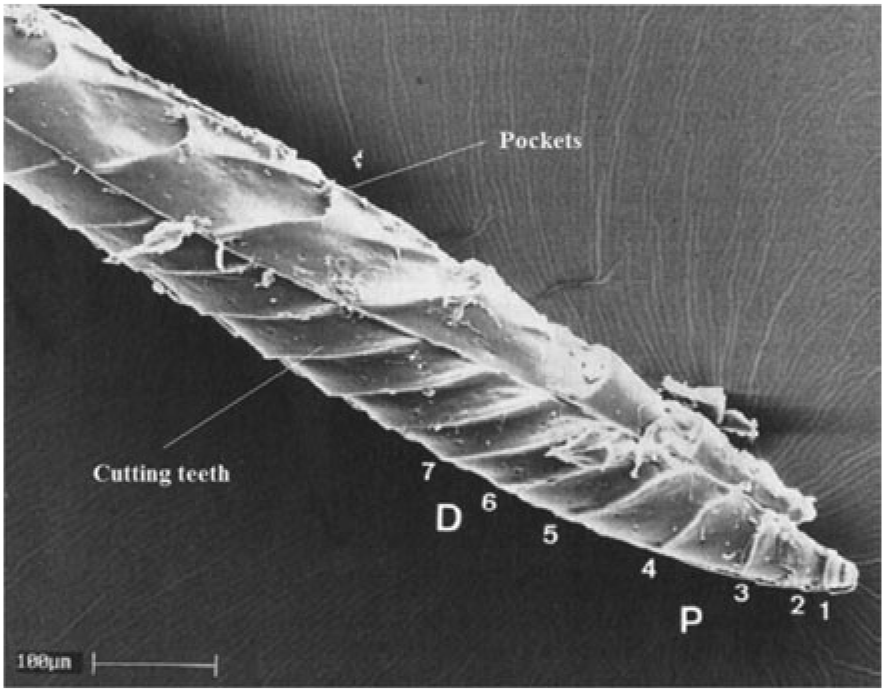
From an architectural perspective, there is an important distinction to be made between ‘biomimicry’ and ‘biomorphism’. Twentieth-century architects have frequently used nature as a source for unconventional forms and for symbolic association. Biomorphism has produced majestic works of architectural form, such as Eero Saarinen's TWA terminal (fig. 2), and was used to great symbolic effect by Le Corbusier (fig. 3). But, in contrast, biomimicry is concerned with the way in which functions are delivered in biology. The distinction is important because we require a functional revolution of sorts, and I firmly believe that it will be biomimicry rather than biomorphism that will deliver the transformations described above.



3. Le Corbusier, possibly the greatest symbolist architect of all time, appears to have made deliberate reference to the cleansing function of kidneys in the design of the washrooms for the unbuilt Olivetti Headquarters project

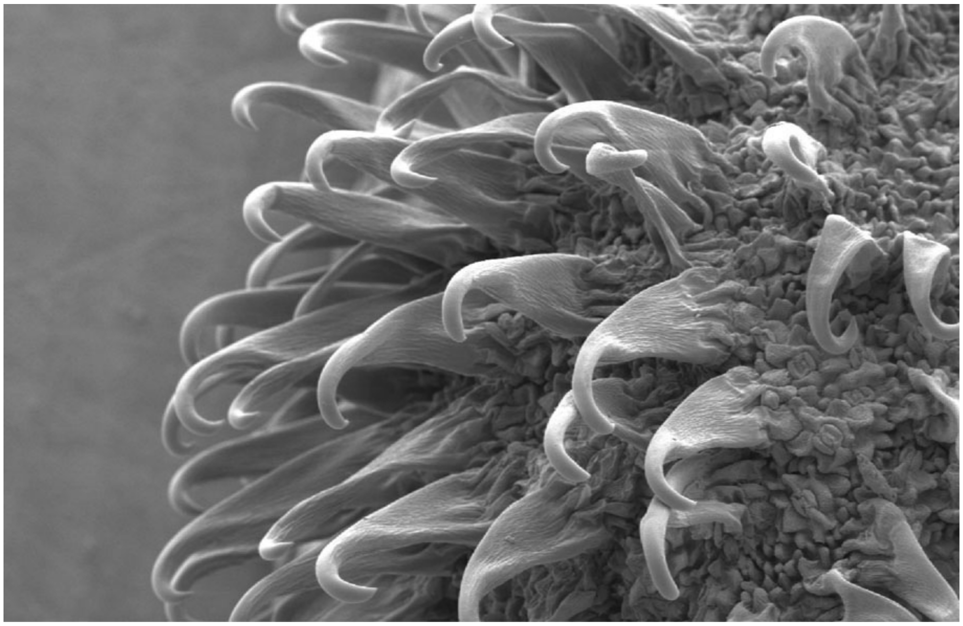
There is still a role for biomorphic architecture. Biomorphism's use of forms from nature, and its use of associative symbolism, can be deeply compelling. The two approaches can co-exist in one building, and biomorphism can add further meaning than would be achieved from a purely technical use of biomimicry. Biomorphism is a formal and aesthetic expression; biomimicry is a functional discipline. It is also worth considering the limitations of biomimicry. Just as with any design discipline, it will not automatically produce architecture, and we should be wary of trying to become purely scientific about design. Architecture always has a humane dimension – it should touch the spirit, it should be uplifting, and it should express the age in which it was created.

The word 'natural' is used in many contexts to imply inherent virtue or 'rightness', and it would be easy to misconstrue biomimicry as the pursuit of solutions that are 'more natural'. This is not the aim. There are certain aspects of nature that we definitely do not want to emulate: voracious parasitism to name just one. There is also a danger in romanticising nature. What I believe nature does hold that is of enormous value is a vast array of products (for want of a better word) that have benefitted from a long and ruthless process of refinement. Evolution could be summarised as a process based on genetic variability, from which the fittest are selected over time. The pressures of survival have driven organisms into some almost unbelievably specific ecological niches and into developing astonishing adaptations to resource-constrained environments. The relevance of this to the constraints that humans will face in the decades ahead is obvious.



4. The wood wasp shows how biology has solved the problem of drilling into wood without a rotating axle

What about sceptics who regard human achievements as superior to nature? There are no combustion engines in biology, plants are less efficient at converting solar energy than modern photovoltaics and there are no high-speed rotating axles in nature either. All true – but no one is suggesting that what exists in biology should be the limit of what we should consider exploring in technology. In many cases, biology has solved equivalent challenges with greater economy of means. As a case in point: without a rotating axle, how can you drill into wood? The wood wasp's solution is a reciprocating drill, made of two shafts that are semi-circular in cross-section, each with a barb at the pointed lower end (fig. 4). The two halves can slide back and forth relative to each other so that, when a barb on one side latches into a shallow groove in a tree, the wasp can pull against that side to push the other half of the drill further into the wood. The result is a zero net pushing force drill, which prevents breaking and buckling, and which is the perfect solution for very human applications, such as delicate neurosurgery. A neurosurgical probe has been developed based on the wasp ovipositor principles, offering advantages that rotating axles cannot match: it can drill around bends.[14] In summary, biomimicry is a powerful innovation tool that can allow architects to go beyond conventional approaches to sustainable design and deliver the transformative solutions we need.



5. Highly magnified view of a burdock burr, which inspired one of the best-known examples of biomimicry – Velcro

Origins

We know from Leonardo da Vinci’s sketchbooks that he closely studied the forms of skulls and birds’ wings: he was, in many ways, a pioneer of biomimicry. We also know that Filippo Brunelleschi referred to the forms of eggshells when designing the Duomo in Florence and it is quite likely that deriving design inspiration from nature goes back even further.

More recently, there are some well-documented examples, such as the invention of Velcro (fig. 5) around 1948. In the past decade there has been a phenomenal flourishing of biomimicry, as more and more designers respond to the demand for sustainable products. The Daimler Chrysler biomimetic concept car, inspired by the surprisingly streamlined and roomy boxfish, surgical glue developed from an understanding of sandcastle worms[15] (fig. 6) and even ice cream that embodies lessons from arctic fish[16] have all delivered a superior product by learning from adaptations in natural organisms.

6. A colony of sandcastle worms, assembled with the biological equivalent of two-part epoxy adhesive

The state of the art

Since the publication of the first edition of this book, the discipline of biomimicry has grown substantially. According to academic Dr Nathan Lepora,[17] fewer than 100 papers per year were written on biomimicry in the 1990s; this figure has increased to several thousand papers per year in the first decade of this century. Much of this activity has been in the fields of robotics and materials science (fig. 7). The opportunity now exists for architects to fully embrace a source of innovation that has transformed other fields of design. The Mediated Matter design research group, founded by Neri Oxman at MIT, is showing the potential for using biologically derived materials combined with additive manufacturing (often referred to as 3D printing). Achim Menges and his colleagues at the University of Stuttgart are showing, in compelling built form, what can be achieved from a deep understanding of biological structures combined with new digital design and fabrication tools.

The projects featured in this book follow a fairly typical pattern for innovation: starting at a conceptual level, then realised as small-scale experiments and subsequently as large-scale but relatively simple enclosures. The first examples of more complex and integrated approaches to biomimicry are just emerging, as indicators of progress towards wider market acceptance. While the pace of innovation can be painfully slow, I believe that biomimicry has the potential to accelerate this, by identifying a truly sustainable end-goal and through its wealth of source material.

Biomimetic projects completed to date offer a tiny glimpse of the potential that could be created from a sourcebook we are just beginning to explore. High-strength polymers and super-efficient structures, fire detectors and fire retardants, materials made from atmospheric carbon, zero-waste systems: all of these exist in biology as a resource of ideas from which architects can learn to create buildings and cities better tuned to the demands of our age. While much sustainable design has been based on mitigating negatives, biomimicry points the way to a new paradigm based on optimising positives and delivering regenerative solutions.

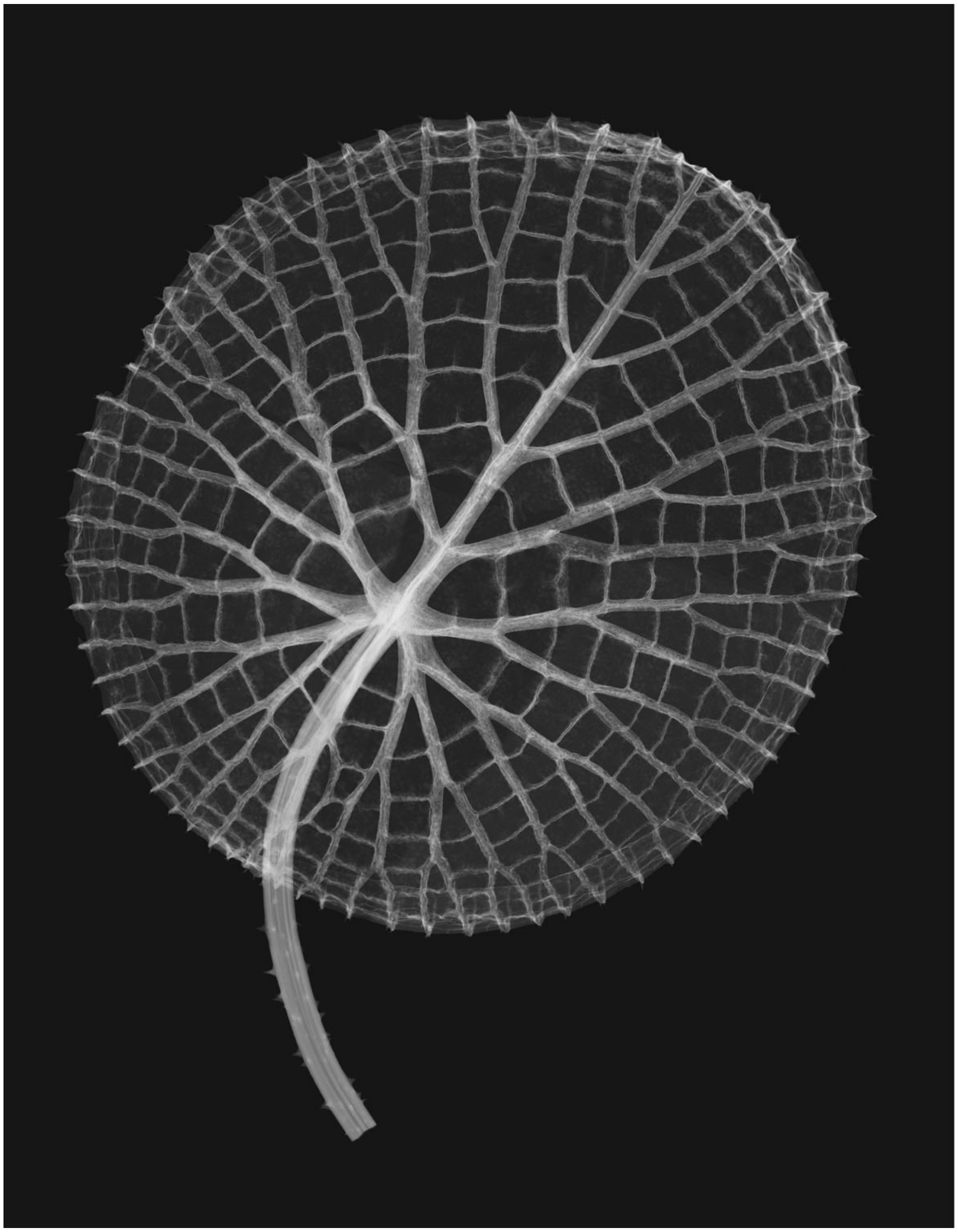
7. Festo robotic jellyfish. Robotics is the field in which there has been the greatest surge of interest in biomimicry over the past decade

One of the key questions is how we can accelerate the pace of innovation in the construction industry and in design for solutions that deliver substantial improvements in performance and contribute to people's well-being. I believe that increasing knowledge and new biomimetic projects help to drive the high-level discussion and action that can help to bring about a step-change in the speed of uptake of biomimicry in architecture.

> *You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete.*
> RICHARD BUCKMINSTER FULLER [18]

Chapter One

How can we build more efficient structures?

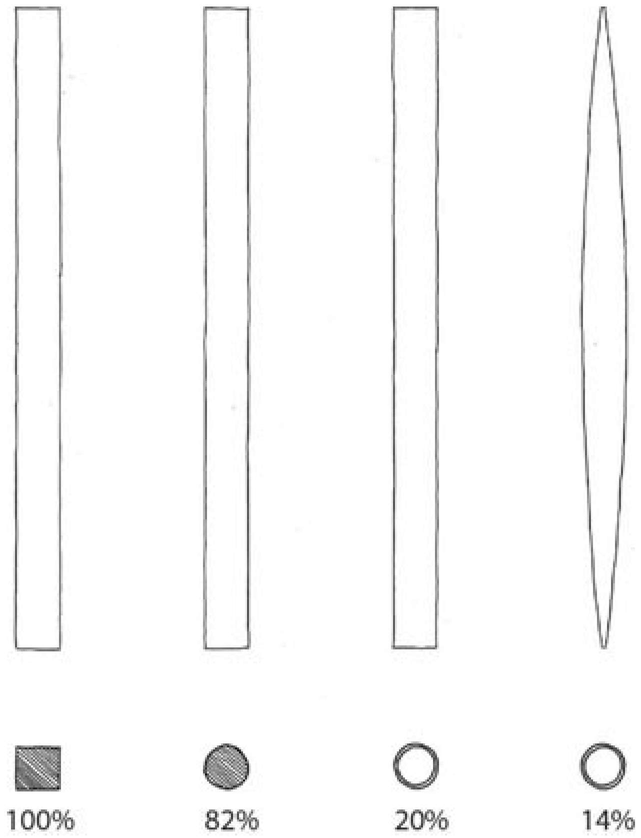


8. X-ray image of an Amazon water lily leaf showing an example of how robust structures are created in nature with a minimum of materials. The network of ribs stiffens the large area of leaf without adding excessive thickness

In nature, materials are expensive and shape is cheap.
PROFESSOR JULIAN VINCENT [19]

This observation captures the essence of biological structures. In technology, it is generally the shape that is expensive instead.[20] Nature makes extremely economical use of materials, often achieved through evolved ingenuity of form. Using folding, vaulting, ribs, inflation and other means, natural organisms have created effective forms that demonstrate astonishing efficiency. The many manifestations of this in natural organisms provide a rich sourcebook of ideas for structures that could be radically more efficient than those found in conventional architecture.

Why is nature this way? The pressures of survival in all its varied aspects – finding sustenance, thermoregulating, mating and avoiding predation, among many other factors – have, over aeons, ruthlessly refined the structures and other adaptations that genetic mutation and recombination has created. The process continues, of course, but what we can observe in nature today is many of the best structures, evolved throughout the history of life on earth. The principle for architecture that emerges from observing is: **less materials**, **more design**. Exploring this paradigm, we will see an array of examples showing how minimum materials can be used to maximum effect.



9. Sketch showing how four equally stiff structural elements can be made with varying degrees of efficiency. By using shape and putting the material where it needs to be, it is possible to use only 14 per cent of the material of a solid square section (after work by Adriaan Beukers and Ed van Hinte in *Lightness: The Inevitable Renaissance of Minimum Energy Structures*)

Hollow tubes

Nature builds simply and economically, often meeting both goals simultaneously by making hollow tubes. Nature is abundant in examples that demonstrate this structural principle, such as human bones, plant stems and feather quills. If one takes a square cross-section of solid material with a side dimension 24 mm (fig. 9), it will have the same bending resistance as a circular solid section of diameter 25 mm with only 81.7 per cent of the material. Similarly, a hollow tube with only 20 per cent of the material of the solid square can achieve the same stiffness. In engineering terms, material has been removed from areas close to the neutral axis and placed where it can deliver much greater resistance to bending – achieving the same result but with a fraction of the material.

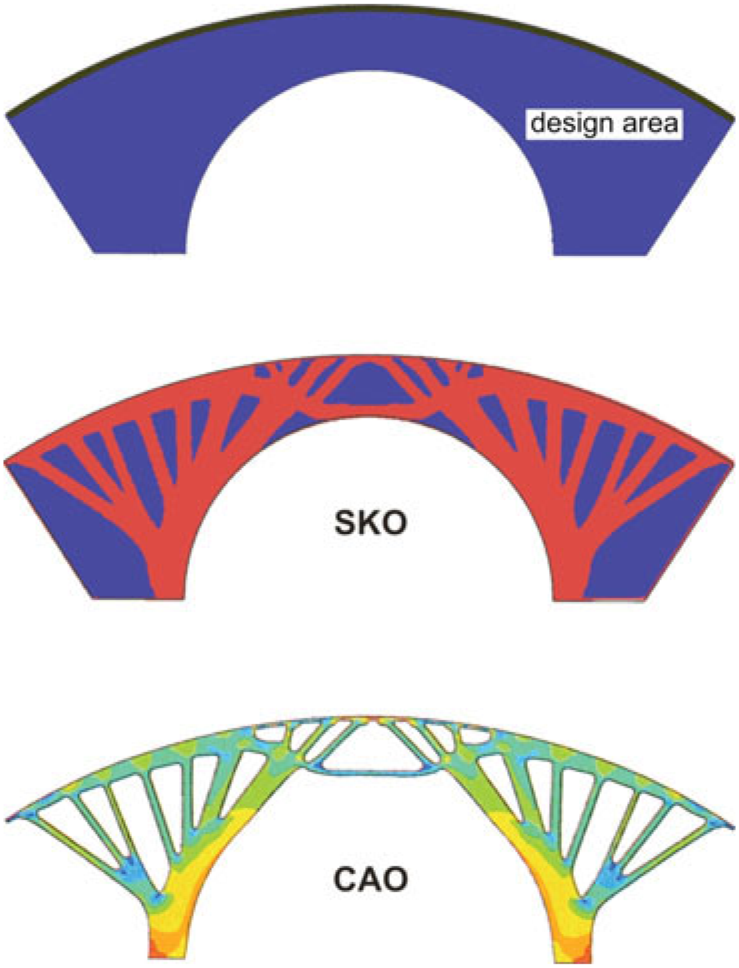
One plant in particular shows how hollow tubes can be applied at larger scales in nature. Bamboo species can reach 40 m in height. How do they maintain strength over this length? One of the ways in which a tubular element can fail under loading is through one side of the tube collapsing in towards the central axis, leading to overall buckling. Bamboo solves this by interrupting smooth tubular growth with regular nodes, which act like bulkheads (fig. 10). The nodes provide great resistance to structural failure, and are part of what has facilitated bamboo's lofty accomplishments. Bamboo is, by strict taxonomy, actually a species of grass which has achieved such wild success that it resembles the scale of a tree. This plant's solution seems to apply so widely that it begs the question: why aren't more trees hollow tubes? The answer derives from the different forms that they strive to grow into: trees generally create a canopy of cantilevering branches, rather than the multiplicity of stems characteristic of grasses. Bamboo offers solutions to tubular structural elements, while trees offer a biomimic further solutions to holistic structural issues, since they face different pressures than grasses.

10. The regular nodes in the stems of bamboo act like bulkheads stiffening the tube and preventing the normal way in which tubular structures fail

Trees: solid forms

Our understanding of trees and how lessons from them can be applied to engineering has developed enormously in recent years, particularly with the work of Claus Mattheck.[21] In nature, biological forms follow a simple rule, which he describes as *the axiom of uniform stress.* In locations of stress concentration, material is built up until there is enough to evenly distribute the forces; in unloaded areas, there is no material. Trees also demonstrate the idea of optimised junction shapes that avoid stress concentrations and can adapt over time. The result approaches optimal efficiency, in which there is no waste material and all the material that exists is carrying its fair share of the load. By contrast, many steel and concrete structures are designed so that the most onerous load conditions (which only occur in specific locations) determine the size of the whole beam or column.

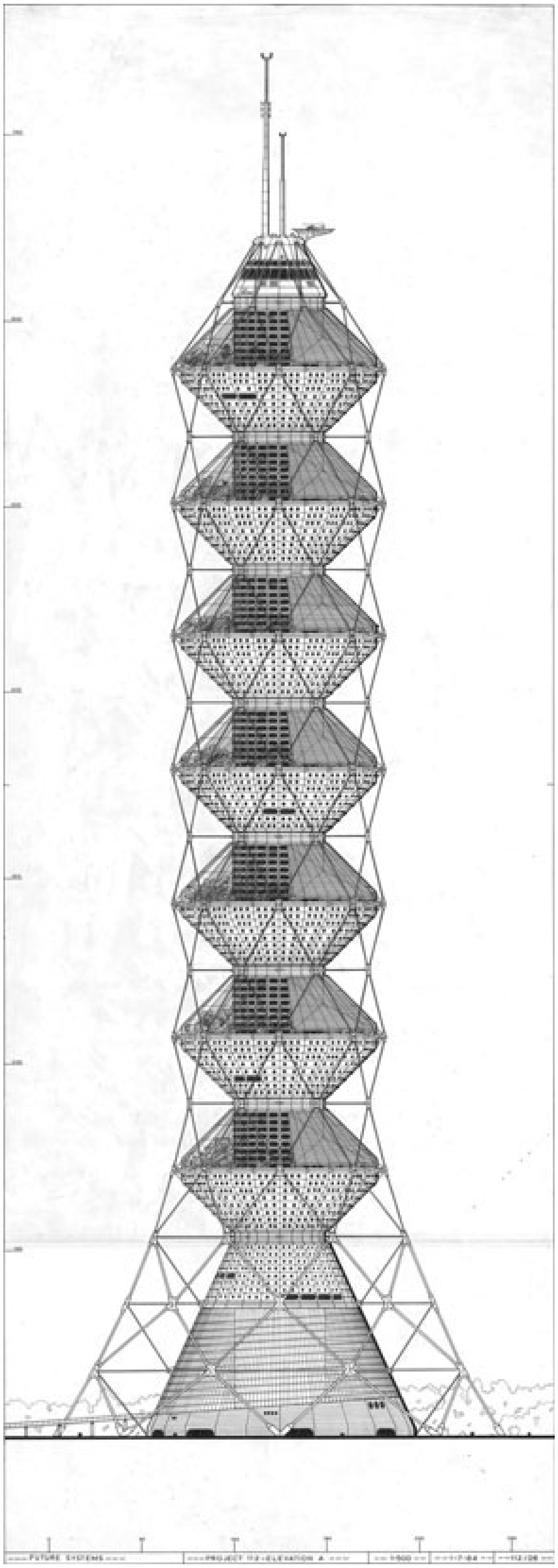
With his team at Karlsruhe Research Centre, Mattheck developed a design method that utilises two software processes (fig. 11) to create forms of biological design that are effectively identical to the refinements found in nature. The program allows designers to subject a rough structural computer model to the kind of forces that would be experienced in reality. These include snow, wind and seismic loading, as well as loads imposed by the building's use. The first stage uses 'Soft Kill Option' (SKO) software to eliminate material in zones where there is little, or no, stress. Then a 'Computer Aided Optimisation' (CAO) program refines the shapes and, where necessary, builds up material at the junctions to minimise stress concentrations that could lead to failure. The designer is free to decide whether they like the output and find alternative ways to achieve structural integrity. Mattheck likens this process to starting with a roughly axed piece of timber, which is then carved to the near-final shape (the SKO stage) before being sanded and polished (CAO). The results can be surprisingly organic in form, and far more efficient than conventional structures.[22] The designer Joris Larman used this to develop a number of elegant pieces of furniture and a bridge that is to be 3D printed and will span over a canal (fig. 12). We could do the same with buildings and achieve huge increases in material efficiency while producing more elegant and structurally legible forms.



11. Diagram showing Claus Mattheck's design refinement process using 'Soft Kill Option' (SKO) and 'Computer Aided Optimisation' (CAO) software

The key difference between trees and bones is that, in the former, material cannot be removed whereas in bone tissue it can be. Trees consequently grow as solid forms. This might seem surprising, given the hollowness of many bones. The explanation probably lies in the fact that there is not the same selective pressure for lightness in stationary trees as there is in animals that must move at speed to either catch, or avoid becoming, prey. Most of the bulk of a tree is dead material (only the outer layers remain alive), whereas bones are continually being reformed and recycled. One other possible explanation is that the solid core of trees functions to some extent as a compression core to resist the tension created by the outer sapwood, which grows in helical patterns up and around the trunk. This structural form has some similarities with Future Systems’ Coexistence Tower (fig. 13).

12. 3D-printed bridge by Joris Larman Lab demonstrating the expressive and material-efficient results of designing with SKO software


FUTURE SYSTEMS
PROJECT 112 : ELEVATION A
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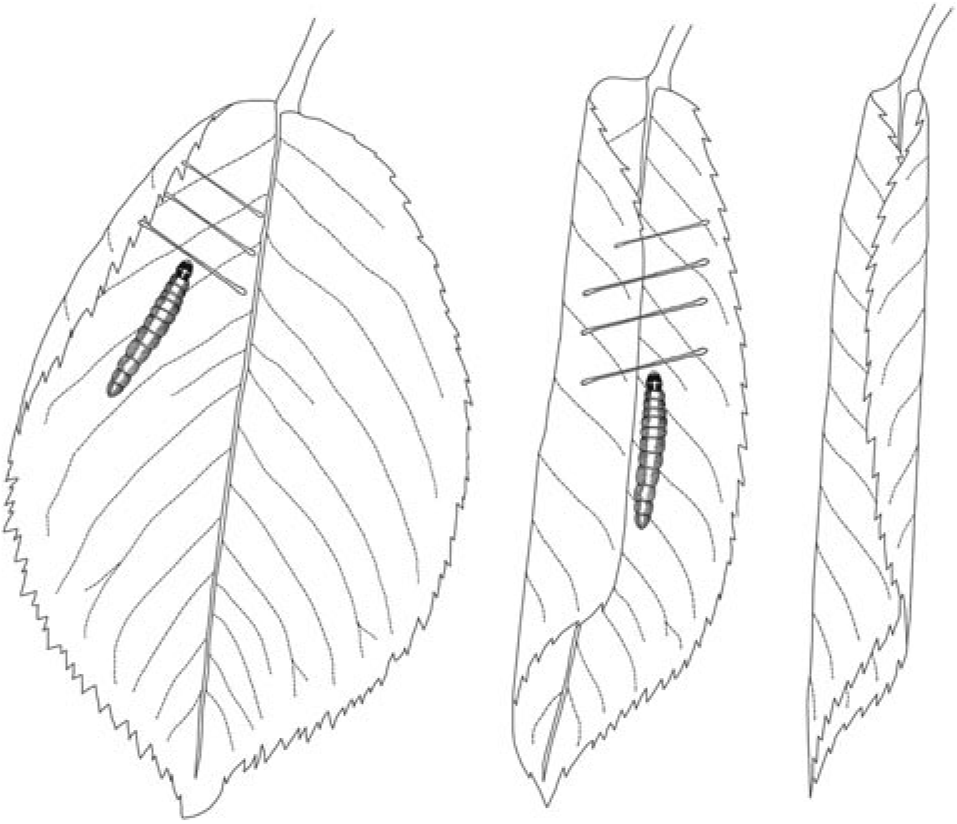
13. Coexistence Tower by Future Systems. The compression core and the helical arrangement of tension members around the perimeter have functional similarities with the structure of tree trunks

14. Trees growing in the shallow soils of rainforests have evolved buttress roots that resist overturning

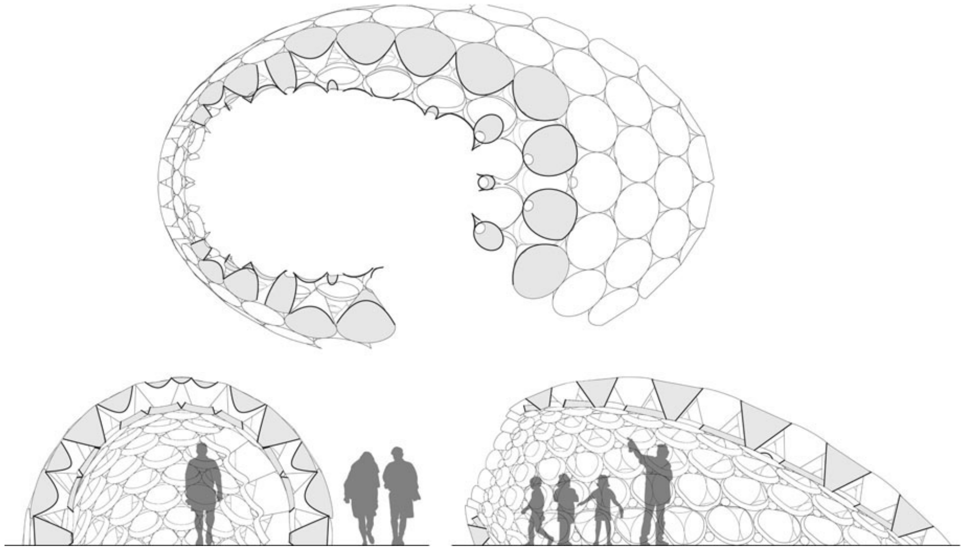
The root forms of trees could also inspire new approaches to creating foundations for buildings. The formation of a wide, stiff base effectively moves the pivot point some distance from the trunk and, on the opposite side, a branching network of roots mobilises a vast amount of soil as ballast to resist overturning.[23] In rainforests, where soils can be relatively shallow and therefore cannot provide the same resistance as those in temperate climates, trees have evolved pronounced buttresses (fig. 14) which actually work in tension to prevent overturning.[24]

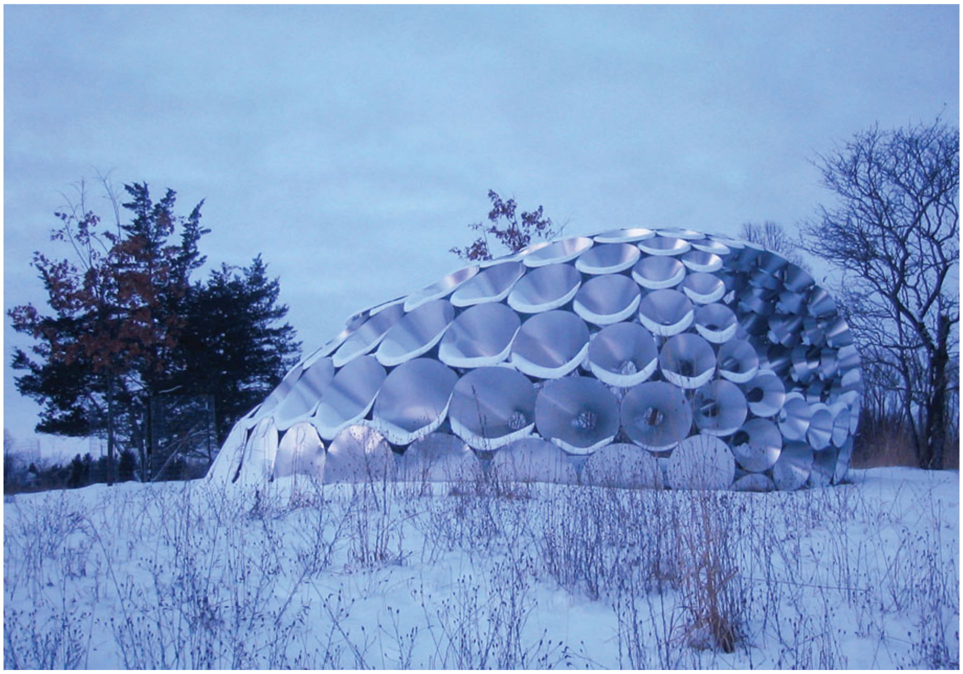


15. The leaf roller caterpillar manipulates flat leaves into tubular forms by attaching threads across the surface and then shortening the threads in a manner similar to a ratchet strap

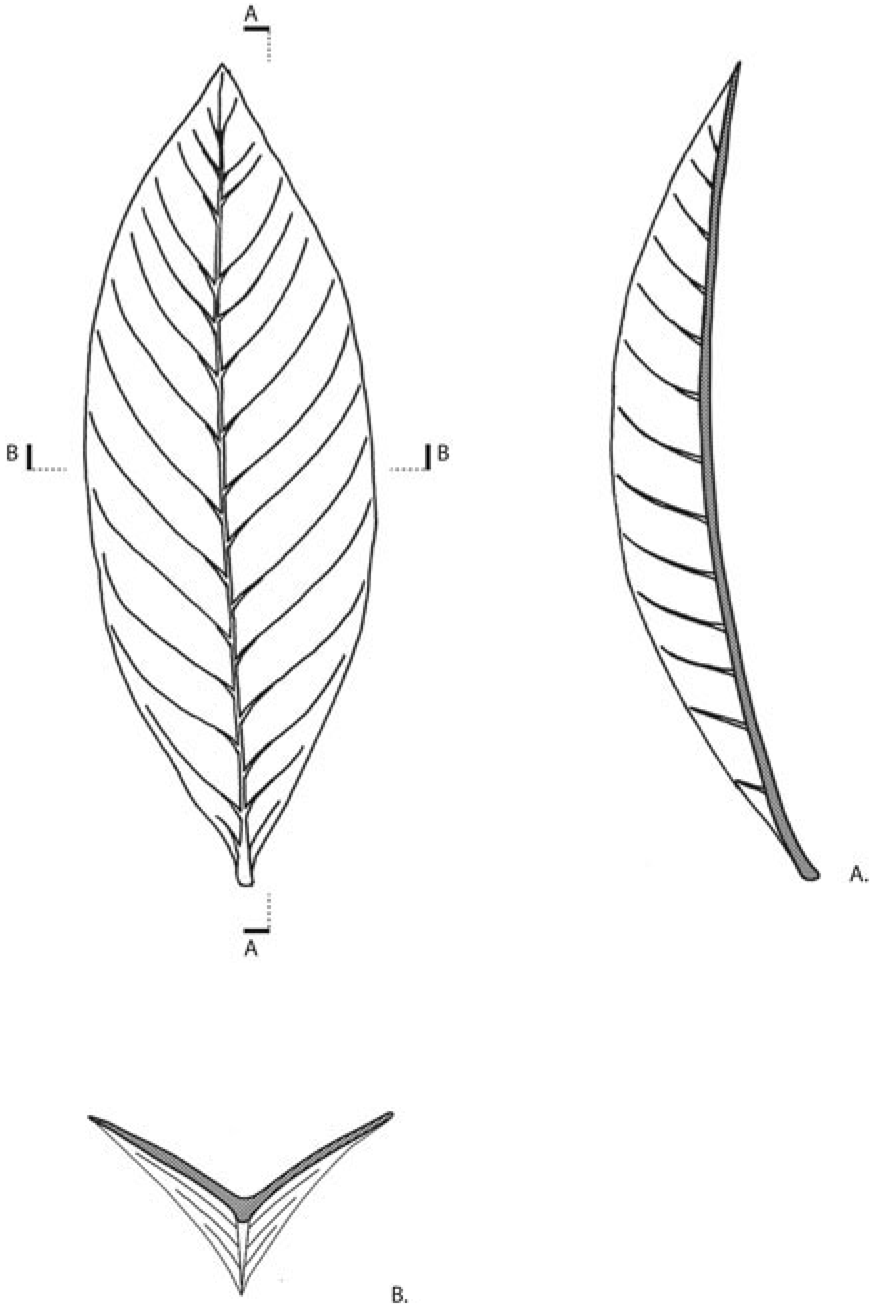
Transformations of planar surfaces

One of the simplest ways to transform a planar surface into something that provides protection is to roll it. The leaf roller caterpillar (genus *Aenea*) wraps a leaf into a tube, secures it with silk, and thus makes a structure within which it carries out its metamorphosis (fig. 15). The caterpillar uses this tube structure for a week, but recent research shows that it is then used by other organisms, and plays a significant role in increasing the density and diversity of arthropods. Similar ingenuity is evident in PLY Architecture's elegant pavilion in Matthaei Botanical Gardens, Michigan (figs 16 & 17). Sheets of laser-cut aluminium were rolled into cones and then assembled based on patterns of phyllotactic geometry.

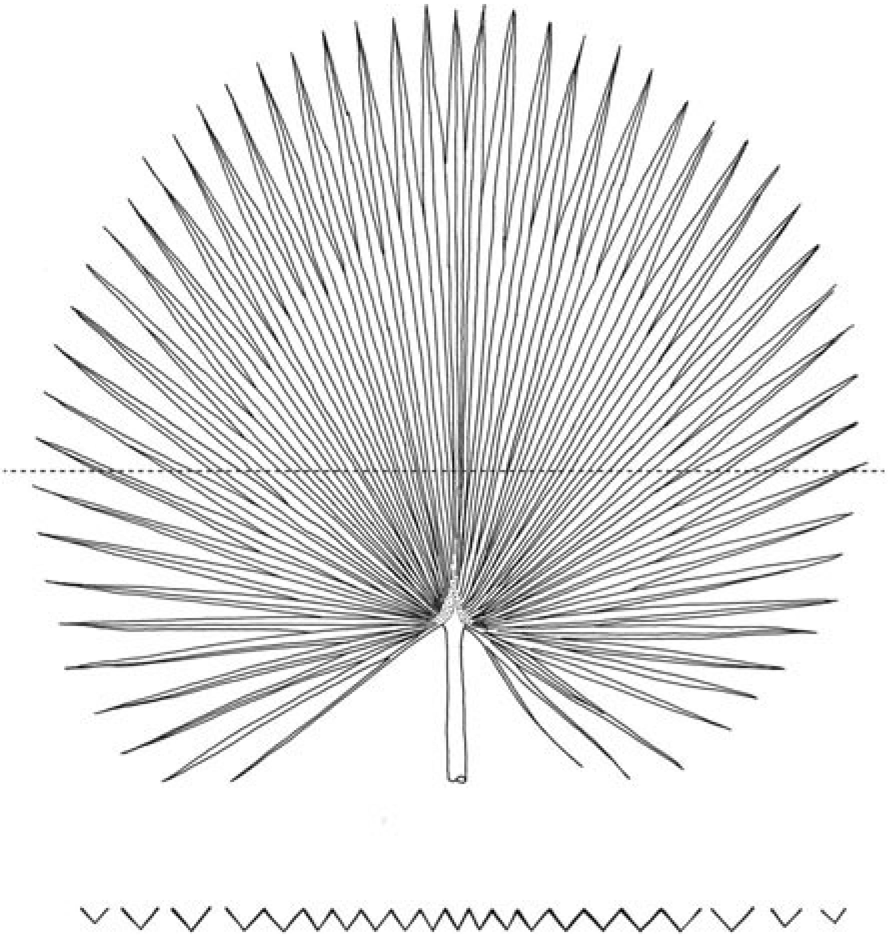




16–17. The Shadow Pavilion by PLY Architecture showing how a thin planar surface can be rolled into an element that generates a distinctive building form



18. The Southern Magnolia leaf, stiffened through a combination of a curve and a fold

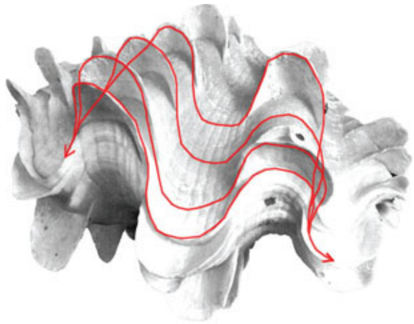


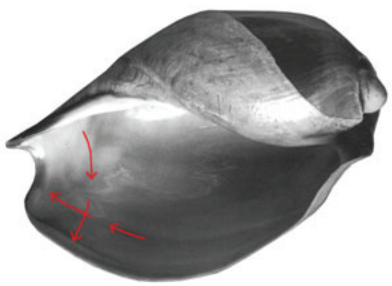
19. Fan palm leaves – an elegant example of how folds can transform a large, thin surface into a structure that can cantilever from a single point of support

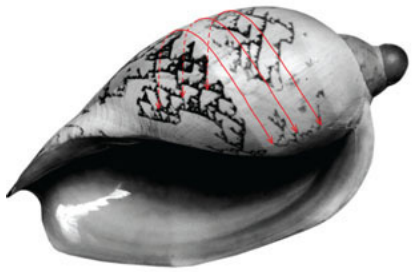
Plants have had to evolve ways to present large amounts of photosynthetic surface to absorb light. But a larger surface area needs more structuring, since growing bigger leaves by increasing their thickness has significant drawbacks. Curves and folds have evolved to create stiffer elements out of thin material. In the case of the Southern Magnolia, the fold occurs along the midrib and each half of the leaf is curved (fig. 18). Both the fold and the curve contribute to the leaf's stiffness. In rainforest environments, daylight at forest-floor level is scarce and many plants have responded with large leaves folded into fan forms (fig. 19).

A stunning example of stiffening a thin surface can be found in the giant Amazon water lily (*Victoria amazonica*). Leaves of up to 3 m in diameter with smooth top surfaces are strengthened on their undersides by a radial, branching, network of ribs to an extent that can support the weight of a small child. The principle of using ribs to stiffen a thin surface may well have inspired engineers to design similarly efficient structures, and the concept could be applied widely.

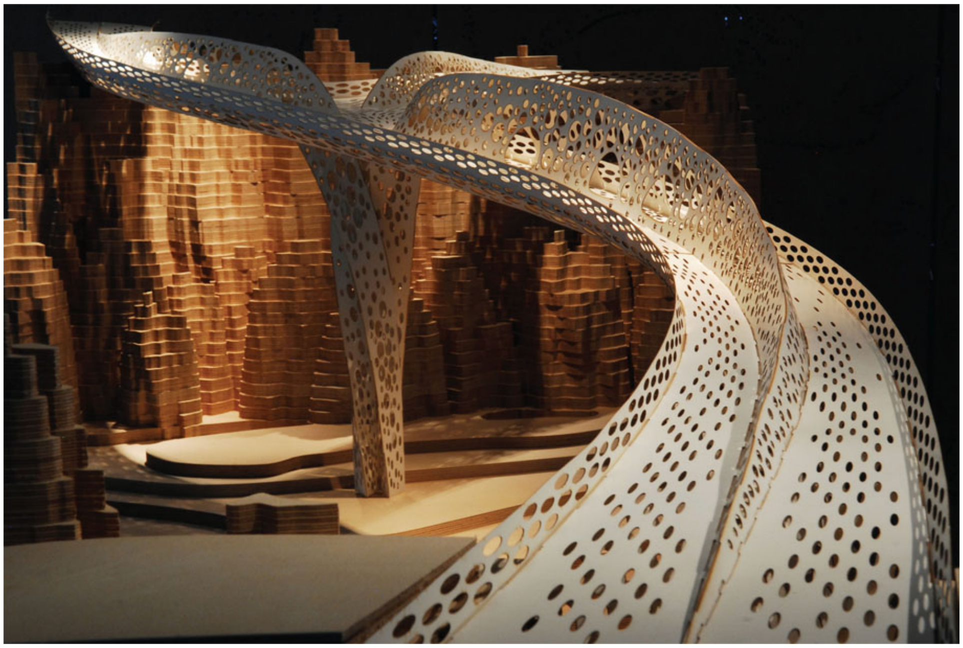
Architects Tonkin Liu, working with structural engineer Ed Clark at Arup, were inspired by the forms of marine molluscs and techniques from tailoring to develop a new form of construction derived from planar surfaces. They refer to this as a 'shell-lace structure' (figs 20 & 21). Just as in the molluscs, the structure derives its stiffness from the articulation of a thin surface: folds increase the effective structural depth, curves create added stiffness and twists provide a degree of triangulation. The end product is an extremely elegant structure, constructed with a minimum of materials, deriving its strength from its shape rather than its mass.







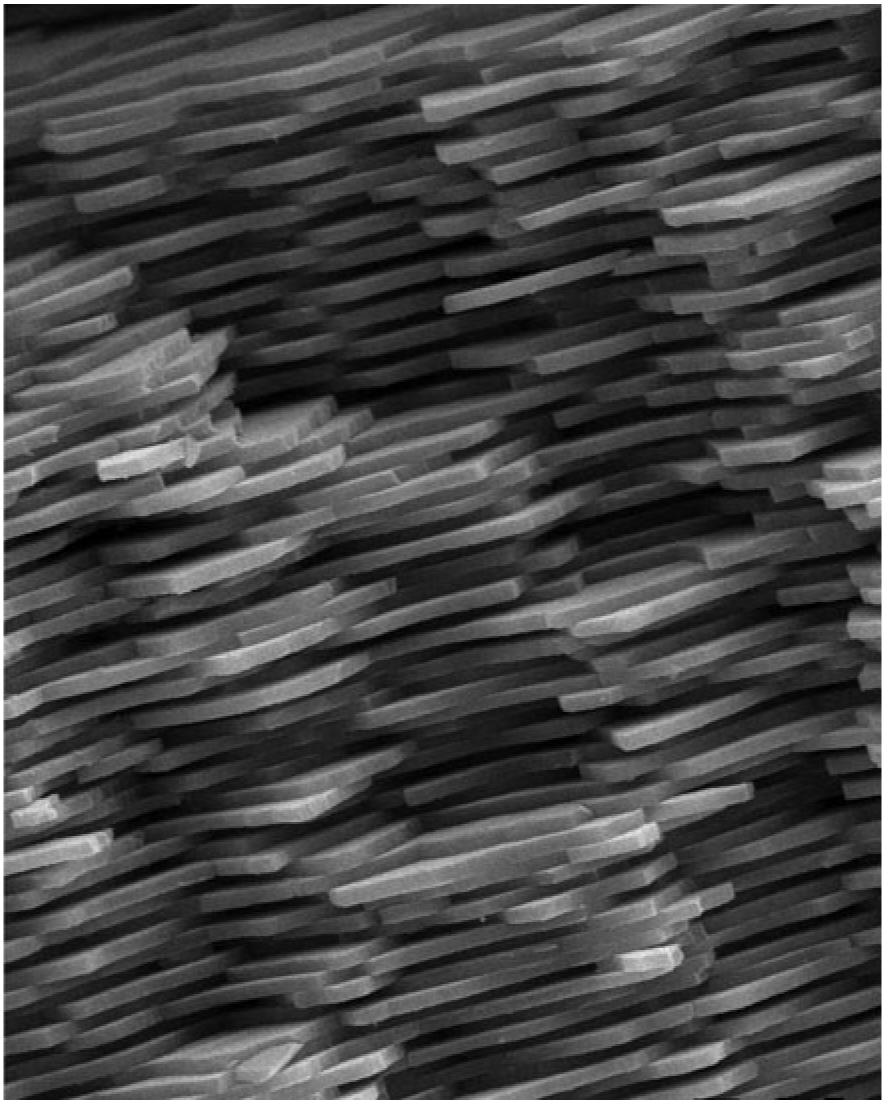
20. Diagrams by Tonkin Liu Architects showing how structural principles from shells were analysed



21. The Shi Ling Bridge designed by Tonkin Liu Architects and structural engineer Ed Clark of Arup – an example of a 'shell-lace structure' that achieves efficiency of materials by exploiting vaulted, folded and twisted forms from shells

Shells and domes

Nature is an accomplished maker of shells and domes.[25] One such builder whose specifications have been thoroughly scrutinised is the abalone (fig. 22). It has evolved a shell that electron microscopy reveals to be made of polygonal plates of calcium carbonate, bonded together with a flexible polymer mortar. The result is a material 3,000 times tougher than the chalk that makes up 95 per cent of its bulk. Whereas we tend to make homogenous materials through which a crack, once started, readily propagates, nature has evolved a matrix of hard platelets with phenomenal resistance to cracking. Each platelet creates a point at which a crack stops and must then start afresh on a new platelet if it is to continue through the material. A degree of flexibility in the polymer helps to spread concentrated loads over a larger area of shell.



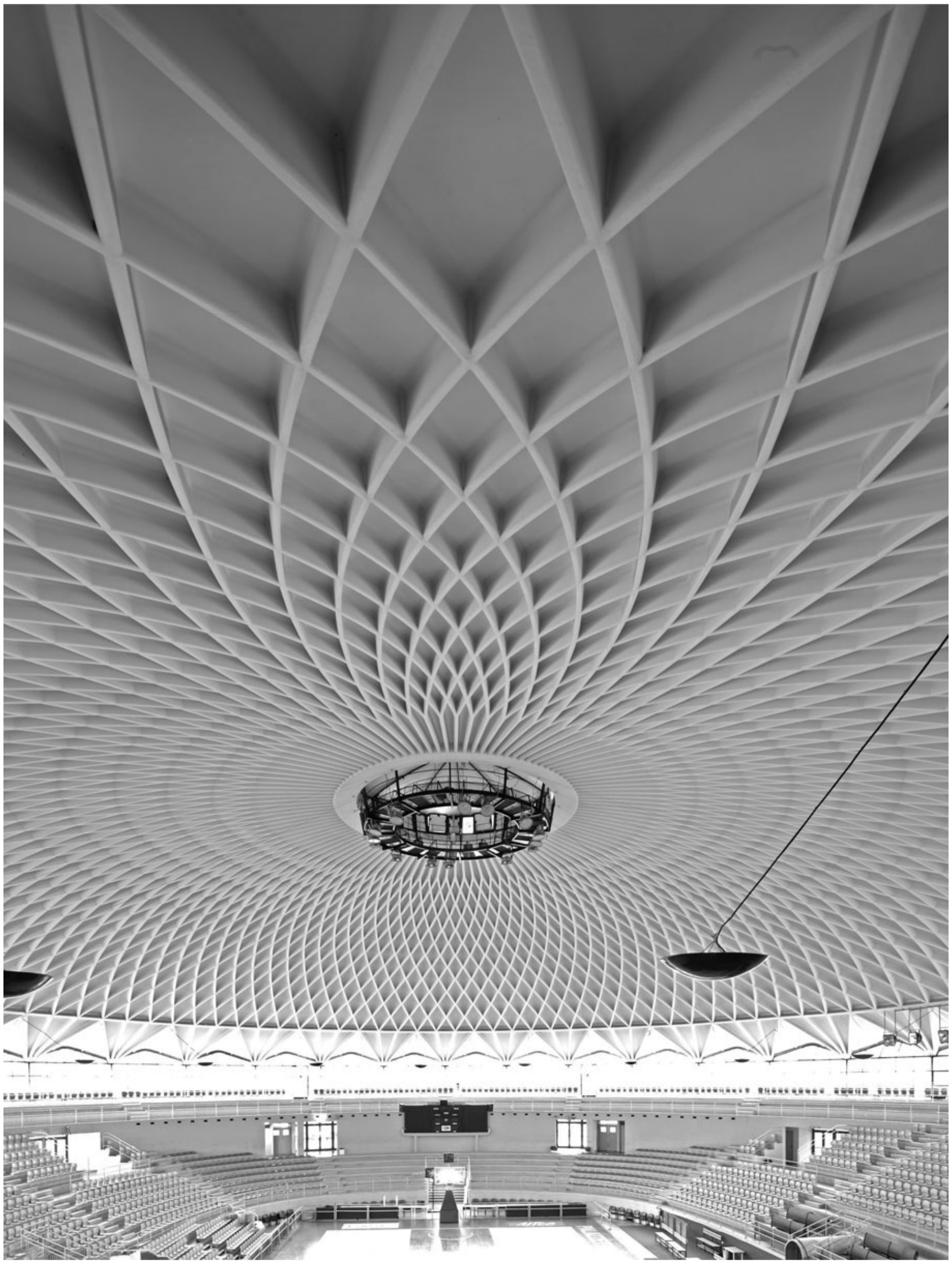
22. Shells may be one of the earliest sources of biomimicry, but now designers can benefit from the scientific knowledge that reveals how their microstructure contributes to their phenomenal toughness

23. Mapungubwe Interpretation Centre designed by Peter Rich Architects using Guastavino vaulting – similar to an abalone shell and made with basic materials, such as sun-baked earth tiles

There is a vernacular method of construction called Guastavino vaulting (fig. 23) that has interesting parallels with the abalone and recently experienced a return to favour. This technique, named after the Valencian architect and builder Rafael Guastavino (1842–1908), involves, at its simplest, building a lower layer of terracotta tiles out from a circular concrete ring beam. This can be achieved without formwork as a plaster of Paris mortar is used, from which the tiles absorb moisture rapidly enough to form a good bond after half a minute. A second layer of tiles laid at a diagonal is applied on top with a stronger cement mortar, and then a third layer at the opposite diagonal. The result is an extremely strong shell structure that can span large distances and can be worked into a rich variety of forms. While this form of construction predates our current understanding of the detailed structure of the abalone, this does not stop us developing the idea further with biological inspiration. Is the origin biomimetic in the sense in which we use it now? This is an interesting question, as some vernacular architectural solutions could be adopted as genuinely biomimetic, allowing biomimicry to demonstrate its range of application from lowtech to cutting-edge contemporary technologies. Taking inspiration from the abalone's functional properties, we could potentially use a flexible mortar to increase a structure's crack resistance and spanning capabilities. We could also learn from molluscs to form corrugations and push spanning distances even further while using minimal quantities of material. In countries where earth tiles baked in the sun are commonly used, this approach offers huge potential to maximise the effectiveness of local materials and local labour to shape expressive and efficient structures.

24. The Savill Building by Glenn Howells Architects. By using small sections of timber in a highly efficient form, gridshells can achieve factor-15 savings in resource use

Timber gridshells (fig. 24) could be considered transformations of planar surfaces; indeed, they are often built by starting with a flat grid and then distorting it into shape. However, the structural aim is not to form a stiffened plane but to get a series of linear elements – usually wood – to act together as a shell. Domes and shells were almost undoubtedly first inspired by studying natural examples. Some gridshells have achieved factor-15 savings in resource use: the Weald and Downland Gridshell by Ted Cullinan Architects with Buro Happold and Green Oak Carpentry weighed only 6 tonnes, compared to an estimated 100 tonnes for a traditional barn of equivalent size. The elegance of gridshells shows what can be achieved by using ingenuity rather than brute force.[26]



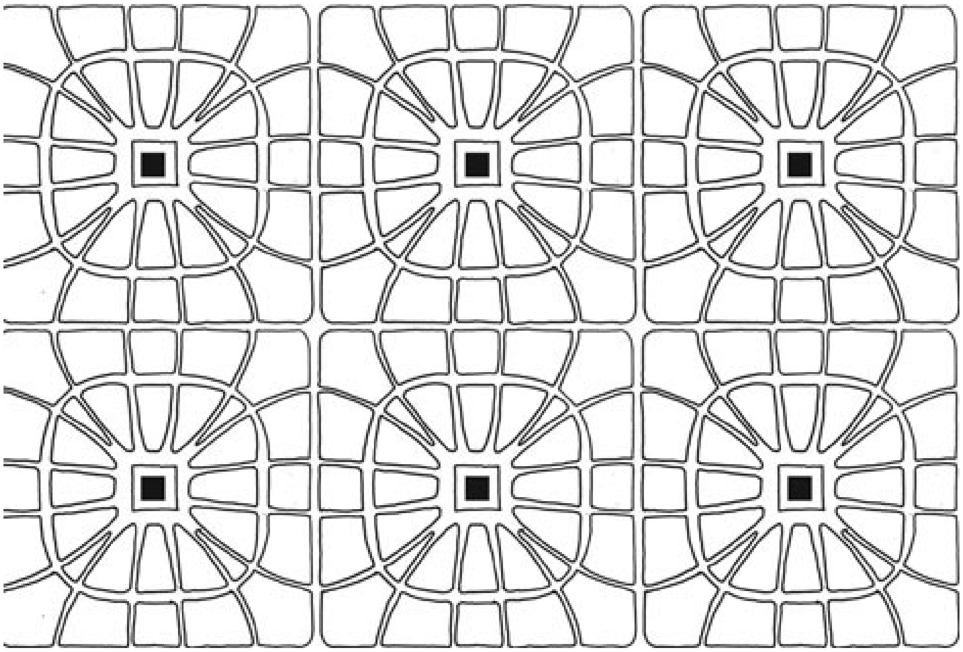
25. The engineering genius Pier Luigi Nervi frequently used examples from nature to inspire more efficient structures, as in this example of the Palazzetto dello Sport, which

has a striking resemblance to the leaves of the giant Amazon water lily. In both cases downstand ribs are used to stiffen a thin surface

As Mario Salvadori has observed, domes could be regarded as a continuous series of arches arranged in a circle and joined monolithically.[27] The engineering advantages become clear when one looks at the ratio of thickness to radius. For an arch, this ratio is typically between 1:20 and 1:30, whereas for a dome it is between 1:200 and 1:300. Little wonder, then, that this form of construction can be seen in biological examples as diverse as micro-organisms, seed pods, carapaces and skulls.

As we discussed with Guastavino vaulting, there is often potential to combine a number of biologically inspired approaches on a single project. The brilliant structural engineer Pier Luigi Nervi closely studied structures in biology and explored strategies to develop shells towards even greater efficiency. In the Palazzetto dello Sport (fig. 25), completed in 1957, he employed the principle of using ribs to give effective structural depth to a thin planar surface, combined with the benefits of dome/shell behaviour. In cooperation, radial bifurcating ribs reduce the distance over which the outer surface must span, while the outer surface in turn connects all the ribs together, so loads are more evenly distributed.

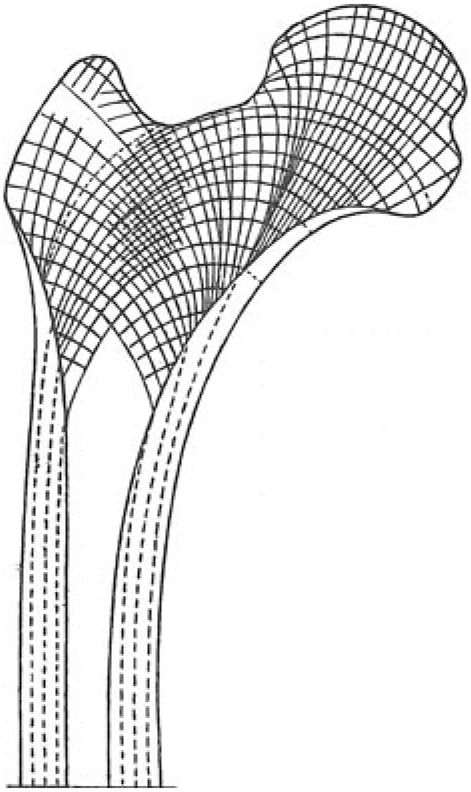
A challenge for architects and engineers in trying to emulate natural forms has been in achieving efficiency through complexity of form without adding excessive cost. While structures in nature are assembled molecule by molecule, human artefacts are constrained by the practical and economic limitations of our construction technology. For Nervi, the miracle material that allowed him to achieve his aims was reinforced concrete, about which he said, ‘The very fact of not having at its origin a form of its own … permits it to adapt itself to any form and to constitute resisting organisms’.[28] He viewed reinforced concrete as ‘a living creature which can adapt itself to any form, need or stress’,[29] and there is a sense in which his structures capture both muscular and skeletal qualities. Reinforced concrete was first used in a building structure in 1853, and by Nervi's time its performance was better understood. His mastery of the material is such that, in many of his designs, we see the forces that are resolved made manifest in the forms of the structure. For example, the ribs and downstand beams in his Gatti Wool Factory (1953) precisely follow the lines of principal stresses (fig. 26). This suggests that when we consider biomimetic structural solutions, at the same moment we should be exploiting the performance of materials and seeking biomimetic uses or alternatives. Evolving the structural and materials solutions together is a hallmark of how nature operates, and a process that is also achievable in human design.



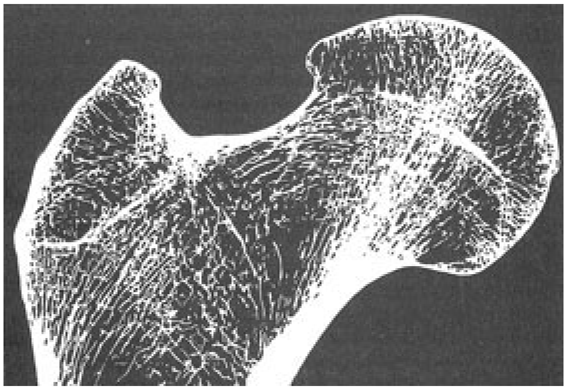
26. Structural layout for Nervi's Gatti Wool Factory in which the alignment of the beams follows the lines of principal stresses

Many of Nervi's projects were won through competitions. The secret to his success was his frequent ability to produce, simultaneously, formally compelling and also extremely cost-effective schemes. In a satisfying parallel with the refining process of evolution, his combination of ingenuity and biomimicry led to a remarkable efficiency of resources.

Skeletons



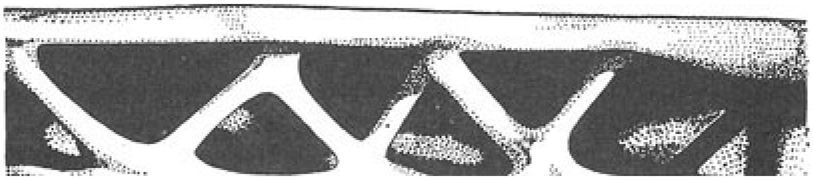
27. Diagram showing the lines of stress passing through a bone



28. X-ray through a bone showing the arrangement of bony trabeculae

Whereas bamboo is a relatively pure embodiment of tubular structural engineering, bones are more complex. Bones frequently reveal ways in which asymmetrical forces are resolved. Figure 27 shows the lines of stress through a femur, and figure 28 shows an X-ray image of the same bone. What we see is a precise match between the density of bone filaments and the concentration of stresses; where there is high stress, there is a proliferation of material and elsewhere there is a void. As biological mathematician D'Arcy Wentworth Thompson's seminal 1917 book *On Growth and Form*[30] documented, the vulture's metacarpal (fig. 29) is identical to a Warren truss. The vulture is an extreme case, where intense selective pressure to achieve high strength with minimal weight yields impressive results.

Birds in general have evolved in response to intense selective pressure on weight, with different species showing various expressions of the 'materials are expensive and shape is cheap' maxim. Avian skulls (fig. 30), such as those of crows and magpies, are little short of engineering miracles. The effective thickness of the skull is increased while weight is decreased. The structure is similar to a space-frame in which two layers of structural members are connected with struts and ties. The bird skull goes one step further in forming a dome shape, with the associated efficiency benefits.



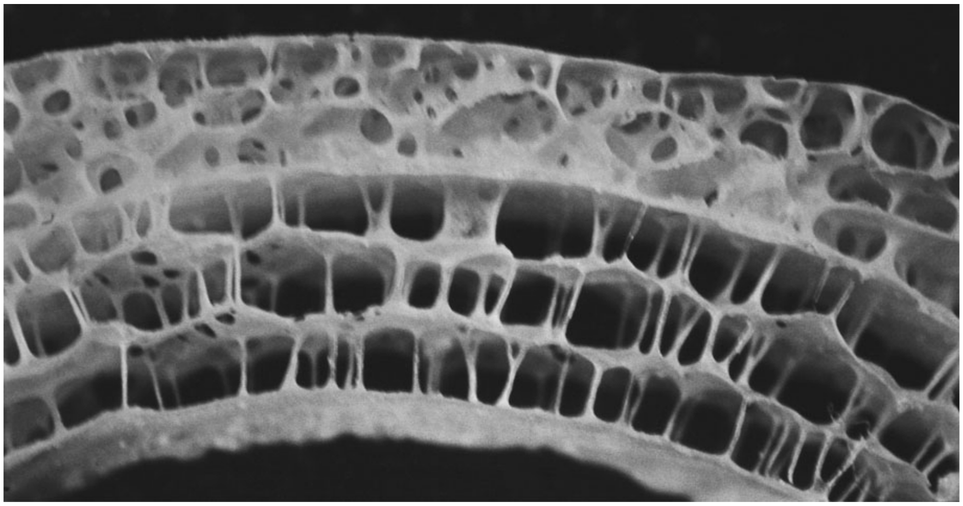
29. As a result of intense selective pressure for lightness, some birds have evolved remarkably efficient structural forms, like this vulture's metacarpal, which is effectively identical to a Warren truss

It's an astounding combination of shell action with space-frame technology – and all in a humble magpie.

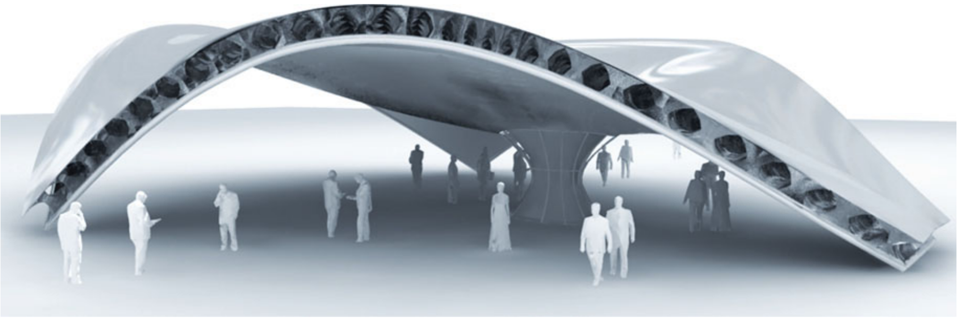
This principle was the inspiration for a canopy structure (fig. 31) designed by architect Andres Harris. The design resulted from a detailed understanding of the way in which bone tissue forms around pressurised cells, creating air voids between solid surfaces. The potential exists to construct the canopy in a way that is very similar to nature: using a web of inflated void formers, around which suitable materials could be cast.

Skeletons have been a source of inspiration for architects ever since Thompson demonstrated the parallels between structures such as the Forth Road Bridge and the form of dorsal vertebrae found in a horse.

Architect Santiago Calatrava is renowned for his love of skeletal structures; he created many of the most graceful bridges in the world. While his exuberance is enjoyable (fig. 32), there is a sense in which the biomorphic extravagance occasionally occludes a rational structural basis for the schemes. It could be argued that the beauty found in nature is derived from its economy, with the absence of the superfluous being part of the rigour that we perceive. This is a selective view because there



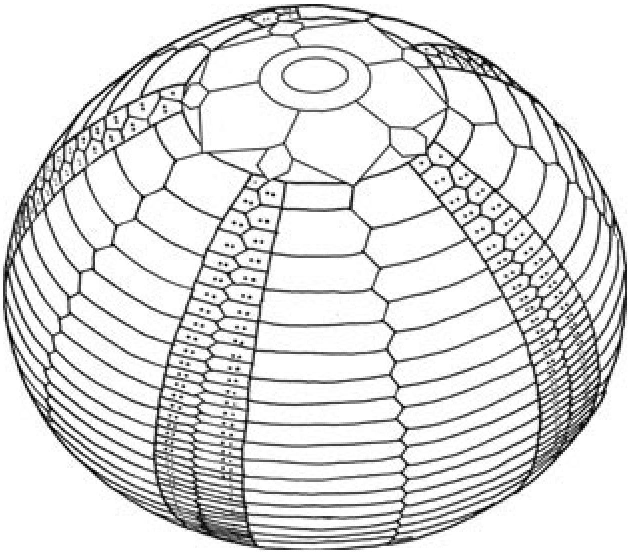
30. Section through the skull of a magpie showing thin domes of bone connected together with struts and ties



31. Canopy structure designed by architect Andres Harris, using the same structural principles as those found in bird skulls

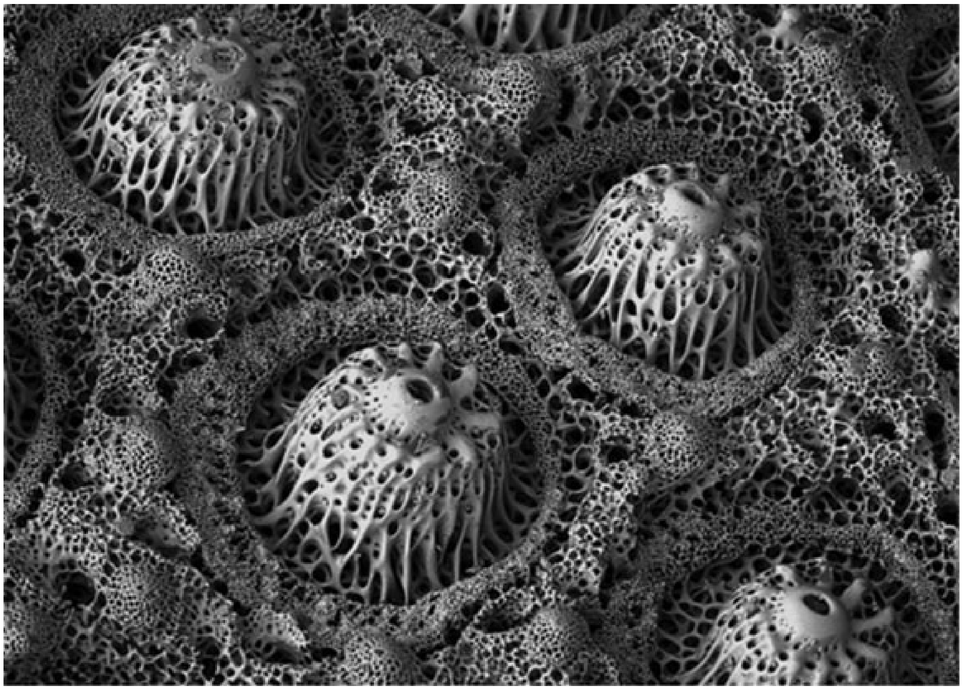
32. Biomorphic exuberance in the Milwaukee Art Museum by Santiago Calatrava

is plenty of extravagance to be found in biology, often associated with various forms of sexual display. But the interesting question to ask is: do the more decorative aspects add appropriate and necessary meaning to the building? If the aim is to produce beautiful, resource-efficient architecture that is enjoyable for people, then both biologically based design approaches can contribute. As I suggested in the Introduction, biomimetic design can deliver important innovation and biomorphic design can convey meaning.

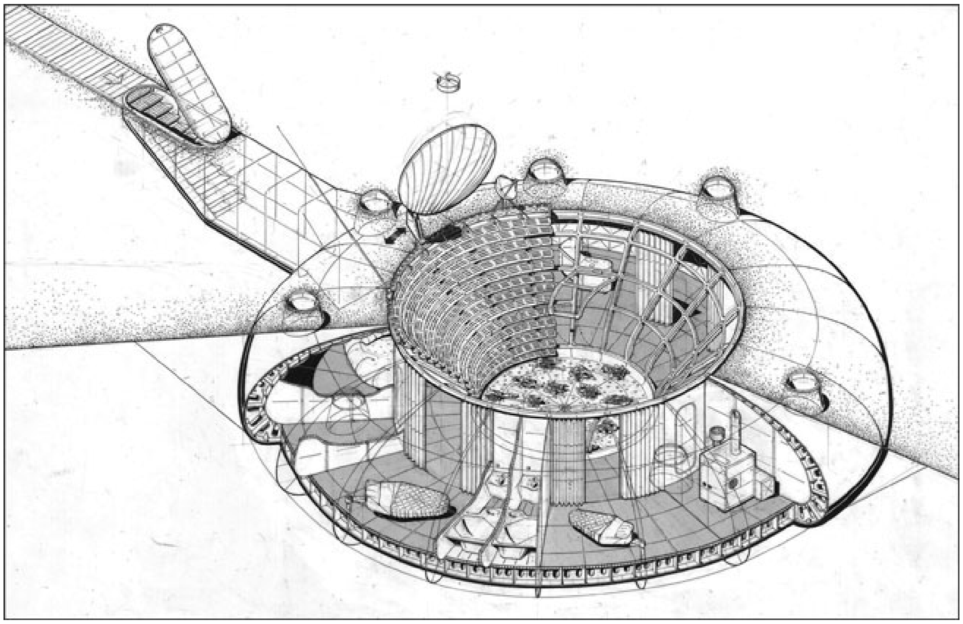


33. Diagram showing the structure of a sea urchin skeleton composed of interlocking plates made from calcite crystals

The sea urchin has inspired both simple biomorphic and thoroughgoing biomimetic architecture. The urchin skeleton (called a 'test') is made of interlocking plates (called 'ossicles') (fig. 33), each of which has the structure of a single calcite crystal.[31] If the calcite were solid, it would be heavy, but the ossicles have a sponge-like structure (fig. 34) that is porous, lightweight and stiff due to its increased effective thickness.[32] Sea urchin skeletons provided a visual reference for the Doughnut House by Future Systems (fig. 35), although the structure, at a functional level, had very little in common with that of the marine organism. A building that has deliberately come much closer to the structure of a sea urchin is the Landesgartenschau Exhibition Hall at the University of Stuttgart, Germany, where some of the most interesting and thorough research into biomimetic architecture is currently underway (fig. 36). The project was the result of a collaboration between the Institute for Computational Design (ICD, Prof. Menges (PI)), the Institute of Building Structures & Structural Design (ITKE, Prof. Knippers) and the Institute of Engineering Geodesy (IIGS, Prof. Schwieger). Sea urchin ossicles, and the way they interlock, were a source of inspiration for the building. It is made out of 50 mm thick plywood panels, connected with precise finger joints. Menges observed that 'in comparison to man-made constructions, natural biological constructions exhibit a significantly higher degree of geometric complexity'.[33] Computational design was essential to resolve this complexity in finding the optimum form. Each panel was then robotically prefabricated. The structure covers an area of 250 m^2 and, in relative terms, is thinner than eggshell.

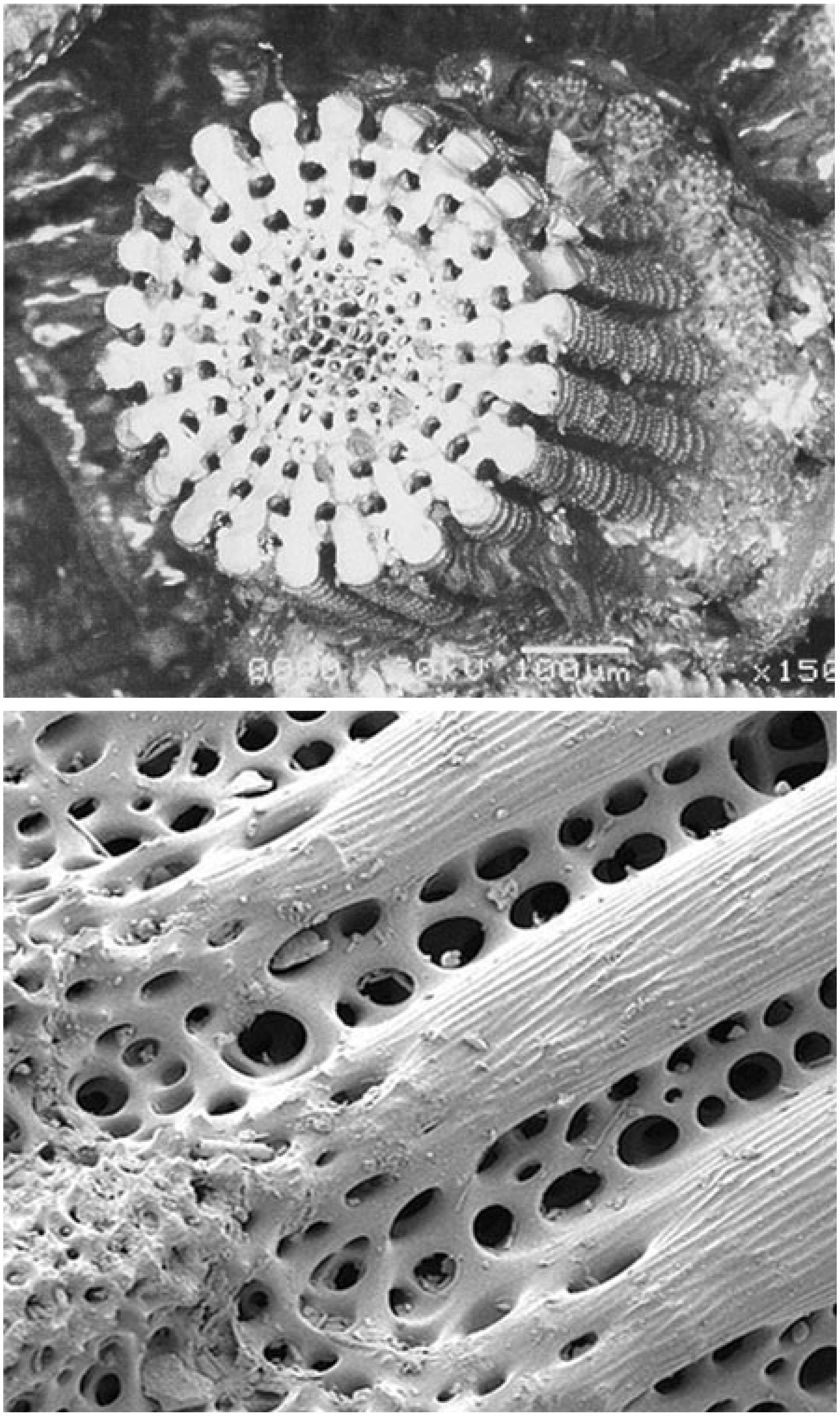


34. Close-up photograph of a sea urchin skeleton showing its porous and lightweight structure



[35]. The Doughnut House by Future Systems – biomorphic rather than biomimetic

[36]. Landesgartenschau Exhibition Hall at the University of Stuttgart – made from interlocking plywood panels based on the structure of a sea urchin skeleton

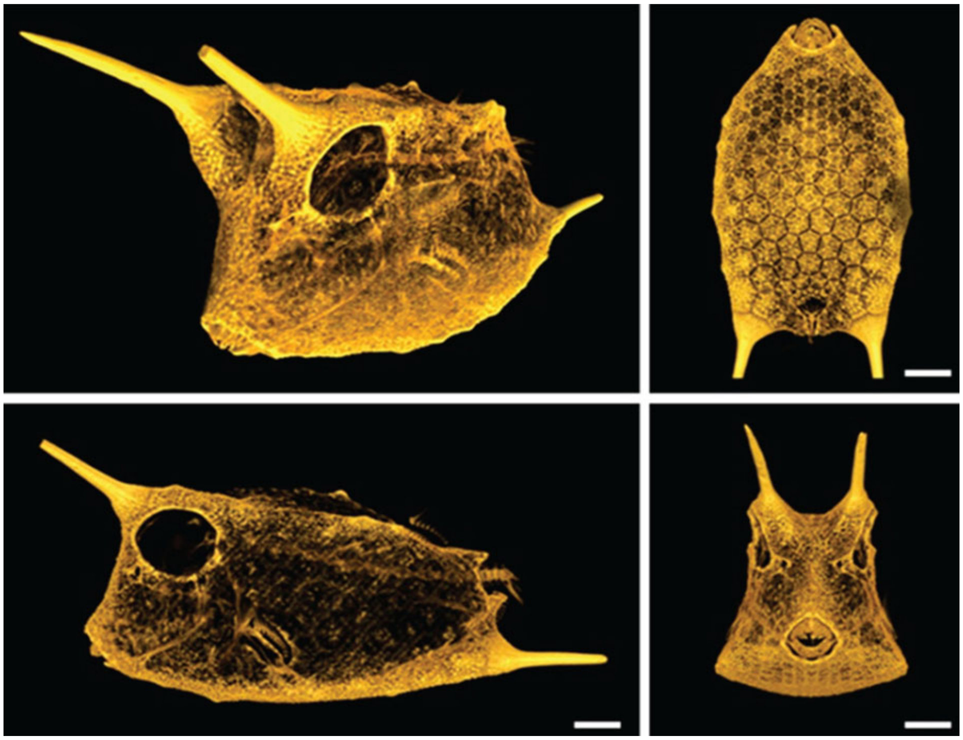


37–38. Close-up photographs showing the remarkable structure of sea urchin spines

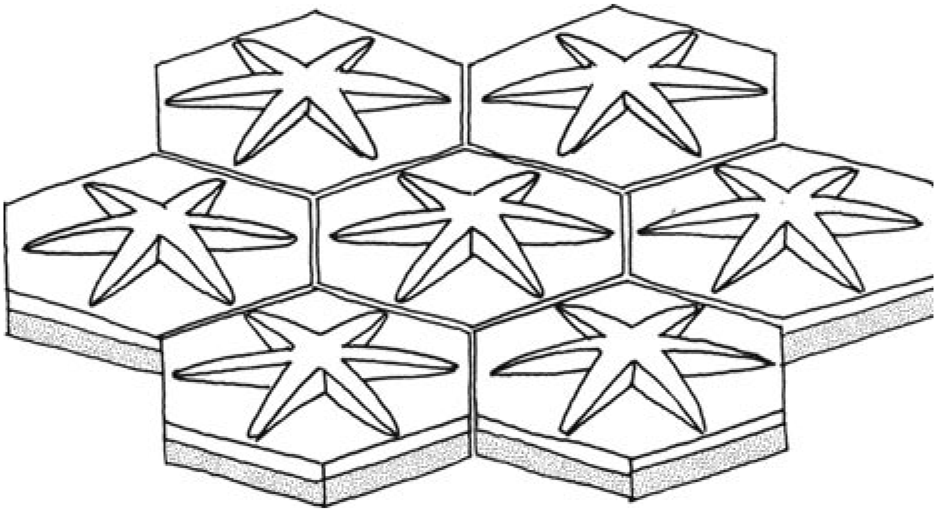
Another noteworthy aspect of sea urchins is the structure of their spines (figs 37 & 38). These provide protection as well as locomotion and sensing. As protection, considerable strength is required to resist impact onto the ends of the spines – or 'axial loading' as an engineer would describe it. If the spines were monolithic, they would be very brittle. Instead, they have evolved in a porous form that blends calcite with proteins. The composite effect of these two materials is enhanced strength and flexibility. Are there applications in architecture that require high resistance to axial loading as well as flexibility? The sea urchin spine is a solution waiting for the right design opportunity.

If Buckminster Fuller had ever designed a fish, one wonders if it might have looked something like the boxfish (perhaps *Lactoria cornuta* or *Acanthostracion polygonius*) (fig. 39). Their carapace is a remarkable geometrical composition of mainly hexagonal and pentagonal plates or 'scutes'.[34] Each of these has a tough mineralised collagen outer layer with a raised pattern of reinforcing struts and a softer, un-mineralised collagen layer underneath.[35] The struts serve to distribute piercing impacts over a wider area (fig. 40). Finely interlocking seams unify the plates into an extremely strong skeleton – it is tempting to refer to it as an exoskeleton but it is actually an endoskeleton because it lies under a layer of skin. Some fish evolved faster swimming to avoid predation; boxfish developed a formidable defensive structure (and some toxicity for good measure). Further protection comes from two pairs of horns – one pair at the front and one at the rear – which would make for uncomfortable swallowing by a predator. The horns have an intriguing structure of their own – an intricate hierarchy of ridges and ribs to provide high strength. While buildings in the twenty-first century generally don't have to be designed to resist attack, the boxfish carapace could still provide clues for how to stiffen thin materials into a robust enclosure using a minimum of resources.

Just as twentieth-century anthropologists were compelled to revise the widely held racist notion of 'primitive' societies, there are certain biological organisms that should encourage us to abandon the idea of single- or multi-celled life forms being in some way ‘lower’ than others. One such example is the Venus’ flower basket glass sponge (*Euplectella aspergillum*) (fig. 41), which we will revisit in the chapters on materials and light.[36] The structure of this marine organism is a complex assembly of spicules (four-pointed star-shaped elements made from silica) forming a tapered lattice tube (fig. 42).[37] This square grid is stiffened with diagonal bracing on alternate cells like a chequerboard, so that every node is braced and open cells allow for filter feeding. The scientists studying this organism have observed that it ‘shares features with the theoretical design criteria for optimized material usage

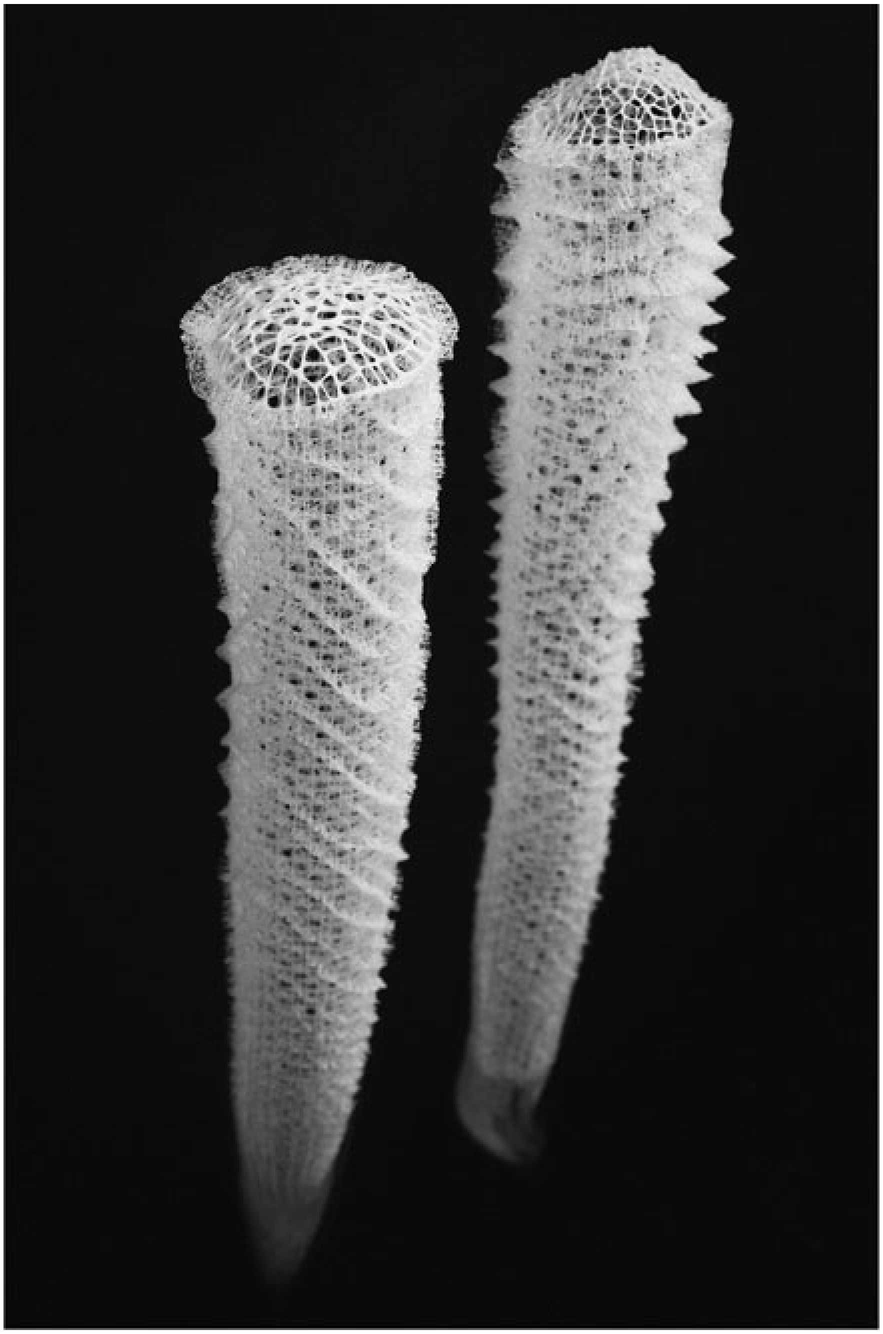


39. The carapace of the boxfish *Acanthostracion polygonius* showing its amazingly geometric arrangement of scutes

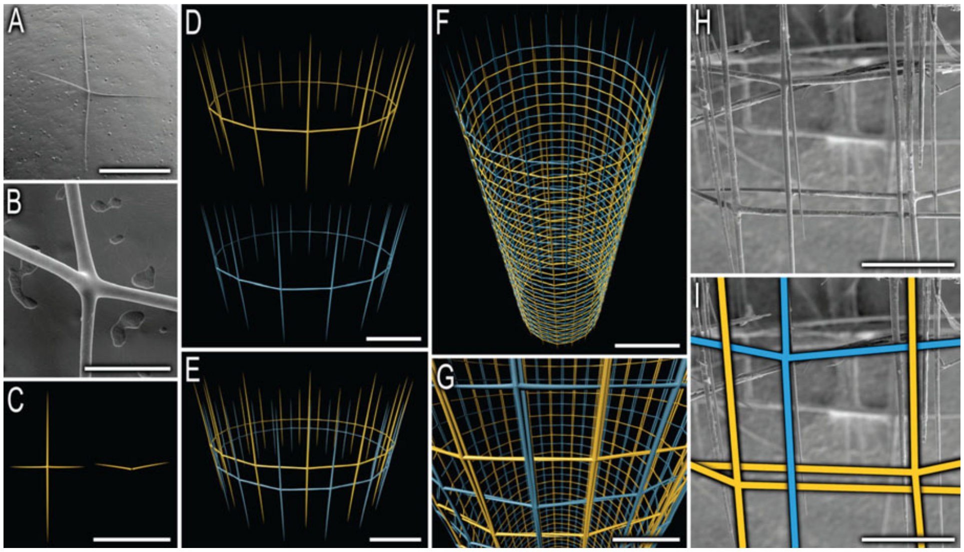


40. Diagram of the scutes that form the boxfish carapace showing the arrangement of reinforcing ribs

in similar two-dimensional structures subjected to shear stresses'.[38] The number, and size, of spicules around the perimeter stays constant along most of the length (only increasing in the top few centimetres[39]), so tapering is achieved by variations in the overlap of the spicules. Should we actually build this way or should we use continuous members that follow the gridded and braced layout? Probably the latter, but we shouldn't rule out the possibility of mass-producing identical elements, like the spicules, which can then be assembled into effective and beautiful structures. There are claims that Foster + Partners' 30 St Mary Axe ('The Gherkin') was based on the glass sponge, but these are unfounded.[40] So far, it seems that *Euplectella*'s lessons are yet to be turned into architecture.

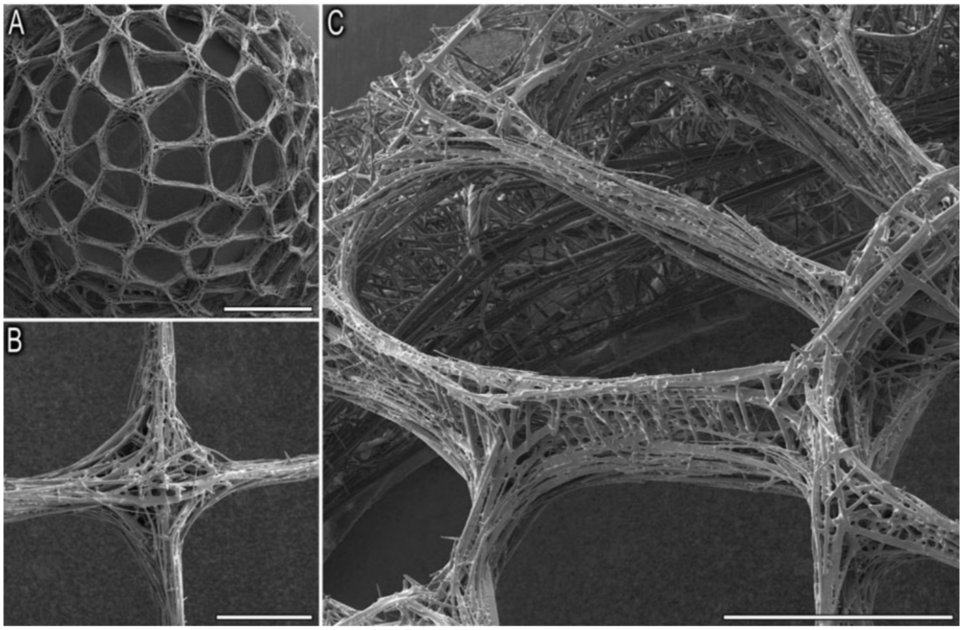


41. The glass sponge *Euplectella aspergillum*, made from silica at ambient temperature and pressure with five or more levels of hierarchy

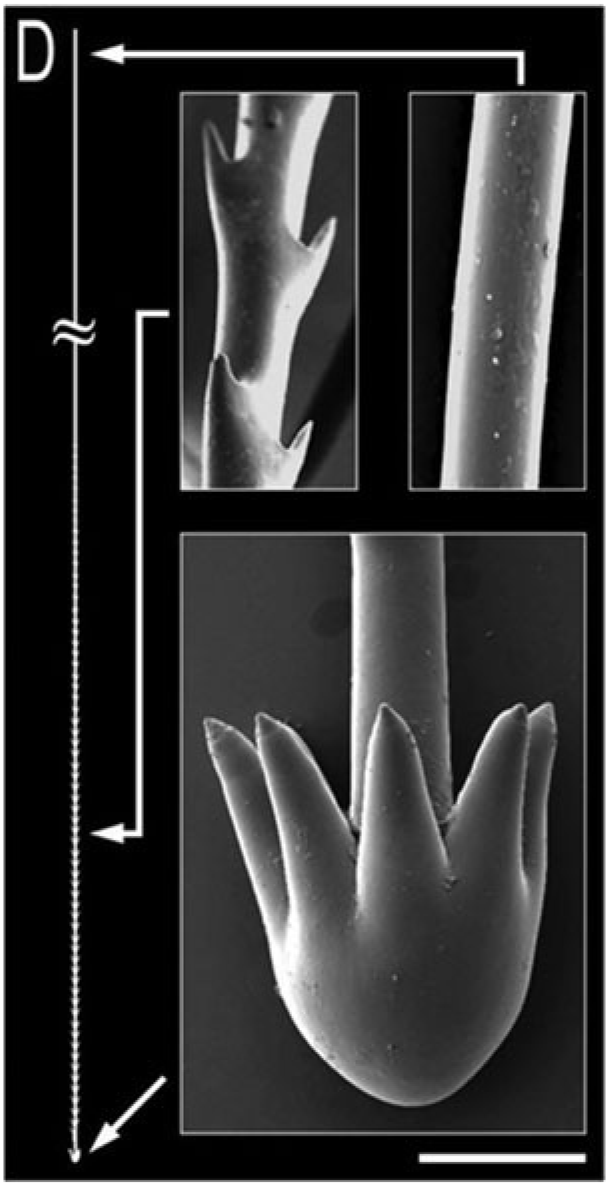


42. Illustration showing how the glass sponge is assembled from a complex arrangement of intersecting, cross-shaped spicules

The glass sponge has a series of helical ridges and a rigid top 'filter plate' (fig. 43) that effectively stiffen the tube against the kind of failure we described earlier.[41] The way that the sponge attaches to the sea bed is also intriguing. Materials scientist Professor Helga Lichtenegger has observed that anchoring can be achieved much more efficiently (in material terms) if the structure allows flexibility rather than rigidly resisting all lateral loads.[42] Saplings demonstrate this phenomenon and so does the glass sponge – there is considerable pliancy at the base (the very point at which the highest stress would accumulate in a more rigid structural attachment). In the lower part of the sponge there is a longer and more fibrous type of spicule, approximately 200 of which extend down into the sediment of the sea floor to form a strong holdfast. Scanning electron microscopy has revealed these fibres to have smooth surfaces above sea bed level, barbed surfaces below and an anchor-shaped termination (fig. 44). Could this be a solution to anchoring offshore wind turbines in soft sediments? The industry recently took a lesson from razor clams, and perhaps the glass sponge is next?



43. Magnified image of the filter plate that stiffens the top of a glass sponge



44. Scanning electron microscope views of the fibrilar spicules that anchor the glass sponge in soft sediments. Above the sea bed the spicules are smooth, while below they are barbed and have a complex holdfast at the termination

Exoskeletons

External skeletons are one of the defining characteristics of the broad phylum of animals known as arthropods, which includes insects, arachnids, myriapods and crustaceans. Because of the diversity of insects on earth, arthropods account for more than 80 per cent of all animal species. Exoskeletons can also be found in microscopic diatoms and radiolaria. Tortoises show off by having both an exo- and an endoskeleton, which offers benefits of protection and mobility. These skeletons can teach us that, for some situations, a hybrid structure can provide additional flexibility.

The complex double-curved forms of arthropod exoskeletons can be a source of inspiration for architects and engineers fascinated by the efficient and expressive potential of monocoque construction. In the case of arthropods, their exoskeletons are made from three raw materials: mainly chitin (a polymer derived from glucose), modified and reinforced with proteins and biominerals.[43] The fibres are arranged in layers with alternating directions in each, similar to plywood, delivering excellent material strength relative to its density and its fracture resistance. The ICD has built a pavilion based on an understanding of arthropod exoskeletons and translated into architectural form with great elan (and some clever robots). Since the form emerged primarily from a profound understanding of the material microstructure, this project is described in Chapter 2.

Woven, fastened and reciprocated structures

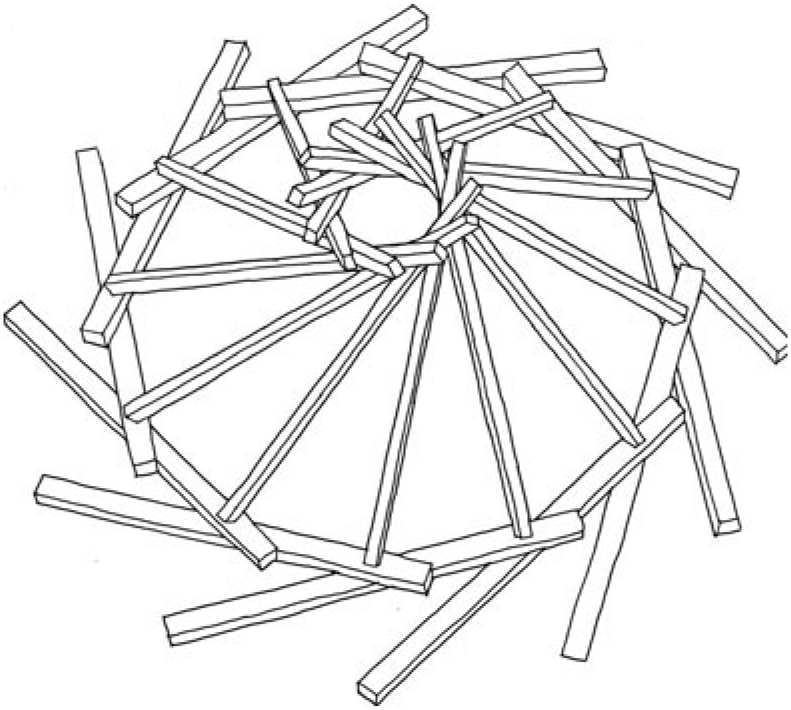
There are a number of examples of weaving in nature, mainly by birds. The appropriately named village weaver birds (fig. 45) (*Ploceus cucullatus*) employ as many as six different knots, including loops, half-hitches, hitches, bindings, slip knots and overhand knots, as well as weaving techniques. Another avian group worth getting acquainted with is the penduline tit family (*Remizidae*), which uses spiderweb, wool, animal hair and plant fibres to make a bag-like hanging nest, so tightly interwoven that even apes are not able to pull them apart. In parts of Eastern Europe they were used as children's slippers.

The long-tailed tit (*Aegithalos caudatus*) uses a combination of spider silk egg cocoons and fine-leaved mosses as a natural form of Velcro to hold its nest of twigs together.[44] There are numerous examples of adhesives made from bodily secretions, including salivary mucus used by the chimney swift (*Chaetura pelagica*) to make its nest, and the little spiderhunter (*Arachnothera longirostra*) uses pop rivets made of silk to attach its nest to large leaves.[45]

45. Nest structures built by the village weaver bird using as many as six different knots

A reciprocal structure is one in which the overall span is longer than that of its individual members and each beam supports, and is supported by, the other beams in the structure. Many birds' nests provide examples of this approach and it is generally employed when the gap to be spanned, say between the branches of a tree, exceeds the length of most of the available twigs. Short lengths of stick can be used to successively bridge the distance between two adjacent members that are at an angle to each other, eventually spanning the desired area as a base for the nest. While some such nests are relatively crude accumulations of sticks that rely on gravity and friction to hold them together, other birds use a range of fixing technologies to bind elements together.

46. The Luxmore Bridge, Eton College, designed by Atelier One and Jamie McCulloch – a reciprocal structure in which a number of short structural elements are assembled to span further than their individual lengths



47. The spiral reciprocal roof structure of the Seiwa Bunraku Puppet Theatre by Kazuhiro Ishi. Could we push the idea even further with lessons from birds' nests?

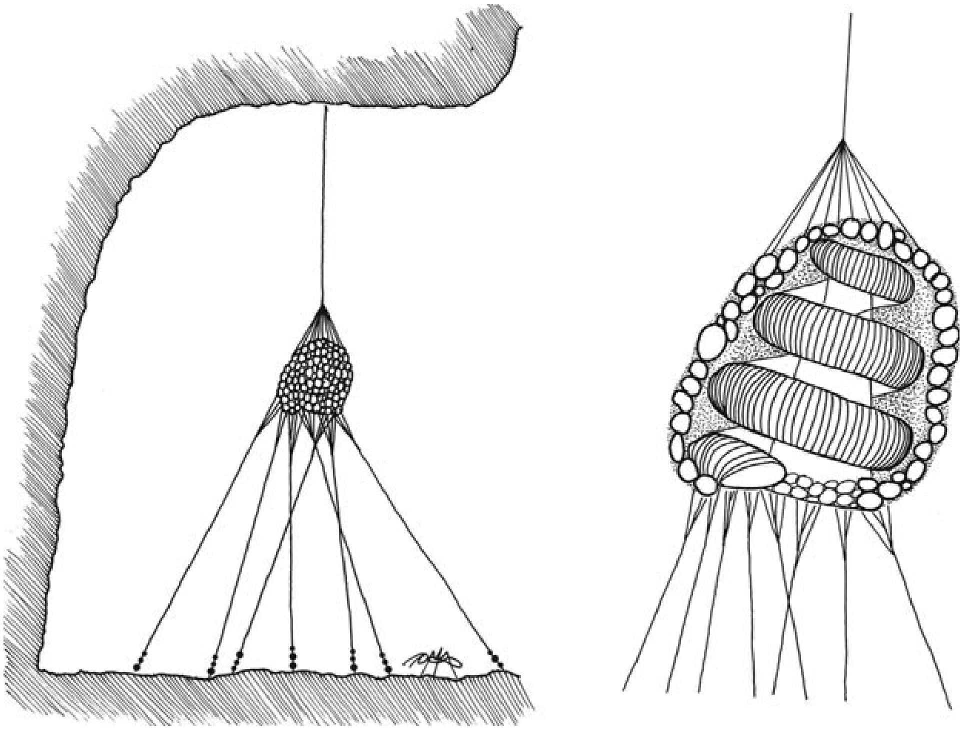
There are certainly some elegant examples of man-made structures that use parallel techniques, such as Jamie McCulloch and Atelier One's Luxmore Bridge (fig. 46) and the Seiwa Bunraku Puppet Theatre by Kazuhiro Ishii (fig. 47). More direct application of these construction methods from natural structures to human-made ones remains to be explored. Perhaps the most relevant lesson to draw is that nature's woven, fastened and reciprocated structures could provide further clues for how we can use relatively small structural members to create elegant spanning structures without the need for large primary beams or trusses.

Webs / tension structures

Webs built by spiders have inspired a number of modern architects and engineers. Their forms range from the commonplace webs created by household spiders to the remarkably architectural tension structures of the grass spider (genus *Agelenopsis*) and the bizarre constructions of the bowl and doily spider (*Frontinella communis*) and the female bauble spider (*Achaearanea globispira*) (figs 48–50).

48. Web made by the grass spider – a tension surface spread over grass ‘masts’

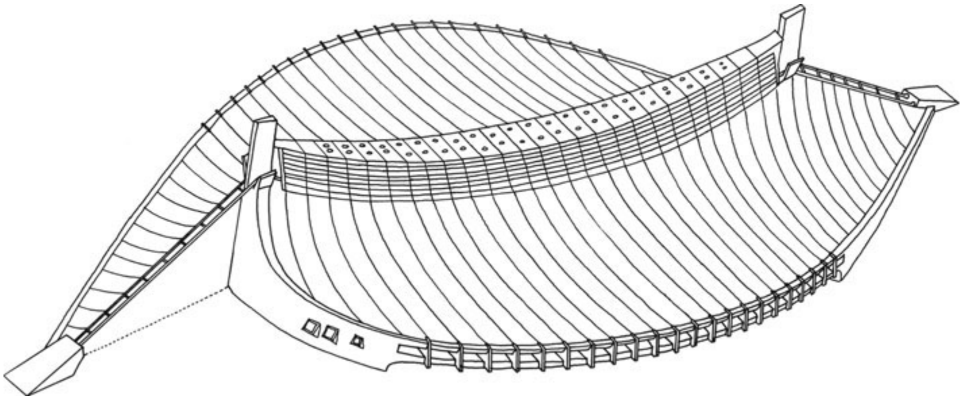
49. The bowl and doily spider’s dining arrangements



50. House of the female bauble spider, apparently under the influence of Bruce Goff

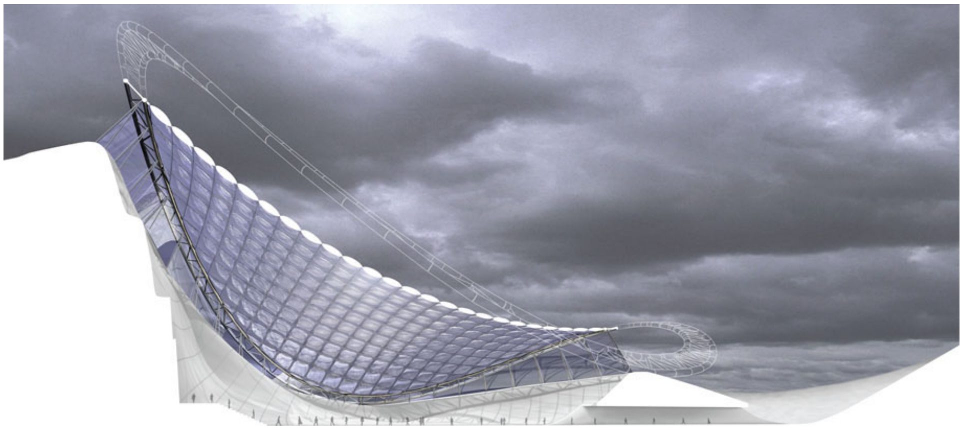
Arguably, there is no greater champion of tension structures than the German architect and engineer Frei Otto (1925–2015). He pioneered cable-net buildings (fig. 51) and, through the Institute for Lightweight Structures that he established, published 32 volumes on structural design principles from nature.[46] Comparing spider webs with cable-net structures, which are apparently very similar, reveals the gap that exists between biological manufacturing and our engineering: the relatively large sizing of the cables and the very visible connections being obvious differences. However, this is a gap that is narrowing all the time and, as we develop more sophisticated materials manufacturing and adaptive structures (see the ‘Integrated approaches’ section at the end of this chapter), we should be able to get closer to the elegant arachnid exemplars.

51. The West German Pavilion at Expo 1967, Montreal by Frei Otto – perhaps the closest we have come to the elegance of spiders' webs



52. Tokyo Olympic Gymnasium by Kenzo Tange – a distinctive form created with just two masts and all the remaining primary structural elements being tension cables

The most common form of tension structure is a cable net, which generally involves a series of guyed masts from which the web is suspended. Although it uses more substantial vertical elements than the tent-type schemes, Kenzo Tange's brilliant Olympic Gymnasium in Tokyo is essentially the same (fig. 52). The Grimshaw team, for the proposed third climatic enclosure at the Eden Project, pursued a different approach. The imperative design requirement for this enclosure was for it to achieve the highest possible light levels. This led the team to explore an approach that placed the heavier compression members around the perimeter of the building, while over the growing area the most minimal arrangement of tension members would be stretched. The Dry Tropics Biome (fig. 53) used a distorted lattice ring-beam to form an anticlastic surface, such that at any point on the surface the cables, and the membrane that they support, would be tensioned in two directions for maximum resistance to wind loading.



53. The Eden Project Dry Tropics Biome by Grimshaw. The scheme aimed to maximise light levels inside by using a ring beam to stretch a minimal web of cables over the growing area

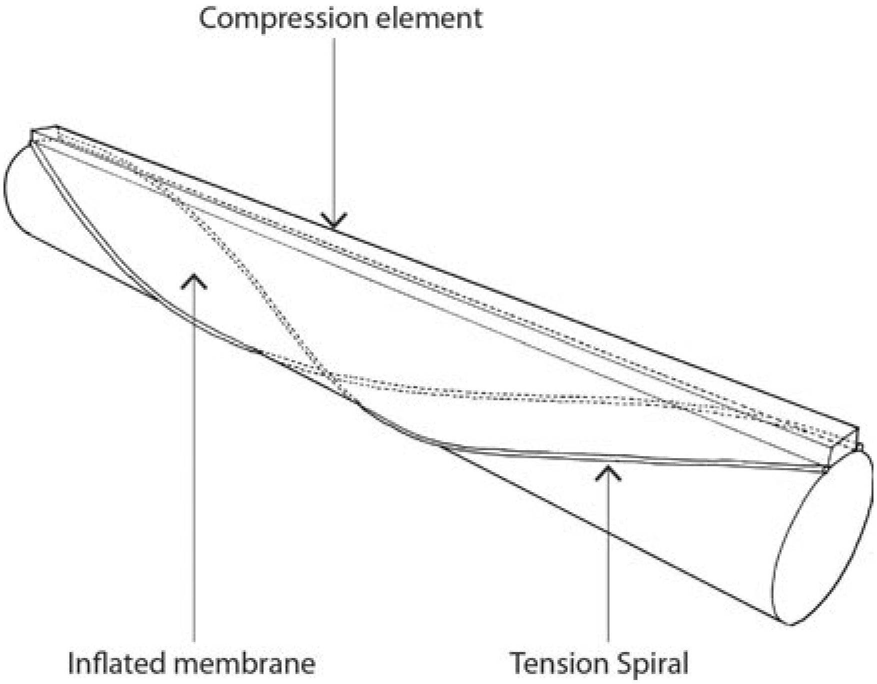
Pneumatic structures

A leaf, generally speaking, has very little woody tissue in it and relies instead for its stiffness on pressurised cell walls. Plants use energy to accumulate sugars in their cells, which promotes the in-flow of water and consequently internal pressure. The force of all the cells pressing against each other is what keeps the leaf rigid and explains why plants wilt when short of water. The effect is similar to a fully inflated lilo that is strong enough to stand upright or span as a cantilever. Scaling this idea up to suit a building would be difficult because the weight of water would become unmanageable. Fortunately, very similar effects can be achieved with membranes pressurised by air.

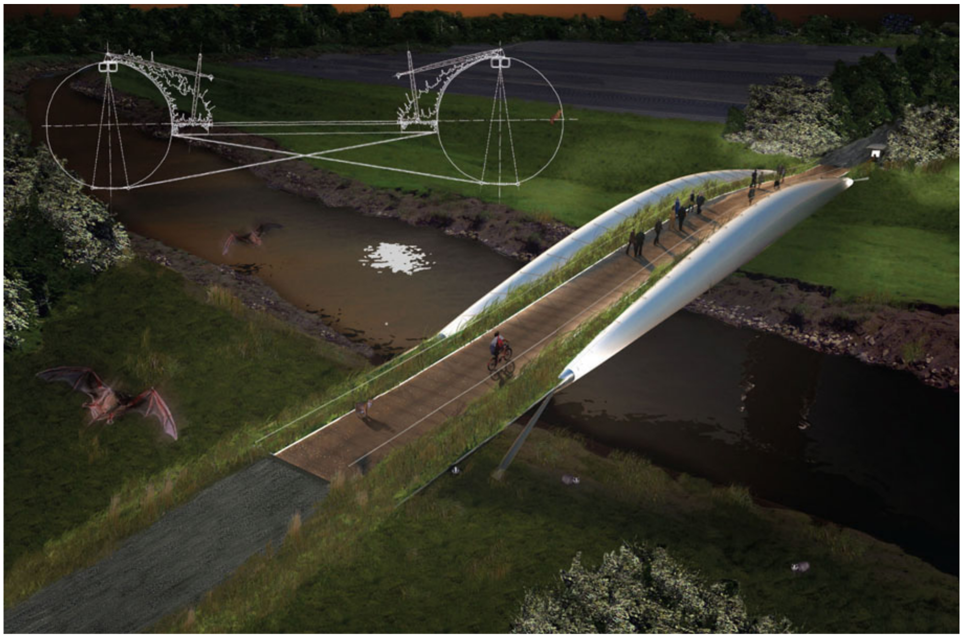
As architect Judit Kimpian has described in her dissertation 'Pneumatrix – The Architecture of Pneumatic Structures in the Digital World', air-supported constructions have had a somewhat chequered history. After considerable advances during the First and Second World Wars, there followed a wave of enthusiasm for pneumatics, culminating in a proliferation of inflatable pavilions at the 1970 Osaka Expo. Unfortunately, the popularity was short-lived as a combination of technical problems, poor workmanship and inadequate design tools led to the technology developing a tarnished image. In spite of all these shortcomings, pneumatic structures have an enduring fascination for biomimics, neatly captured by Reyner Banham's assertion that 'inflatables are alive in ways unknown to other building materials'.[47] The first air-filled objects were quite likely to have been inspired by examples in nature, such as swim bladders in fish. Stephen Vogel explains the basic principle of pressurised structures in *Cats' Paws and Catapults* as follows:

> *Making a fluid-filled strut is simple. A tension-resisting sheath need only be wrapped around a body of compression-resisting fluid to get a structure that has a discrete shape and an appreciable stiffness, strength and so forth.* [48]

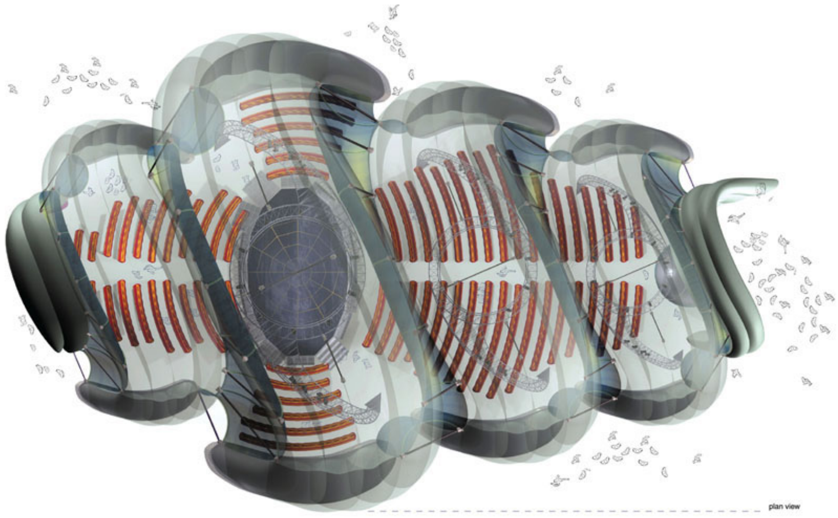
This is the basis of much work by the Swiss–Italian engineering firm Airlight Structures, who have developed air beams with impressive spanning capabilities (fig. 54). The beams are reinforced with a steel compression plate on the top and cable-tension members that run symmetrically from the ends of the plate, around each side of the air beam to the middle of the lower face and then up to the far ends of the plate. The inflated tube both stabilises the compression plate to minimise buckling and creates the structural depth to make it a spanning member. It is exactly equivalent to a conventional steel truss but neatly avoids the requirement for a substantial top compression member and solid struts. The hard work is done by air at modest pressure. Doubtlessly there will be scaling limits to the application of this technology but, for the versions that have been tested, it demonstrates a supremely elegant solution that uses a fraction of the materials to achieve the same result. The entry for the Douglas River Bridge (fig. 55) competition by Exploration with Airlight Structures shows the technology being used to create an ultra-lightweight span as a link between two areas of valuable biodiversity.



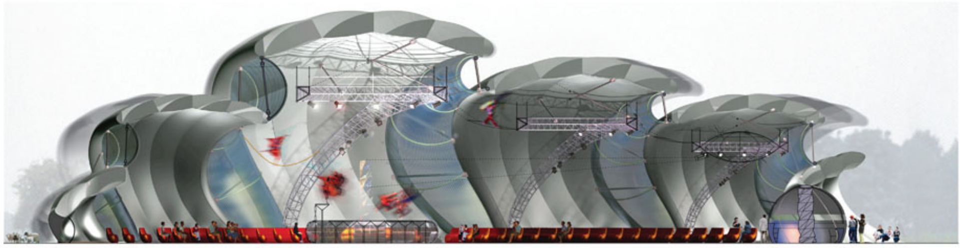
54. A pneumatic beam by Airlight Structures which uses an inflated tube to create structural depth and to stabilise the top compression member



55. The Douglas River Bridge by Exploration – using air structurally to create a lightweight crossing



INFLATABLE AUDITORIUM PLAN Thesis Project



SECTION Thesis Project – Inflatable Auditorium

56. Plan and section of the Inflatable Auditorium by Judit Kimpian – ‘bringing the building fabric “alive” with asymmetrically curved spaces, transient volumes and dynamic structures’

If it were to be built, Judit Kimpian’s Inflatable Auditorium would be a *tour de force* of pneumatic architecture (fig. 56). In many ways, a temporary auditorium is the perfect brief for pneumatic technology. In theatre design there is a continual quest for spaces that challenge and inspire the artists to create ever more adventurous works. In the Inflatable Auditorium, the focus was on ‘increasing the drama and suspense of a touring event by bringing the building fabric “alive” with … asymmetrically curved spaces, transient volumes and dynamic structures’.[49]

The design developed as a series of wide, inflated arch forms that avoided the need for any vertical supports. The arches connect together to form a stable, although not rigid, structure. Inflatables’ strength lies in their ability to transmit loading through deflection – something that characterises many natural structures and provides a stark contrast with the rigidity of much twentieth-century engineering. In nature, strength has evolved not by forming completely rigid structures but by accommodating movement.

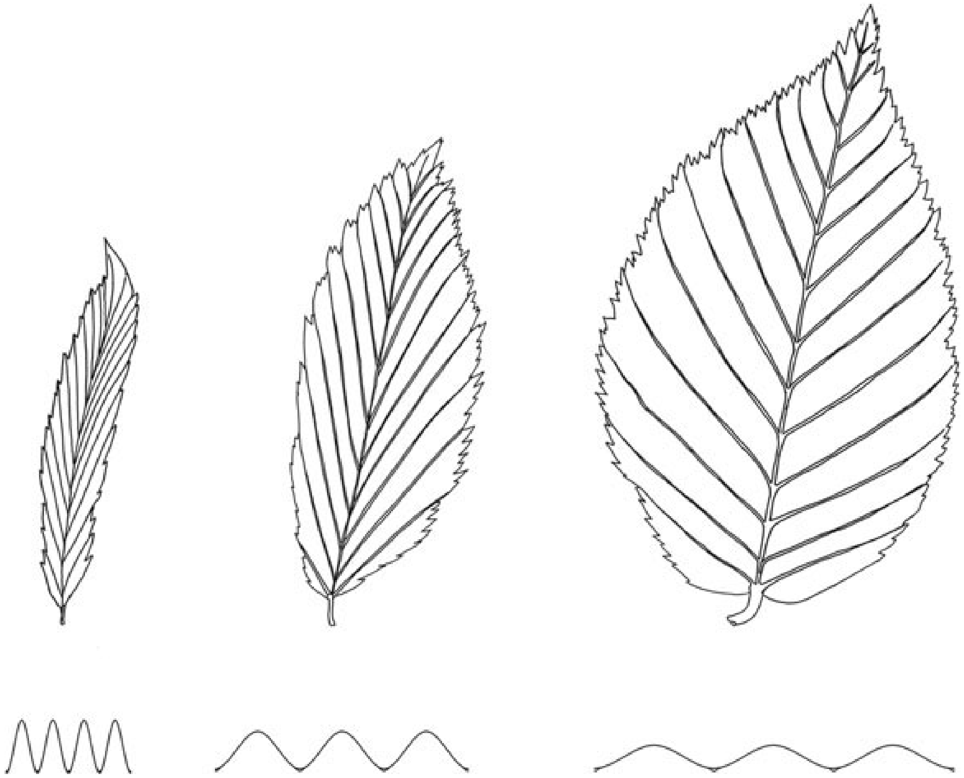
The arches of the Inflatable Auditorium can be moved and their shape modified with pneumatic ‘muscles’. The building thus becomes a dramatic spectacle in itself and broadens the range of events that can be accommodated. While theatres have often been described with mechanistic language, Kimpian shows the potential for a theatre to be a quasi-living organism that can adapt to a wide range of functions.

Kimpian’s work suggests that, with the development of computer software that can accurately model and calculate inflated elements, pneumatic architectural technology has now come of age. Necessary material advances are also within reach, as biomimetic membranes are close to commercialisation. Soap bubbles and cell membranes are able to adapt to minute changes in strain along their surfaces whereas, to date, the membranes that we manufacture are only able to adapt to a very crude extent – by elasticity and local depressurisation. New ‘smart’ membranes are capable of real controlled shape change and could transform the performance of pneumatic structures.

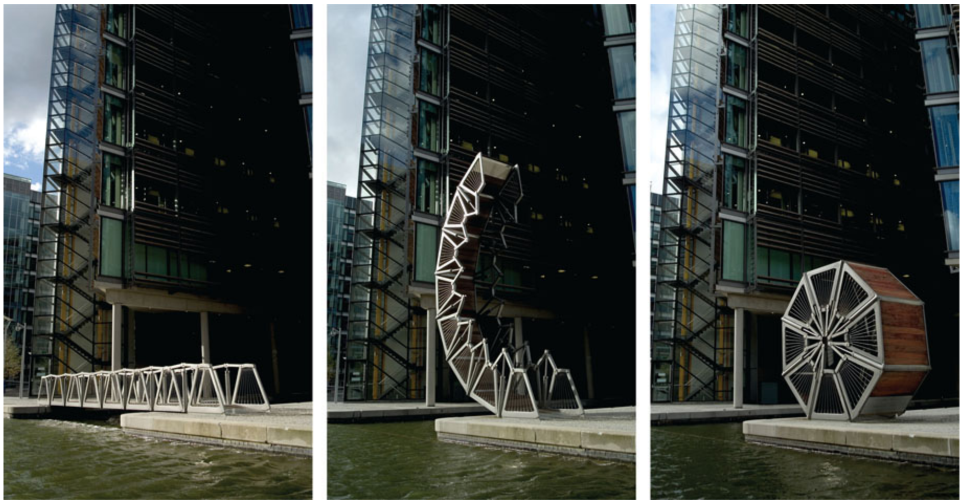
Kimpian believes that, with design advances in pneumatics, air has been redefined ‘not only as a means of support for deployable structures, but as a smart building material which brings the dynamic transformation of space and volume within reach of mainstream architecture’, and that ‘inflatables can provide a means to realise some of the spatial possibilities emerging from a transient and perpetually evolving digital realm’.[50] It is clear that the combination of pneumatics and biomimicry could deliver major breakthroughs: membranes that respond to the environment, with the flexibility to adapt to loads, forming enclosures with a fraction of the resources of conventional approaches.

Deployable structures

The whole notion of adaptive structures is appealing to a biomimic because it allows buildings to do what most living organisms do – modify their form or behaviour in response to changing conditions. Deployable structures can move, expand or contract by changing their geometric, material or mechanical properties.[51] For biological organisms, rapid deployment offers numerous benefits: a leaf or flower can open to take advantage of particular weather conditions, insect wings can be folded and stowed after flight and long tongues can snatch prey before returning to coiled form. Moving limbs and skeletons are another ubiquitous example. We can aspire to equivalent advantage in our buildings with structures that expand to protect us from fierce sunlight, perhaps deploy focusing mirrors when we want more light or stretch out a membrane to harvest scarce rainfall. Roofs can open, walls can fold and whole buildings can move if there is a compelling case for doing so and the technology can catch up.

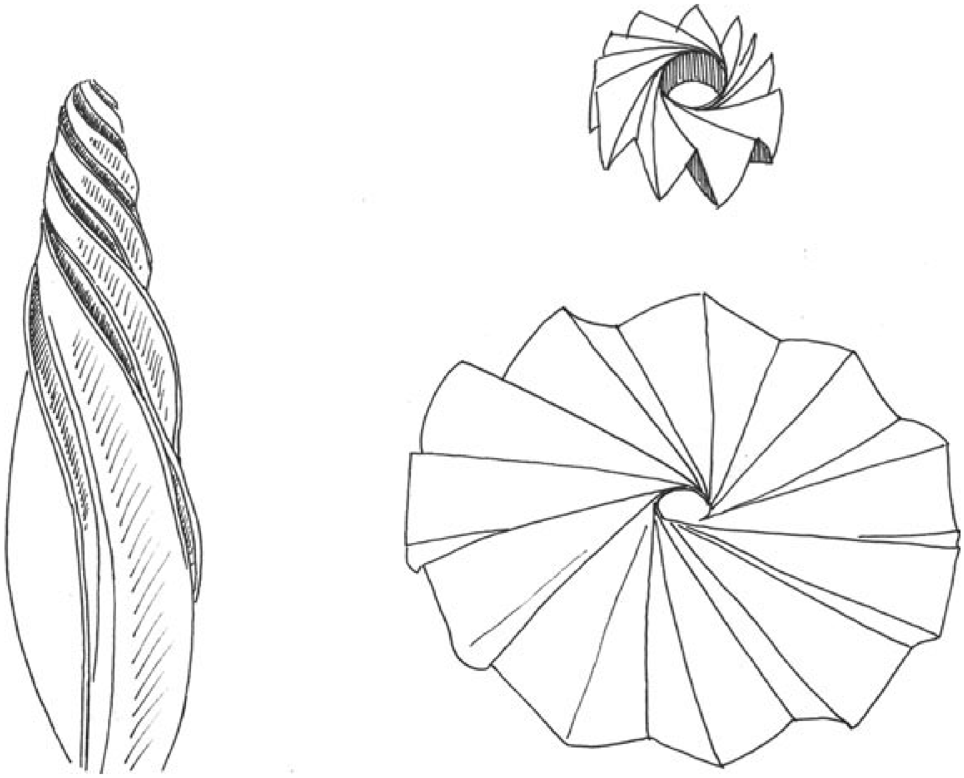


57. Hornbeam leaf – a simply folded surface that can be deployed by pushing along the centre line



58. Hydraulic rams acting as muscles and steel sections as spinal vertebrae in Thomas Heatherwick's 'Rolling Bridge'

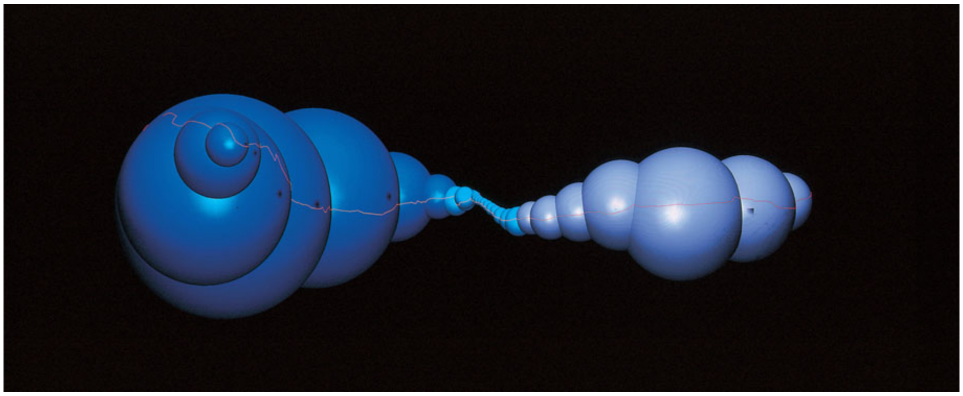
Examples of this can already be found in satellite solar arrays modelled on the simple unfolding pattern of the hornbeam leaf (fig. 57) and structures like Thomas Heatherwick's 'Rolling Bridge' (fig. 58), which is effectively identical to a series of vertebrae with protruding spines that are connected by muscle-like hydraulic rams. Inspiration for pneumatic deployables could come from the pumping of seawater in the sea anemone.[52]



59. Convolvulus flower and a deployable pattern based on the same geometry. Some plants have evolved flower petals that can be rapidly deployed from a compact form to fully extended when the conditions are right. The deployable structure is designed by Guest & Pellegrino

60. Umbrella for the forecourt of the Al Hussein Mosque, Cairo

Designer and pioneer of deployable structures Chuck Hoberman is now part of the Wyss Institute for Bio-inspired Engineering, so we can expect to see more examples of nature's deployables being used to develop more effective solutions for humans. Conceivably, elegant examples like the convolvulus flower[53] (fig. 59) or folding beetle wings could lead to sun-shading systems that can transform quickly from highly compact to fully deployed. Deployable biomimetic architecture has a humane quality of change which is deeply appealing, as well as promising refinements in form and energy efficiency (fig. 60).



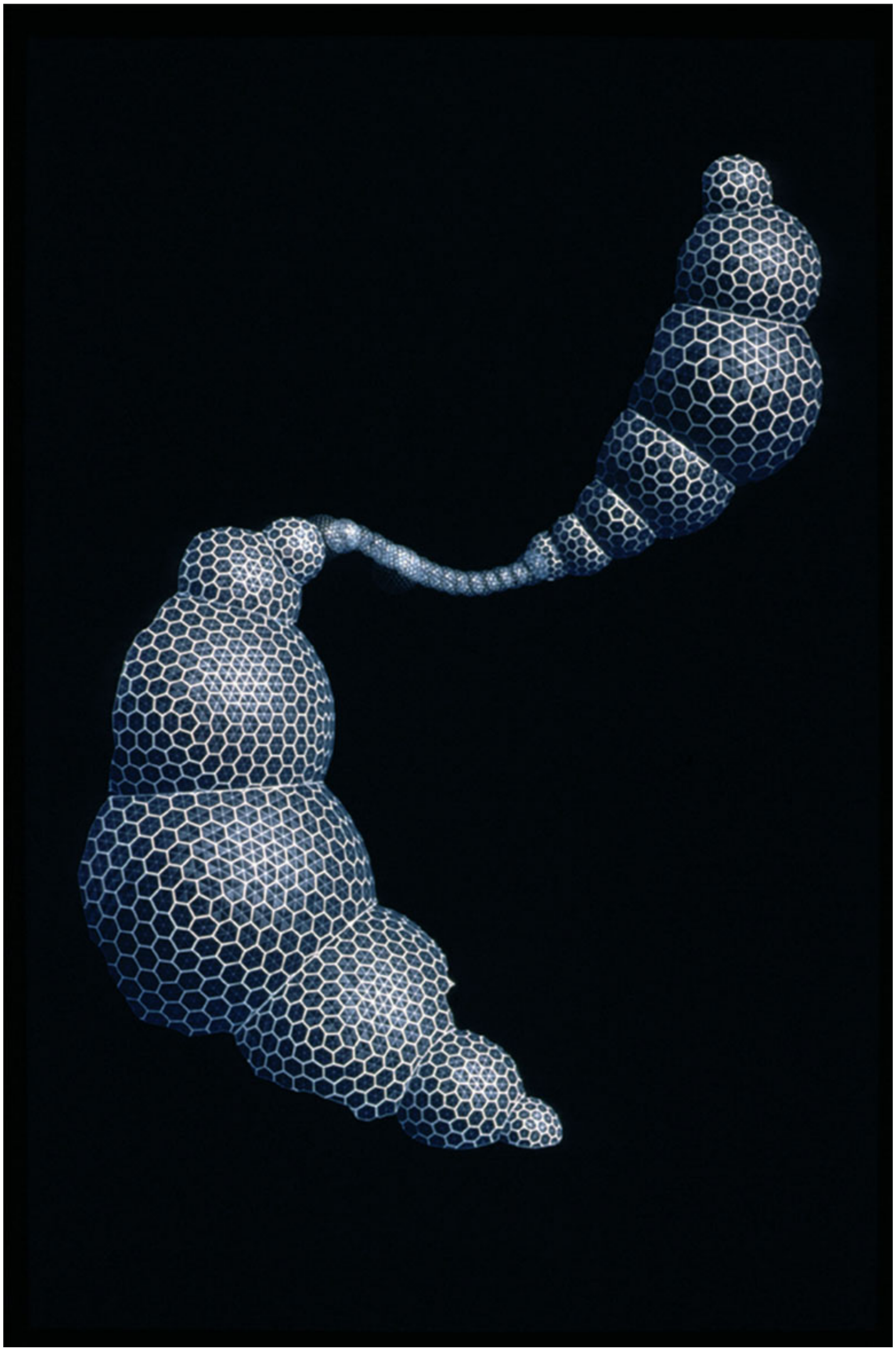
61. An early computer model developed by the Grimshaw team when conceiving of the Eden Project as a string of bubbles to be set into the irregular site

Integrated approaches

The Eden Project, by Grimshaw, is another example of a scheme that drew on a range of solutions from biology – from the initial site selection and analysis through to the strategic form generation and the detail resolution.

The brief called for the world’s biggest greenhouse. The site was a deep, unstable china clay pit that was still being quarried. How were the team to design the building when there was no certainty about the ultimate shape of the site? Biomimicry was used throughout the design process to solve some of these seemingly intractable problems. A solar analysis first established the most beneficial parts of the site to inhabit: the south-facing quarry walls, which could absorb the sun’s heat during the day and then radiate that heat into the greenhouse – substantially reducing the number of days when additional heat input would be required. The irregularity of the topography, combined with the uncertainty over the final ground levels made conventional, rectilinear solutions all but impossible. The master-stroke came from team member David Kirkland, who proposed a radical solution inspired by soap bubbles (fig. 61). The idea was to create a string of bubbles, the diameters of which could be varied to provide the right growing heights in the different parts of the building, and to connect these along a necklace line that could be arranged to suit the approximate topography. The team explored different iterations of this bubble necklace and set them into 3D terrain models of the site. By cutting away everything that was below ground, the team arrived at the first images that resembled the final scheme (fig. 62).

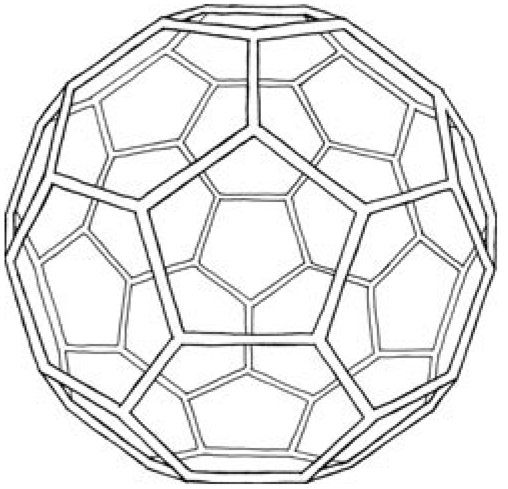
The next challenge was to strive for the lightest possible structure. Studying a whole series of natural examples – from carbon molecules and radiolaria through to pollen grains (figs 63–66) – revealed that the most efficient way of structuring a spherical form is with a geodesic arrangement of pentagons and hexagons. Richard Buckminster Fuller pioneered the technology and even has a form of carbon molecule (the ‘Buckminster Fullerene’) named after him. The design started with conservative structural assumptions and then refined these using scale models in a wind tunnel to establish the wind loading. The most significant move in this process was in trying



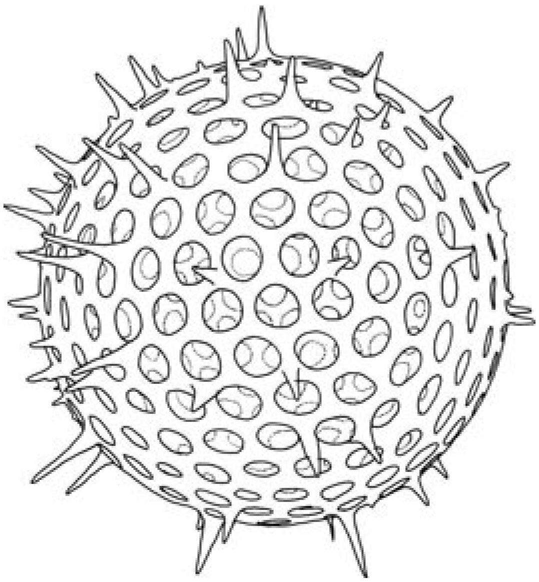
62. Computer-generated image showing the sections of geodesic structure of the bubbles that protruded above the ground

to maximise the size of the hexagons so that light penetration could be increased. Glass would have been a serious constraint, both in terms of its unit sizes and weight, so the team explored a material that had, at the time, only been used at a much smaller scale. The team were aware that many efficient solutions in biology, from cell membranes to spiders' webs, use pliable materials in tension rather than rigid materials in compression or bending. Ethylene tetrafluoroethylene (ETFE) is a high-strength polymer that can be formed into an ultra-lightweight cladding element by welding the edges of three layers together and then inflating it for stiffness.[54] This represents another connection with Buckminster Fuller in that one of his students (and later a colleague), Jay Baldwin, invented the 'pillow dome' – a geodesic dome enclosed with inflated pillows, initially made from laminated vinyl and subsequently from ETFE. The great advantage of ETFE was that it was 1 per cent of the weight of glass (a factor-100 saving) and could be made in much larger 'pillows' than the biggest available sheets of safety glass. Thorough material testing allowed the design of the enclosure to be tuned to the specific conditions of the site.

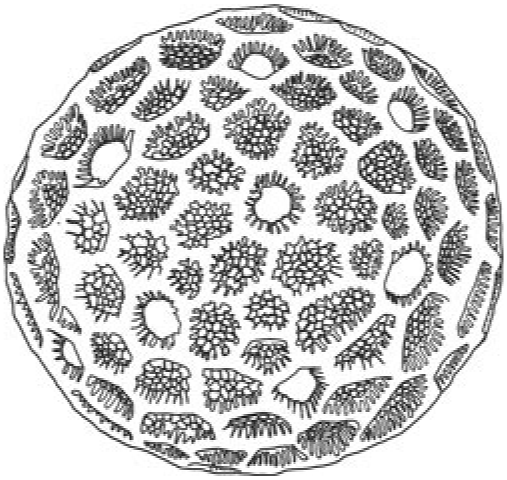
63. Protective enclosure formed by the Sisyridae sponge-fly



64. A carbon molecule known as a Buckminster Fullerene



65. Radiolarian structure



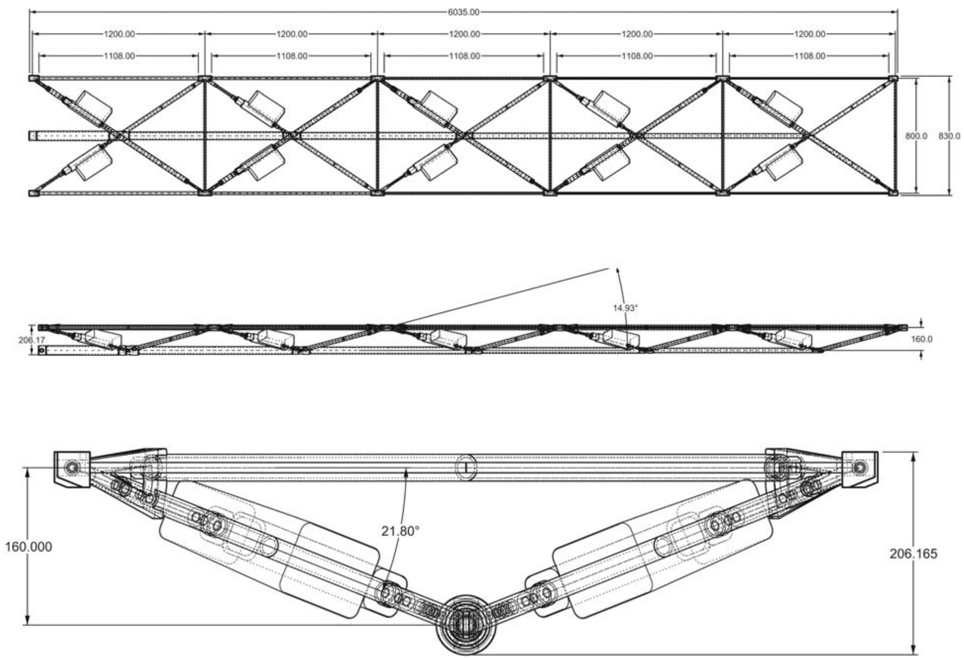
66. Pollen grain showing a geodesic structure

A positive cycle of design occurred in which one breakthrough facilitated another: larger pillows meant there was less steel, which in turn admitted more sunlight and reduced the amount of heat that would be needed in winter. Less steel also resulted in substantial savings in substructure. The result was a scheme that used a fraction of the resources of a conventional approach and cost a third of the normal rate for a glasshouse. The weight of the superstructure for the Humid Tropics Biome (fig. 67) is less than the weight of the air inside. If the team were to tackle the same challenge again, with more advanced materials technology and learning further lessons from biology, it is likely that further radical increases in resource efficiency could be achieved. For instance, 3D printing will, in time, allow steel tubes to be manufactured in a way that is closer to a biological approach – putting the material exactly where it needs to be according to stress concentration, rather than having a uniform diameter and wall thickness.

67. Interior of the Humid Tropics Biome

In contrast to many of the historical precedents that were studied, the biomimetic approach resulted in a much more sympathetic relationship with the landscape. Examples such as the Palm House at Kew – a highly symmetrical building on a flattened site – can be read as an expression of the view of nature that prevailed at the time, as something that could be dominated by humans. The Eden Project Biomes accommodate the existing form of the site with a minimum of excavation and suggest a more respectful reconciliation between humans and the natural world.

One of the key differences between biological structures and those made by humans is that, with the exception of deployables, ours don't move. Most of the time we actively want to reduce the amount that things move, so that people feel safe and less inclined to revisit their lunch. This means that the amounts of material used in our structures can look extremely inelegant compared to the more pliant



68. Adaptive truss by University College London and Expedition Engineering. Radical resource efficiency was achieved by employing the same adaptive strategies as biological structures

forms found in nature. Recent research by University College London and Expedition Engineering has shown how this approach could be transformed with the development of their ‘adaptive truss’ (fig. 68).[55] To explain the significance of this, it is worth clearly distinguishing between strength and stiffness. Strength is what is required to resist a load without breaking and stiffness is what is required to keep any deflections within acceptable limits. In many structures it is the required degree of deflection control that accounts for the vast majority of the structure. This adaptive truss is directly comparable to a skeleton controlled by muscles. Imagine you are holding a large tumbler at full stretch and someone fills it with water. As the weight increases, you would sense what is happening and compensate by making your muscles work harder. The adaptive truss works in exactly the same way: the bones are represented by compression members, the muscles by actuators and the nervous system by strain gauges, all controlled by a central computer. The amount of tension in the actuators can be increased or decreased according to the load. The sizing of the compression members can be close to the minimum required for strength. The result is an astonishing slenderness ratio (the depth of the structural element divided by its span) of 1/80 for a simply supported beam (1/12 – 1/20 is normal for a passive structure). It also means that an 80 per cent reduction in material can be achieved and whole-life energy savings of 76 per cent (taking into account both the embodied and the operational energy). Adaptive structures are at their best for structures that are only heavily loaded for a limited amount of time – perhaps a sports stadium, which may only accommodate a crowd for two hours a week, or a long-span roof, which is only subject to strong winds a few times each year.

The adaptive truss cleverly uses much less material yet still provides the required stiffness. There may be many other situations in which we can safely allow greater movement and, by doing so, save further resources.[56] The leg bones of gazelles are an interesting biological example. Rather than being straight, which one might think offered the greatest strength, the bones have a gentle curve. This allows them to absorb much higher shock loading, such as might be experienced when making extreme jumps to escape from a predator. There are vernacular examples of this, such as crook-frame barns, for which trees were specifically grown in curved forms in order to create a degree of flexibility. Using large amounts of material to achieve rigidity could be described as a twentieth-century aberration and now we can deliver what biology and vernacular design both do: a more intelligent and resource-efficient form of responsiveness.

Conclusions

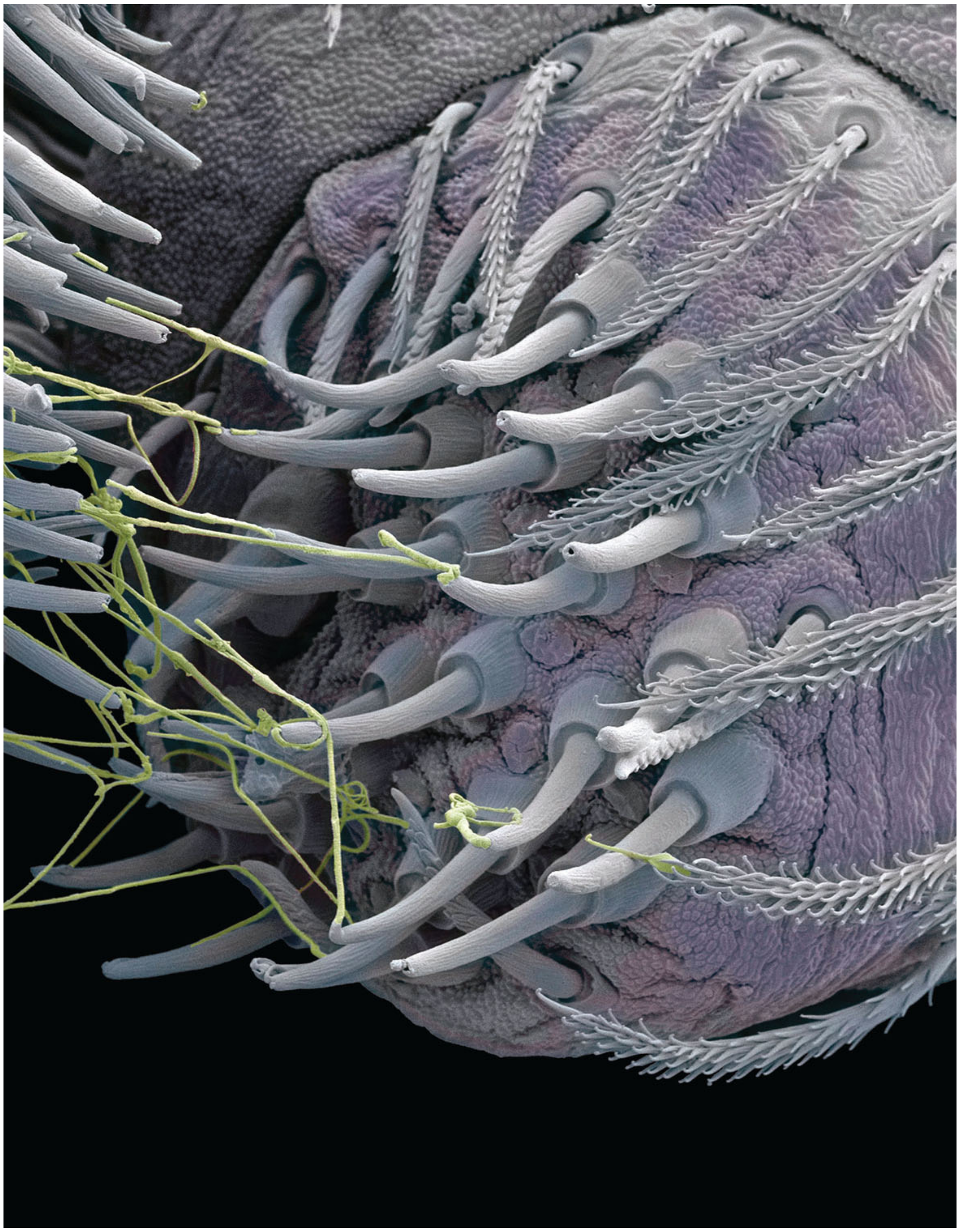
The axiom with which we started this chapter could now be extended to '**more shape**, **less material**, **greater responsiveness**'. At the start of the Industrial Revolution, resources were abundant and people were scarce; now we have the opposite situation. The case for approaches that use more human resources and fewer physical resources is even stronger. The biological paradigm translated into architecture means putting people at the centre: employing their ingenuity during design, involving them in the richly rewarding act of building[57] and the enjoyment of beauty. Some of the biomimetic structures described – such as vaulting, weaving and reciprocating basic materials into elegant structures – would be perfectly suited to developing countries where resource pressures are most acutely felt. Lessons from vernacular structures could be reinterpreted to deliver both resource savings and a sense of cultural continuity.

We can use biomimicry to evolve towards more integrated design, sidestepping foundation–structure–cladding–finishes approaches. Many of the examples outlined above demonstrate the potential to achieve radical increases in resource efficiency by using biological structures as a model: manipulations of thin planar surfaces, Nervi's ability to out-compete through lightness, domes and shells achieving factor-10 increases in efficiency and thin pressurised membranes taking this even further to achieve factor-100 increases in resource efficiency. With access to ever-improving scientific knowledge, designers will be able to draw on the many examples of ruthless refinement in nature, as well as the processes that led to that level of refinement, in order to create structures with beauty and efficiency. Concentrating our efforts on even just the easier and more accessible resource savings that biomimicry offers architecture, we can secure substantial wins.

This is of far more significance than passing technical interest. As described in the Introduction, we need to learn to do more with far less resource input if we are to address the combined pressures of a growing global population and resource shortages.

In the next chapter we will see some of the distinctions between our materials and nature's and how we can benefit from approximating the molecular-level manufacturing that goes on in nature.

Chapter Two
How will we manufacture materials?



69. Spinneret glands on the abdomen of a spider from which a fibre is spun that is tougher than steel but made with a fraction of the energy

This chapter is all about assembly: using the right elements and putting them together in the right way. Let's first look at some contrasts between the way biology assembles, and what this offers in preference to what Janine Benyus describes as the 'heat, beat and treat' way we conventionally manufacture.[58]

To produce strong fibre, spiders make their silk with an array of spinnerets[59] that produce an aligned stream of polymers which are then 'spun' into a thread with the spider's back legs. When dry, the silk is stronger than Kevlar (aramid fibre by another name and, prior to graphene, the strongest synthetic fibre that we have been able to manufacture to date[60]). Human manufacturing of aramid fibre requires petroleum to be boiled in sulphuric acid at around 750 °C. The mixture is then subjected to high pressure to get the molecules into place, producing large quantities of toxic waste. Yet spiders manage to do the same at ambient temperature and pressure with raw materials of dead flies and water. How can nature coach us to bridge this gap between contrasting manufacturing methods?

Aramid fibre exemplifies the contrast between natural and engineering mentalities. Its first lesson is to examine our expectations about materials. Our manufacturing methods typically start with energy-intensive mining, crushing, smelting, refining and forming. The process then frequently continues with other stages of treatments, protective coatings and adhesives. This intensive treatment differs, unfavourably, from the manufacturing that goes on in nature. Given our existing challenges of resource depletion, an expanding population and climate change, it seems a worthy goal to try to emulate nature's efficiency in our manufacturing processes.

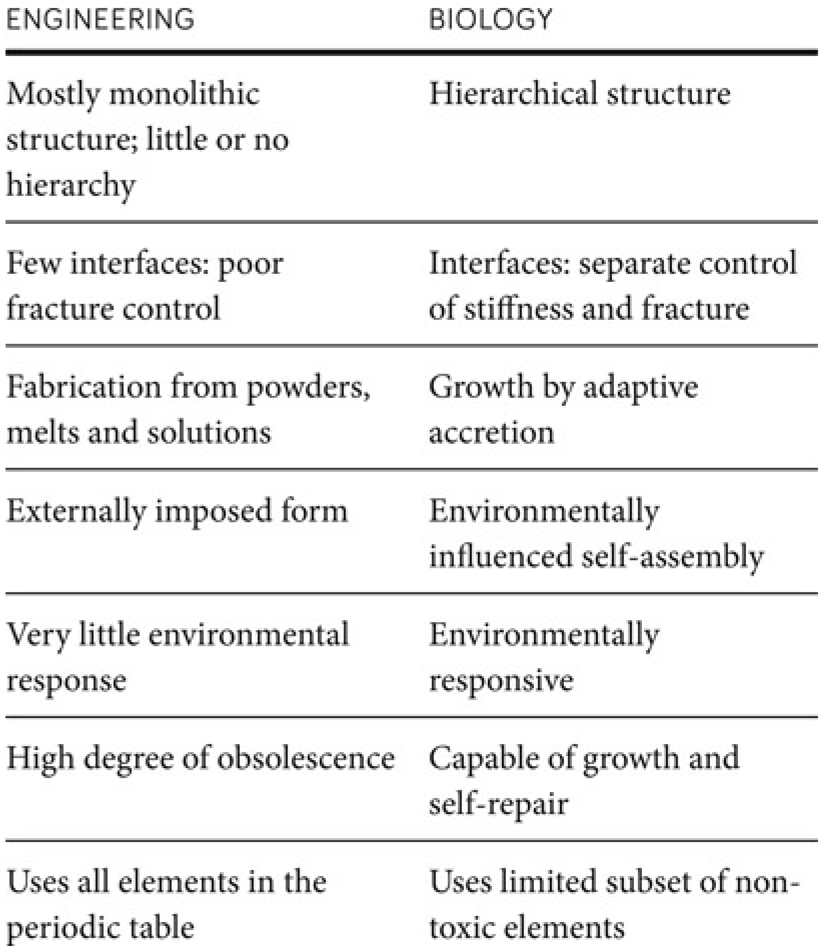
Our use of resources can be characterised as linear, wasteful and polluting, whereas in nature resources are maintained in closed-loop cycles. Our processes regularly produce toxic emissions, which can persist in the environment indefinitely; in the few circumstances in which toxins are used in biology, they biodegrade soon after they have served their specific purposes.

What elements should be used? The differences between engineering and nature become even clearer when one looks at which elements of the periodic table are used in the two approaches. Roughly 96 per cent of all living matter is made from four elements: carbon, oxygen, hydrogen and nitrogen. A further seven elements constitute nearly all of the remaining 4 per cent: calcium, phosphorous, potassium, sulphur, sodium, chlorine and magnesium. There are then a small number of trace elements that are used in absolutely minute quantities. So, nature uses a very limited subset of the periodic table, whereas we use virtually every element in existence, including some that really would be better left in the laboratory.

Emphasising the idea of assembling the right materials in the right ways, Professor Julian Vincent has described how, with just proteins, polysaccharides and some salts (mostly of calcium), nature has formed materials that have many of the same properties as human-made ones, stretching from polymers through to high-strength composites.[61] While there are some metals included within the trace elements referred to above (many of which are critical to various biological processes), living organisms do not actually make anything out of metals.[62] Some might argue that the only truly sustainable materials are ones that can be grown and recycled through biodegradation. For me, that is an extreme position: just because nature does not make things from, say, aluminium does not mean that we shouldn't. However, what we can do is to apply some of the principles of resource stewardship found in nature to some of the metals and minerals that are safe to use. We may also find that there are biomimicry-inspired alternatives for many of the applications for which we currently use metals, and that those alternatives would involve a fraction of the manufacturing energy and environmental impacts.

Can we learn to manufacture in the same way that nature does?

There are seven key distinctions to guide biomimetic thinking, summarised below:[63]



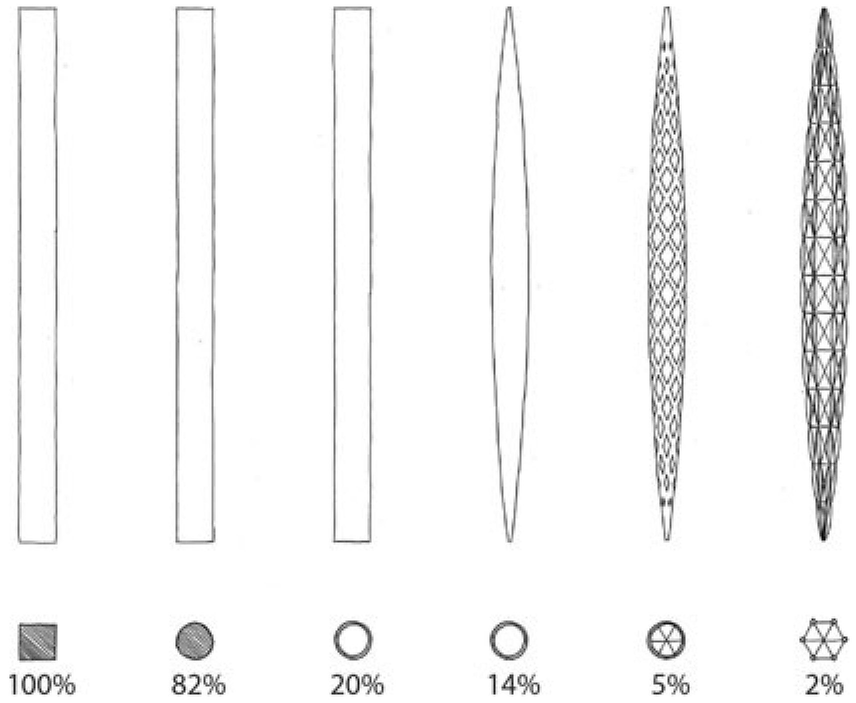
ENGINEERING	BIOLOGY
Mostly monolithic structure; little or no hierarchy	Hierarchical structure
Few interfaces: poor fracture control	Interfaces: separate control of stiffness and fracture
Fabrication from powders, melts and solutions	Growth by adaptive accretion
Externally imposed form	Environmentally influenced self-assembly
Very little environmental response	Environmentally responsive
High degree of obsolescence	Capable of growth and self-repair
Uses all elements in the periodic table	Uses limited subset of non-toxic elements

These principles form the structure of this chapter. What do these principles imply for mimicking biological manufacture?

How nature builds: hierarchy and interfaces

Structure and materials are indistinguishable in nature, which is a radically different way of thinking to grasp in an architectural context, where these concerns are more easily separated, and where traditional manufacturing techniques and drawing packages both reinforce this separation. Nature organises structure and materials together through hierarchy.

Perhaps a good way to begin exploring hierarchy is to visualise a range of bridge designs. One means of spanning a modest distance would be to use two solid steel beams that sit on piers at either end. This would represent a monolithic approach with no hierarchy. A more efficient way to span the distance would be to use a pair of steel trusses instead. That represents one level of hierarchy. Supposing we went one step further so that each compression member in the truss became a small box truss and each tension member became a cable made from stranded steel. That would represent two levels of hierarchy. With increasing levels of hierarchy, the structure becomes more efficient in terms of the amount of material used to achieve a given objective (fig. 70).

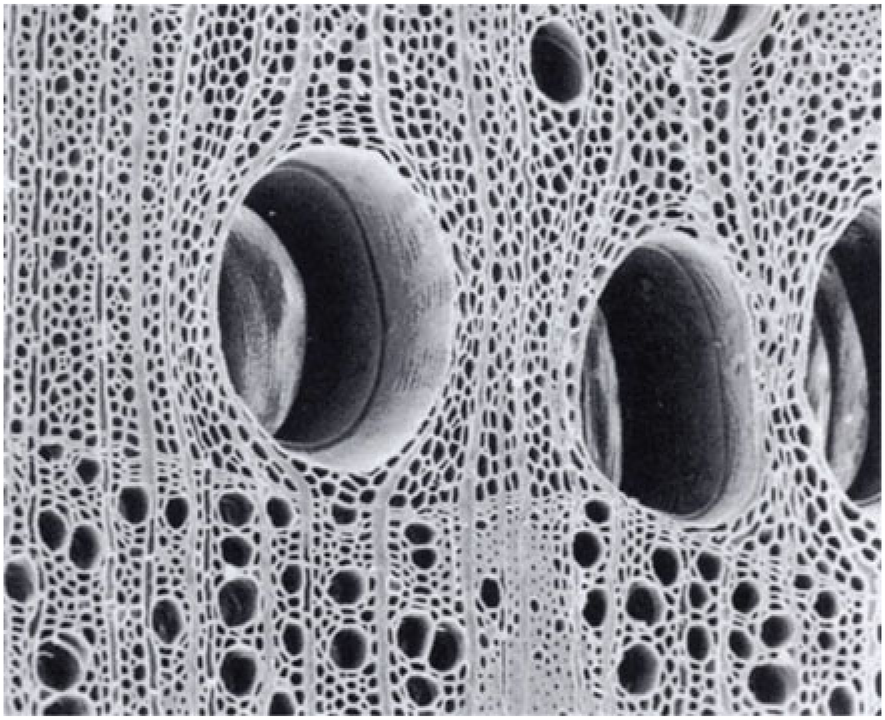


70. Diagram showing how, with levels of hierarchy, an element of structure can be further refined to use as little as 2 per cent of the material of a solid section (after work by Adriaan Beukers and Ed van Hinte in *Lightness: The Inevitable Renaissance of Minimum Energy Structures*,[64] with input from Fluid Structures)

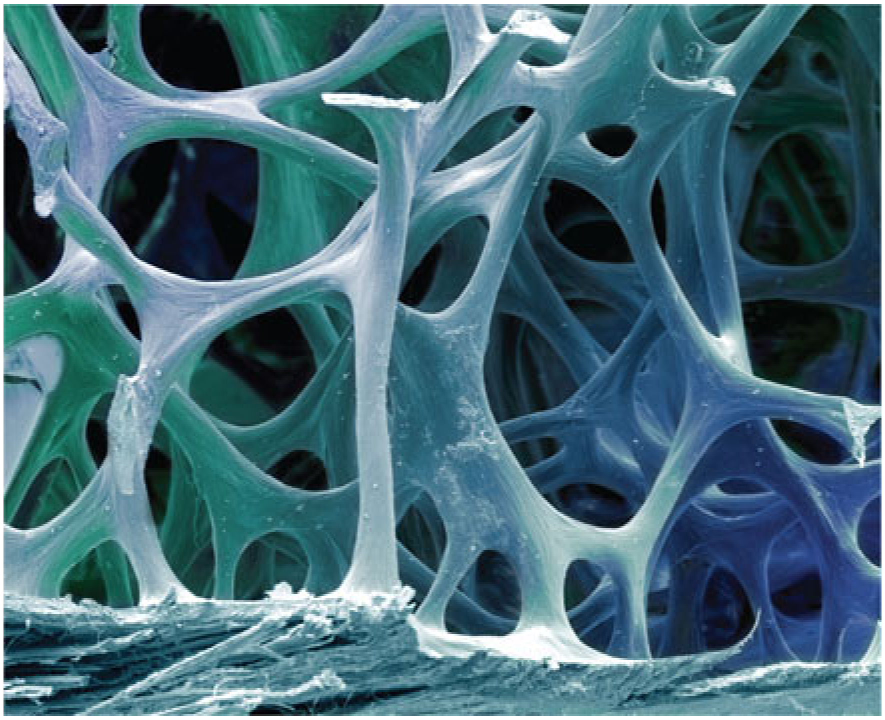
71. Trusses within trusses within trusses on the Eiffel Tower – showing three levels of hierarchy

The Eiffel Tower (fig. 71) demonstrates three levels of hierarchy, but the majority of human engineering uses only one level. In biology, it is not uncommon to find six levels of hierarchy and proportionately higher performance because the structure benefits from bonds at every level from atoms to molecules to cells to organisms and upwards.[65]

The bridge example shows the material decreasing in quantity and changing form at the same time (solid steel sections become steel cable). At this point some readers may be feeling confused about the difference between structures and materials and that is quite justifiable because in biology there really is no distinction between the two. The way that nature makes things from the bottom up, molecule by molecule, means that what we might think of as a biological material is also a structure. Wood (fig. 72), for instance, is a microstructure of lignified cell walls, and bone (fig. 73) is a hierarchical structure of calcium phosphate and collagen molecules in fibrous, laminar, particulate and porous form.



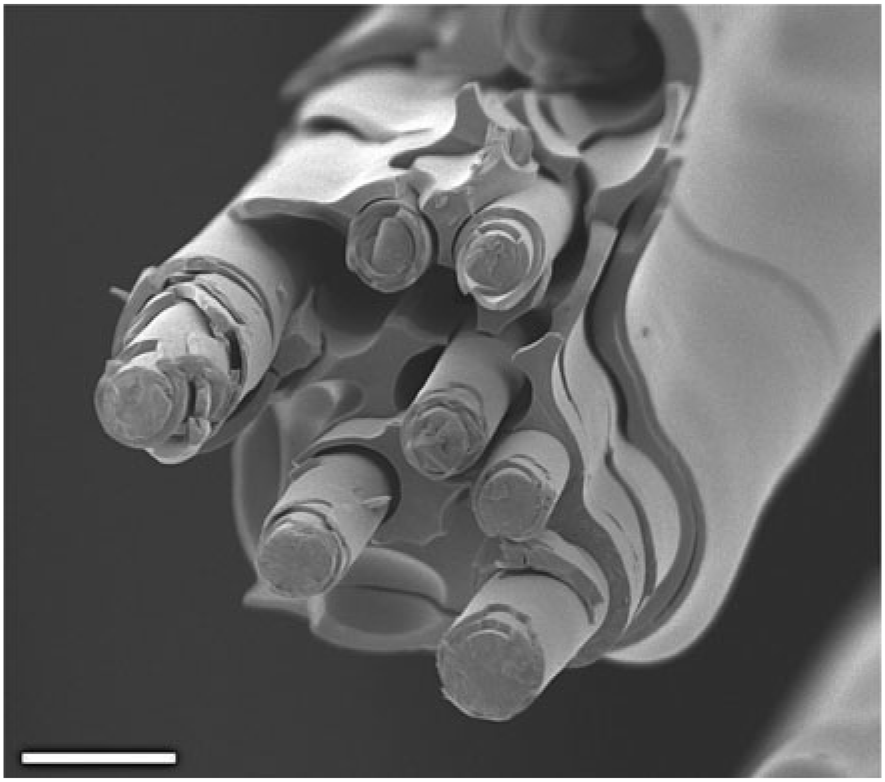
72. Scanning electron micrograph showing the microstructure of oak (*Quercus robar*)



73. Scanning electron micrograph of cancellous (spongy) bone tissue

Hierarchical structures also deliver benefits in stiffness and fracture control and this is achieved through interfaces between, and within, each level of hierarchy. The abalone shell (see Chapter 1) is made from platelets of aragonite (a form of calcium carbonate) bonded together with a flexible polymer mortar. The polymer forms the interface and, as is typical in biology, the material used at these points is weaker than the surrounding material. Materials scientist J. E. Gordon explains: ‘this is not because Nature is too incompetent to glue them together properly but because, properly contrived, the weak interfaces strengthen the material and make it tough’.[66] Toughness, in engineering terms, means resistance to fracture. Although 95 per cent of an abalone shell is made from the same raw material as chalk, it achieves 3,000 times the toughness through its hierarchical structure and interfaces. Artificial nacre is already being constructed, with research aiming to create ceramic materials and composites with far greater strength than has conventionally been possible.[67] Currently, these experiments are at relatively small scale (by architects' standards, that is – an abalone would take the opposite view) but could lead to substantial increases in spanning capabilities of Guastavino vaulting and related forms of construction.

The previous chapter described the macro-structure of *Euplectella*; its microstructure is also worthy of study because each spicule is a hierarchical structure in itself.



74. Scanning electron micrograph showing the hierarchical structure of glass sponge spicules

Professor Joanna Aizenberg has revealed the way that the spicules are built up in layers of silica of gradually increasing thickness towards a central cylinder (fig. 74). Each of the layers is joined with a thin interface of protein which results in a robustness similar to that of nacre. As Aizenberg describes it: 'During mechanical loading, the thin outer layers fracture first, resulting in the dissipation of large quantities of energy primarily via the spreading of cracks through the delamination of the silica layers.'[68] The glass sponge has evolved to grow these remarkable structures at ambient temperature and pressure. Aizenberg's work points the way towards low-energy manufacturing of high-performance composites.

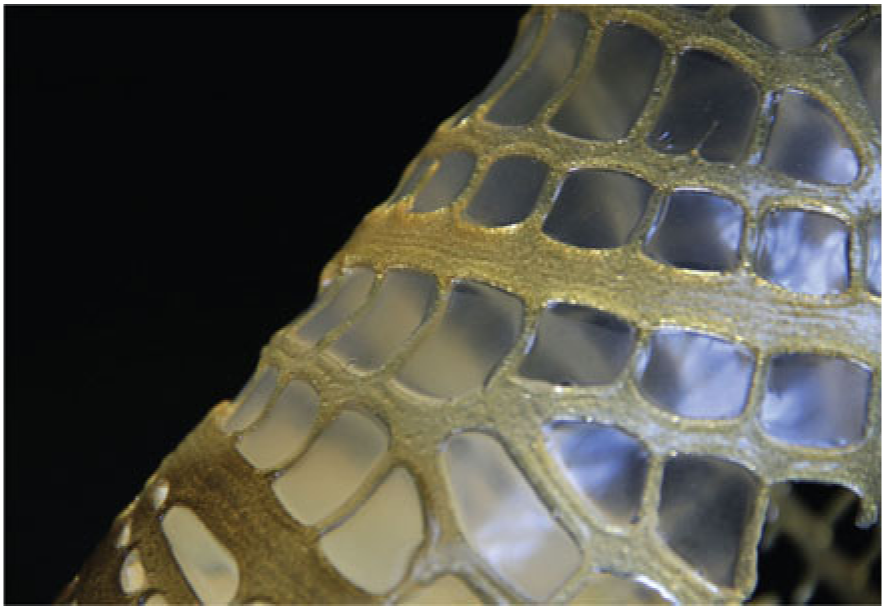
Growth by adaptive accretion and additive manufacturing

Nano-scale self-assembly is crucial to how nature operates. Molecular self-assembly in nature is the process by which molecules take on an ordered arrangement without external guidance or management, and also by which they fold into macromolecular assemblies. A major opportunity to mimic this is the prospect of growing materials for buildings by accretion or self-assembly that mimics natural processes. Initially called 'rapid prototyping' or 'rapid manufacturing' (RM), now generally referred to as '3D printing' or 'additive manufacturing' (AM), it was a significant breakthrough for designers in the digital revolution because it allows a three-dimensional computer model to be turned directly into a physical model with a very high degree of accuracy and without the laborious process of making a prototype by conventional means. Coincidentally, what AM also allows is to approximate the bottom-up manufacturing that goes on in nature, in the way that material can be positioned exactly where it needs to be. Consequently, it offers the ability to achieve efficiency of materials through complexity of form at no added cost – in fact, it can achieve lower costs simply by using less material.[69]

The designer and authority on AM, Geoff Hollington, has asserted that the technology now challenges the three traditional ways of making things that have been used since antiquity. The old methods can be summarised as 'subtractive' (such as shaping flint, carving wood or modern machining), 'moulding' (clay pottery, cast metal or moulded plastic) and 'forming' (bending, forging and stamping).[70] New approaches will pioneer additive approaches that approximate the molecular, from-the-bottom-up, manufacturing that occurs in biology.

Machines now exist that allow mixed materials, as nanoparticles in solution, to be deposited from a jet that is similar to that of an inkjet printer. The very small scale of the material allows low-energy bonds, such as van der Waals forces, to assist in assembling the particles. If one material that cures to a hard finish is used in combination with another material that dries in a flexible form, then it is possible to produce an element that can be either very tough (exploiting the interfaces), very flexible, or even varying in these properties along its length (referred to as 'functionally graded materials') (fig. 75). While we have yet to achieve equivalent technology to biological growth processes, we are getting tantalisingly close.

75. *Pneuma* by Neri Oxman, demonstrating the potential for 3D printing to produce functionally graded materials in complex forms



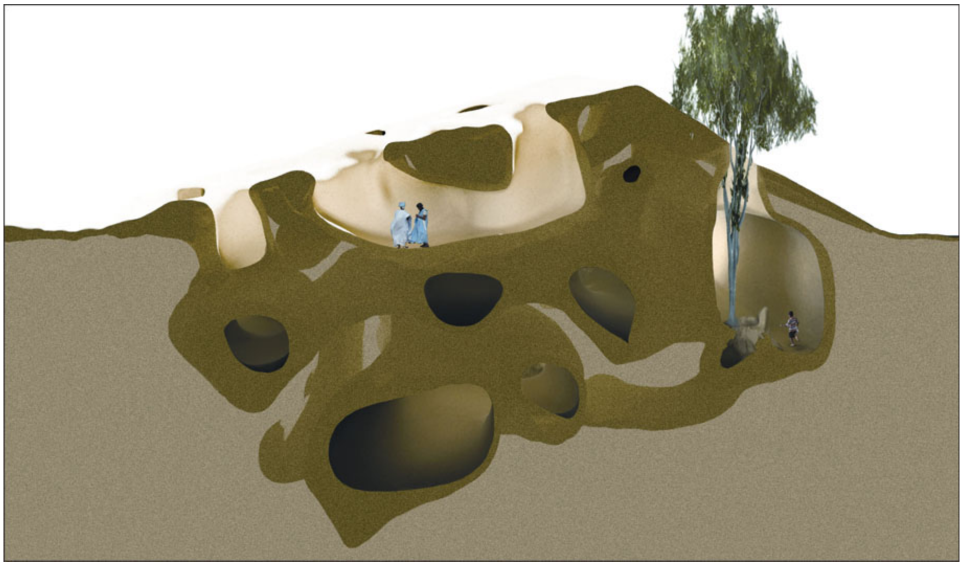
76. Chitosan structure 3D printed with biological raw materials by Neri Oxman and colleagues at MIT Media Lab

What should these machines print with? What we ideally want is to be able to use a biological raw material, get it to self-assemble into polymer chains and then be able to assemble those chains in a controlled way. Perhaps the closest to achieving this has been the work of Neri Oxman and colleagues at the 'Mediated Matter' laboratory at MIT Media Lab, who have managed to print with chitosan (a deacetylated form of chitin – one of the substances from which insect carapaces, prawn shells and crabs shells are made) and functionally graded materials with spectacular results (fig. 76). Mogas-Soldevila *et al.* have observed that natural polymers and polysaccharides represent a vast renewable resource and that:

> *In the fields of architecture, engineering and product design, property gradation of single materials with multiple functions hold the potential to revolutionize how products and buildings are form-found, designed and fabricated. Ultimately, such advances will lead the way towards the design of multi-functional material systems with variable properties reducing the need for complex assembly of multiple parts with homogenous properties and discrete functionality.* [71]

Eventually, it will be possible to include interfaces and many levels of hierarchy. This could achieve a degree of resource efficiency and resilience similar to that found in many of the biological sources that will continue to be studied by collaborative teams of scientists and designers. Most, if not all, AM is carried out at ambient temperature and pressure and therefore offers the potential for much lower-energy fabrication than conventional approaches.

Another widely used natural material is cellulose. It is an underutilised resource from algal biofuel production and would be easy to extract, because algae do not cross-link the cellulose in their cell walls through lignification. Cellulose is one of the most abundant biological materials and, furthermore, nano-crystals of cellulose can be made to self-assemble into sheets and fibres.[72] Taking inspiration from Buckminster Fuller's assertion that 'Pollution is nothing but the resources we are not harvesting',[73] we could use the blanket weed (*Spirogyra*) that has clogged countless lakes and rivers around the world, where agricultural fertilisers have been overused, as a further source of cellulose for additive manufacturing. At a large scale, this could be another drawdown technology that would be effectively growing materials from atmospheric carbon (with some obliging intermediaries, such as prawns, algae and insects).



77. 'Dune' – Arenaceous Anti-Desertification Architecture by Magnus Larsson, which uses microbial deposition to create habitable structures within sand dunes

While AM is a form of technical self-assembly, it is also possible to employ some biological assistance. Exploring microbially grown materials is something that has now successfully reached market deployment, thanks to Ginger Krieg Dosier at biotechnology startup bioMASON. Dosier's concept developed when studying micro-organisms in coral reefs and led on to the idea of using *Sporosarcina pasteurii* bacteria to bind sand with calcium carbonate. The inoculated sand is placed in moulds, fed with calcium ions and hardens into bricks in two to five days – the same amount of time as it takes to kiln-fire a conventional brick but with a fraction of the energy input.[74] The architect Magnus Larsson has pursued a similar form of microbial precipitation but with the intention of forming structures in situ in desert areas (fig. 77). Experimental architectural practice The Living has explored bacterial growth as another way of literally growing materials – namely, using fungal mycelia to bind together discarded corn stalks into bricks with sufficient compressive strength to be used in construction. The firm assembled these into a temporary installation called 'Hy-Fi' (figs 78 & 79), the form of which is reminiscent of chopped sections of highly magnified mycelia. After dismantling, the bricks were composted and completely reabsorbed into the biological cycle. Similar schemes have been assembled by drones, such as Gramazio Kohler Architects' 'Flight Assembled Architecture'. It could be argued that this approach of using micro-agents to precisely position small components is getter closer to the self-assembly that occurs in biology. Despite a big difference in scale, it marks a dramatic new direction when compared to the conventional approach of large components assembled by large human agents.

78–79. ‘Hy-Fi’ by The Living, constructed using bricks that were grown using fungal mycelia

80. The living bridges of Cherrapunji – an example of a grown structure that is still alive, which would more accurately be referred to as bio-utilisation rather than biomimicry

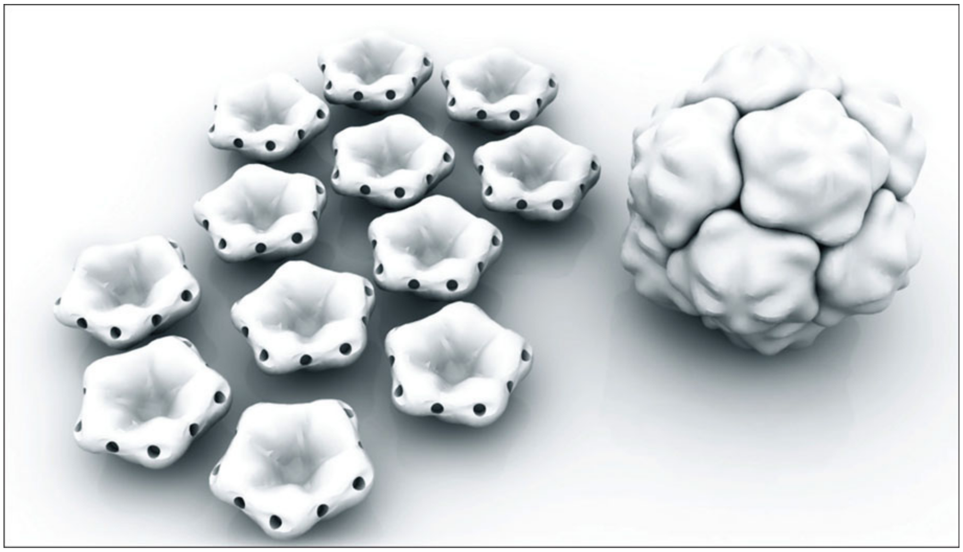
Environmentally influenced self-assembly

Nature offers another arena to inspire current building practices: epigenesis. Epigenesis is the process by which growth is significantly influenced by the environment; it is an additional determinant of growth to genetics. A straightforward example would be the way that trees grow partly in response to the forces that act on them. A branch joining the trunk is subjected to stress in windy conditions and will grow thicker in the affected areas in response (part of Claus Mattheck's axiom of uniform stress referred to in Chapter 1).

Because buildings generally do not yet grow in any sense that is truly comparable to biology, there are very few existing examples of epigenesis in architecture. One that comes close is the proposal for the Biorock Pavilion by Exploration, based on the technology pioneered by marine biologist Thomas J. Goreau and engineer/architect Wolf Hilbertz.[75] This uses electro-deposition in seawater to form accretive mineral structures. An electrical current, low enough to be safe for marine life, is passed through a steel frame submerged in seawater, resulting in dissolved minerals being deposited on the structure. To date, the technology has only been used to restore coral reefs by growing mineral structures on which corals can become established and flourish.[76]

81. The Biorock Pavilion, which is to be grown in seawater in a way that is comparable to epigenesis

The Biorock Pavilion (fig. 81) is intended to be a small auditorium that will be grown in seawater and then floated to the surface and transported to an urban location, where it will be a venue for small-scale performances. Design team member Professor Julian Vincent suggested using strain gauges to determine the amount of current supplied to each member, making the growth process epigenetic. Since the rate of accretion is partly determined[77] by the current, the members that were subjected to greater strain would be the ones that would grow more in response. The rate of accretion can be as high as 50 mm per year and, depending on the speed of deposition, the compressive strength can exceed that of reinforced concrete. The minerals continue to be deposited for as long as the current passes through the frame and damaged areas will repair themselves. Offshore wind turbines could use small amounts of surplus electricity to reinforce their foundations with Biorock, or build reefs that help to restore marine ecosystems.



82. Bio-molecular self-assembly by Skylar Tibbits – exploring the potential for individual elements to self-organise into structures

The work of the MIT Self-Assembly Lab has explored ways in which elements can be 'programmed' to self-assemble into predetermined forms or self-adapt to particular conditions, often through passive forms of energy, such as ambient heat, vibration or magnetic fields. They define self-assembly as 'a process by which disordered parts build an ordered structure through only local interaction'[78] (fig. 82). The founder of the Lab, Skylar Tibbits, has proposed that one of the most useful applications of this approach would be for construction in extreme environments where it may not be safe or feasible for humans to go.

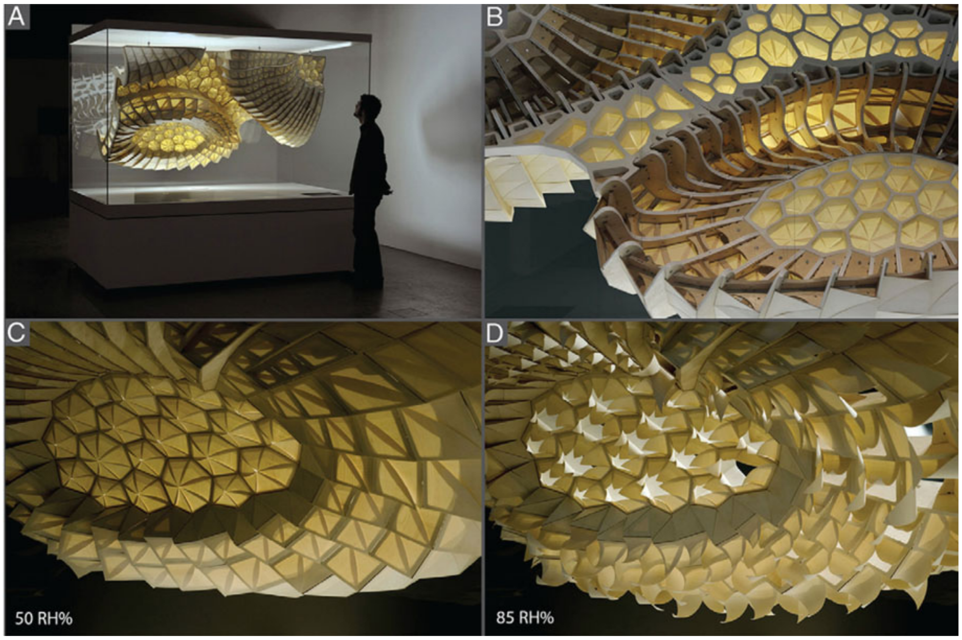
Environmental responsiveness

Materials that can sense and respond to changes in their environment are often referred to as ‘smart’. Clearly, in architecture we create many systems that do this at the level of a building and it is worth making a distinction here. In most of our systems engineering there will be a sensor, a processor and an actuator; in a truly ‘smart’ material, the sensor and actuator is the same thing and there is no processor.

One example originally studied at the Centre for Biomimetics at Reading University is the pine cone, which stays firmly closed when it is on the tree. When the pine cone falls, it starts to dry out and open up, eventually releasing the seeds inside. The opening occurs because the scales of the pine cone are sandwich structures made from two materials that react differently to humidity: one of them shrinks more than the other and the bending effect is similar to a bimetallic strip. This hygroscopic actuation was developed into a multilayered textile with lots of small flaps that would open up when the wearer started to sweat and close again when the skin beneath had cooled.

A similar idea, also inspired by pine cones, was developed into a stunning installation (fig. 83) by Achim Menges, Steffen Reichert and colleagues at the University of Stuttgart’s Institute for Computational Design using a composite of veneers that would either lie flat or roll up according to humidity levels. They describe this as ‘meteorosensitive architecture’, in the sense that it can respond directly to changes in atmospheric conditions. They make the point that ‘complex electromechanical systems have the disadvantage that they are complex to build and difficult to maintain and tend to frequently malfunction. Material embedded actuation provides a new perspective to these challenges as it intrinsically engages weather conditions’.[79] The potential for facades that can control the internal environment of the building without the need for additional mechanical control is extremely appealing. Architects could develop similarly elegant responses to other environmental changes by studying examples in biology, such as the way certain leaves roll up in windy conditions, which reduces the overall wind-loading on the tree.

Self-repairing materials



83. ‘HygroScope - Meteorosensitive Morphology’, Centre Pompidou, Paris, by Achim Menges in collaboration with Steffen Reichert – materials that respond to changes in humidity without a separate sensing and processing system

As Petra Gruber has observed, self-repair is particularly useful in situations where a local failure could lead to complete system failure.[80] The speed of the repair matters in such systems. Olga Speck and her team at the University of Freiburg Plant Biometrics Group have developed some ingenious self-repair solutions for pneumatic structures based on a liana called *Aristolochia macrophylla*. They observed that the plant rapidly heals a lesion through the expansion of thin-walled parenchymal cells adjacent to the point of damage to initially form a quick seal, and then through the more gradual repair of the tissue by lignification of the cell walls. They translated this idea into a polymer with multiple layers of pressurised cells on the underside (similar to very closely spaced bubble-wrap). When a puncture occurs, the pressurised cells react exactly like those of the liana although with even more impressive speed – the polymer can self-repair in a fraction of a second.

Self-repair is an area in which there is still a large gap between biology and engineering, simply because none of our buildings are 'alive' in a sense that is comparable with a living organism. Promisingly, some pioneering materials provide examples of self-repair that are analogous to biology (as opposed to having been inspired by a specific biological form of self-repair). Dr Carolyn Dry of the University of Illinois has developed a form of concrete that has adhesive-filled hollow fibres embedded into the mix so that, if a crack occurs, the fibres rupture and adhesive flows into the crack.[81] Dr Henk Jonkers at the Technical University of Delft has created 'bioconcrete' that contains limestone-producing bacteria which are activated when a crack occurs, so that the gap is filled and the surface seal is re-established.[82] Many self-repair systems in biology are dependent on vascular networks and it is conceivable that an engineered structure could be designed to have an equivalent system which delivers 'repair liquid' that cures in the presence of oxygen or light.

A broad definition of 'self-repair' includes self-cleaning materials, of which there are already several based on biomimetic ideas. Lotusan, by the paint company Sto, was named after the organism that inspired it, the lotus, which has long been revered for the way that it can grow out of the darkest mud and produce the cleanest white flowers and leaves. The effect in both the plant and the paint is delivered by means of a nano-texture of bumps which changes the contact angle of water droplets on the surface, as well as reducing the adhesion of particles, so that dirt simply rolls off with the water in the first shower of rain.[83]

A team at the Wyss Institute for Biologically Inspired Engineering at Harvard University has taken slipperiness to new levels by studying the pitcher plant (*Nepenthes*) and the result is SLIPS – an acronym for 'Slippery Liquid-Infused Porous Surfaces'. This surface works at lower angles than the products based on the lotus effect and could be useful for a range of applications, such as anti-fouling pipe coatings and self-cleaning surfaces for photovoltaic panels.[84] SLIPS uses a matrix of Teflon nanofibres in combination with a lubricant liquid so, like the pitcher plant, it is a self-repairing surface. Nature's essential principle is '**materials, not finishes**'. Nature builds in the properties needed, rather than adding a layer of paint or film, as is common in design.

Non-toxic elements in a new materials cycle: Cradle to Cradle® for architecture[85]

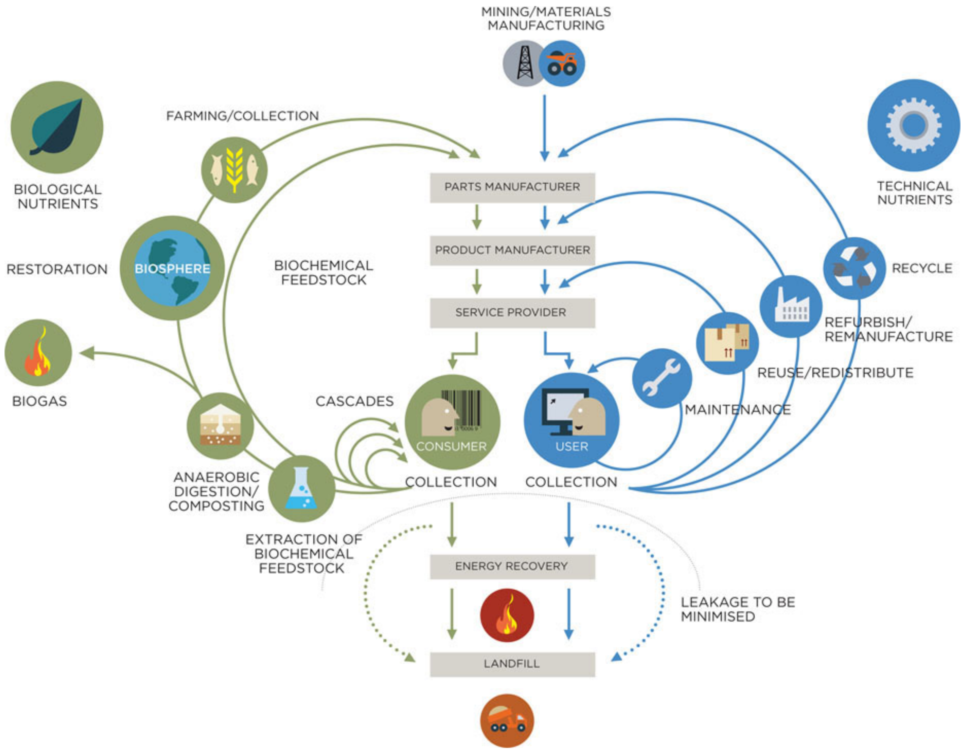
Following nature in using a smaller palette of non-toxic elements in the periodic table also means considering the materials cycle. Rethinking the whole conundrum of materials and manufacturing is the basis of William McDonough and Michael Braungart's brilliant book *Cradle to Cradle* (C2C).[86] They demonstrate the core materials cycle problem and three essential principles for all designers.

Avoid 'cradle to grave'

Most products are manufactured in a 'cradle to grave' manner, with a life of varying length before disposal, generally to landfill or by incineration. Much of what is called 'recycling' is really 'downcycling', where materials are steadily degraded until they ultimately become waste. Downcycling just delays the point at which those resources are lost as waste.

Use the right materials

Cradle to Cradle eloquently describes how being ‘less bad’ is not the same as being ‘good’. Plastics, for instance, are increasingly manufactured to contain less formaldehyde or have higher recycled content, but the aim should be to design without any toxins and for full recyclability. Plastics in the oceans degrade into microscopic debris which can absorb pollutants, which can in turn be eaten by fish, and work their way up the food chain into humans, where they act as endocrine disrupters, often because they are chemically similar to human hormones. European males now have a sperm count that is roughly half that of their grandfathers.[87] Designing for a positive future includes thinking not just about buildings but also about the health of the people that will use them.



84. Diagram of biological and technical nutrient flows by the Ellen MacArthur Foundation created with the support of McKinsey & Company and adapted from the Cradle to Cradle Design Protocol by McDonough and Braungart

Combine materials in the right way

McDonough and Braungart describe certain products as ‘monstrous hybrids’. These are mixtures of materials or assemblies of components from which it is not economically feasible to recycle or salvage the raw materials after their current life. One very common example from the construction industry is composite floor decks, where concrete is poured into profiled steel sheets that are so intricately textured that it is unlikely ever to be practicable to separate the two materials. The second is double-glazed units. The glass is often given a low-emissivity coating (which would contaminate the glass production process if recycled) and then bonded with butyl, silicone, aluminium and desiccants – again confounding economic attempts at recovery of those resources in the future. The aim should be to assemble materials in a way that allows easy separation at end of life.

Design ‘Cradle to Cradle’

McDonough and Braungart set out to achieve ‘100% good’. Their vision is to completely eliminate the concept of waste by following the principles of natural systems and keeping all materials in one of two cycles: ‘**biological**’ or ‘**technical**’ (fig. 84). In the biological cycle, which includes natural fibres, wood, etc., all the materials are grown and used in such a way that they can be fully biodegraded at the end of their tenure as a product, reabsorbed into nature and become nutrients for growing other materials. The technical cycle includes all metals and minerals, which, once they have been mined and refined, should remain permanently in the system.

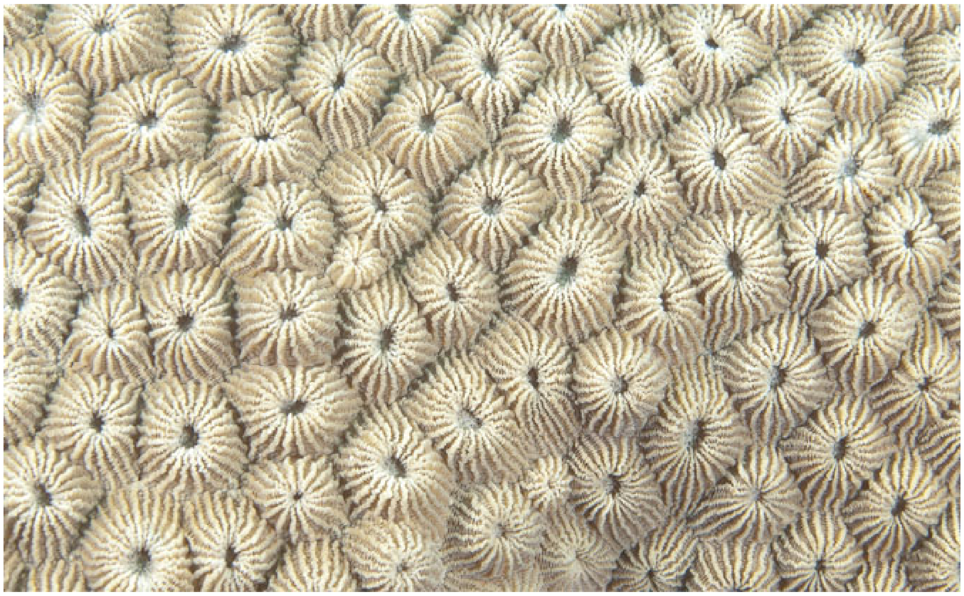
McDonough and Braungart describe cases mainly from the fields of industrial design and product design. We will now look at how the principles described in *Cradle to Cradle* can be extended to construction materials and combined with biomimicry to deliver ‘100% good’ solutions. In

Chapter 3 we will discuss how both of these cycles need to be backed up by information cycles.

Technical cycle solutions

Concrete

Concrete is the universal material of our age. Globally, 15 billion tonnes are poured every year and this is set to continue as less developed nations create the buildings and infrastructure necessary for a decent quality of life. Cement presents a problem in that it prevents full re-involvement in the technical cycle. Consequently, aggregates become steadily downcycled. There may be opportunities with geo-polymer cements to create a form of concrete that can be safely reabsorbed into the lithosphere. Similarly, pozzolanic cements and the naturally occurring cementitious compounds that bind together conglomerate rocks could offer good solutions.



85. Could we master the process of biomineralisation as performed by corals and other marine organisms? If so, the concrete industry could sequester carbon in large quantities

Recent developments led by Brent Constantz suggest that we are on the brink of achieving what corals and other marine organisms have been doing for aeons: creating mineral structures that absorb rather than release carbon in production. Constantz is an expert in both biological and geological mineralisation and, while at Calera, developed a process for cement manufacturing that is equivalent to the biological version. Biomineralisation sequesters an atom of carbon with every atom of calcium in the process of forming calcium carbonate (fig. 85). Cement production, by contrast, releases a molecule of carbon dioxide for every atom of calcium. Since leaving Calera, Constantz has focused his attention on creating carbon-positive[88] aggregates, which have the potential for faster deployment and greater gains in terms of carbon sequestration. If we contemplate the amount of concrete that is still to be used in developing nations like China and India, then it is clear how significant it would be if that concrete were removing carbon from the atmosphere rather than adding to it.[89] This is one example of an emerging field of 'drawdown technologies' which could play a crucial role in mitigating climate change by reducing, and ultimately reversing, the build-up of atmospheric carbon dioxide.[90]

Glass

Glass is another ubiquitous material in contemporary construction. Graham Dodd from Arup has proposed that one way of manufacturing C2C double-glazed units would be to create spectrally selective glass based on biomimicry. Many colour effects in nature, such as the iridescent wings of the blue *Morpho* butterfly (fig. 86), are achieved not through pigments or coatings but through 'structural colour', which is a microstructure that refracts and scatters light rather than reflects it. For glass, it might therefore be possible to create a nanostructure from the glass itself that could perform in a similar way to the low-emissivity coatings currently applied as a separate material.

The other form of ‘monstrous hybridity’ in glazing can be addressed by a thermoplastic seal that is easier to remove and recycle. The thermal performance of this unit would probably not match conventional ones, but it is important to remember that reducing energy use and related carbon emissions, while extremely important, is not the only challenge we have to address. We may find that some of the most comprehensively sustainable solutions are not necessarily the lowest-carbon options.

Metals and finishes

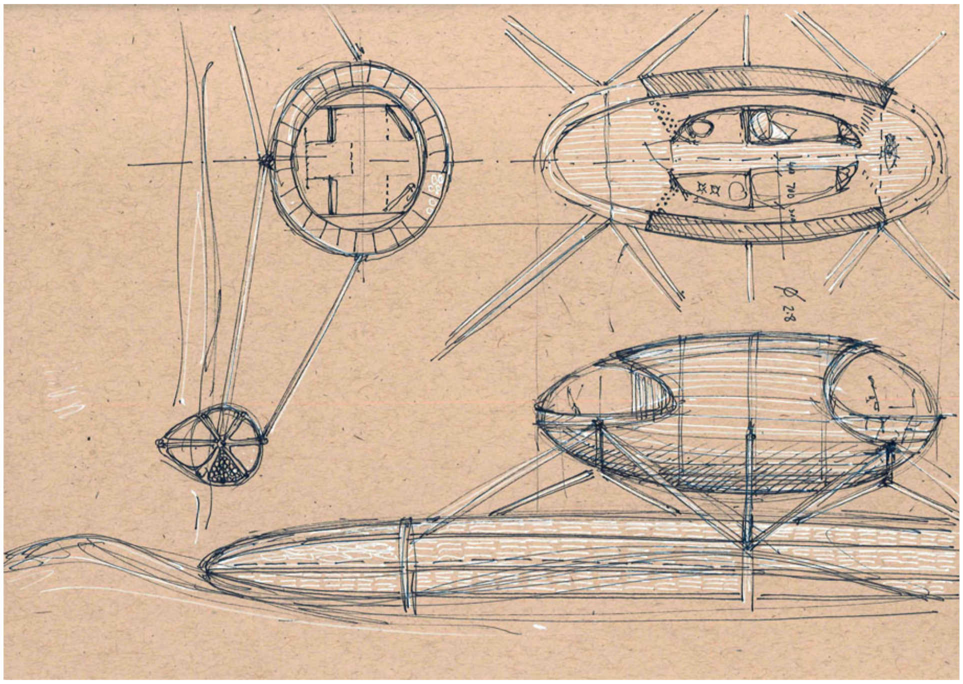
86. The iridescent colour of the blue *Morpho* butterfly is the result of a microstructure that creates a colour effect through refraction, rather than a pigment that reflects particular wavelengths of light

Many standard materials in the built environment are finished with paints, seals and other coatings, which can reduce the materials’ reusability or recyclability. Such coatings are inherently problematic because they are almost certain to end up as pollution. Biological materials are able to repair themselves, whereas our construction materials are inert and, with a few exceptions discussed earlier in this chapter, are likely to remain that way for the near future. In current practice, it is best to promote increasing use of metals that are inherently resistant to weathering, such as aluminium, stainless steel and Corten steel. We can also harness significant advances in technology, such as foamed metals and honeycomb forms, that achieve remarkable increases in resource efficiency. We may find other applications of biological colour creation in products for which we currently use paint coatings.

Composites and their consequences

One of the most problematic classes of materials from a C2C perspective is synthetic composites, such as fibreglass, which combine a fibre with a resin in a way that makes it effectively impossible to recycle. One project that explored an alternative to fibreglass was the Plastiki Expedition, initiated by David de Rothschild. The aim was to design a boat made out of plastic bottles that could be sailed across the Pacific on an expedition that would highlight the problems facing the oceans as well as the kind of solutions that we need to implement. He focused particularly on the two vast areas of floating waste, located in the gyres formed by ocean currents, known as the Pacific garbage patches.

Each of these is the size of Texas and consists mainly of plastic, either in bulk form (which affects seabirds and marine mammals) or as UV-degraded microscopic lengths of polymer, which absorb other pollutants and accelerate their uptake into the marine food chain. Those at the top of the food chain are particularly badly affected, including Inuit mothers who are advised not to breastfeed their children because the level of toxins is sufficient for their milk to be classified as hazardous waste. Similarly to the alarming issue of declining sperm count, this shows how dramatically the quality of our lives is affected by our relationship with materials.[91]



87. Concept sketch of the Plastiki Expedition boat, showing boat hulls made from large bundles of bottles

Working with Exploration as concept architects, the first challenge was to turn a very weak material – plastic bottles – into a structure that would withstand the forces likely to be experienced on a voyage through the Pacific Ocean (fig. 87). The team took inspiration from a number of examples in nature of close-packing and of hydrostatically pressurised cells. This included pomegranates, which consist of a large number of individual segments packed together in a tight geometrical way. This led to a significant breakthrough in the design process: the idea of pressurising each bottle with air – a simple move that transformed the bottles into incredibly solid objects. Tests proved that, just by adding air pressure, it was possible for two plastic bottles on end to support the weight of a car.

While bundles of bottles provided useful buoyancy, there had to be a core material to act as a frame. The team discovered a sheet material called SrPET (self-reinforced polyethylene terephthalate) that had recently been developed from waste plastic bottles. The revolutionary aspect of this product was that it was made entirely out of one material (PET – polyethylene terephthalate) but in two different forms: a fibre and a matrix. At a molecular level, the fibres are chains of aligned polymers, while the matrix is a spaghetti-like tangle of polymers. The structural effect is very similar to the phenomenal toughness of fibreglass but, unlike fibreglass, SrPET can be recycled indefinitely with no loss of resources or material quality – the holy grail of C2C design. In fact, the possibility existed to *upcycle* the bottles and SrPET into products with higher value, such as fleece sweaters that could be auctioned off for charity, further raising the profile of the environmental problem while offering a solution. The Plastiki boat completed its voyage across the Pacific in July 2010 and its broader mission, to demonstrate material solutions to environmental problems, was described in a documentary film.[92]

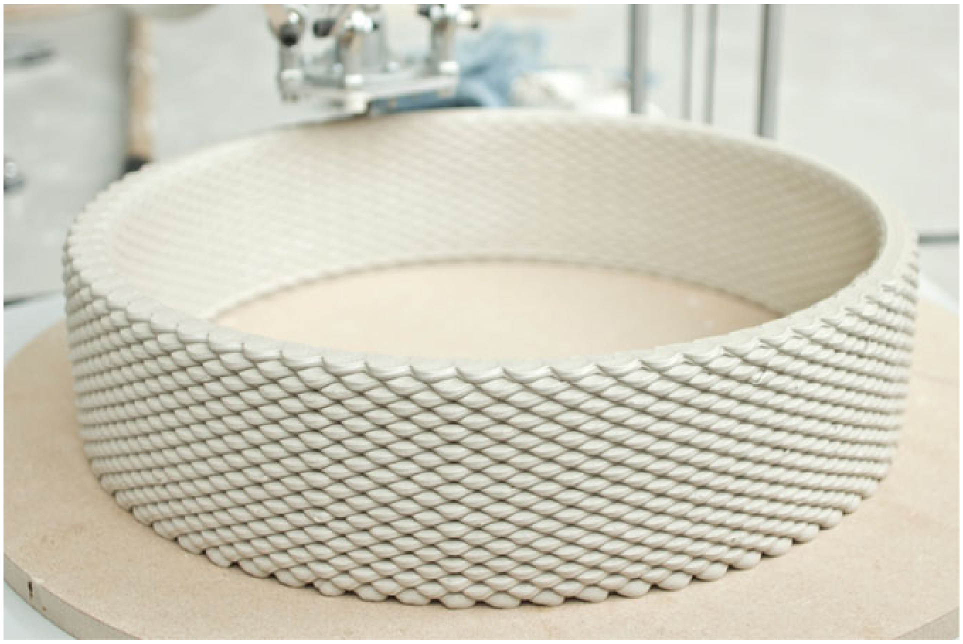
Biological cycle solutions

Timber

Similar challenges regarding coatings apply to timber as they do to metals: current paint and preservative finishes will invariably end up as pollution. Using cellulose in 3D printing is perhaps the most revolutionary way to rethink wood but, in its conventional forms, timber is best selected either for its inherent resistance to weather (woods such as oak, larch and western red cedar) or by specifying products that use non-toxic treatments to extend the wood's life, such as Thermowood® or Accoya®. The first of these uses a short but intense heat treatment to make the wood indigestible to microbes for an extended period, while Accoya® achieves much the same result through a process of acetylation, using a naturally occurring and benign chemical (acetic acid) that also stabilises moisture content. These options allow the timber to be returned to the biological cycle at the end of its useful life.

Rammed earth

Rammed earth has been used as a building material for centuries and has returned to favour owing to its extremely low environmental impact. Conventionally, it is rammed into formwork and it is worth studying how earth is used by various animal builders, who have to make do without power tools. The muddauber wasp (*Trigonopsis*) selects mud of the right consistency and moisture content, holds a pellet against the wall it is building and then exploits the thixotropy of the mud by vibrating its abdomen.[93] Thixotropy is the property of showing a reduction in viscosity when shaken and, for the wasp, it results in very efficient compaction with minimum force.[94] Some birds create a composite material from mud by combining plant fibres that give the benefits of strength in tension as well as compression – similar to the function performed by steel rods in reinforced concrete. Italian company WASP, inspired by *Trigonopsis*, brought a 3D printer range onto the market that can use clay as the raw material. In 2015, they completed Big Delta, a clay printer large enough to print a house.[95] For what is often regarded as a rather crude material, the results are striking (fig. 88). The other appealing aspect of this approach is that it allows us to get closer to the spirit of great builders like birds, mammals and insects that demonstrate what elegance can be achieved with materials that are readily available. We could do the same; instead of bringing materials to the site, we could bring ingenuity and create structures with a fraction of the embodied energy of conventional approaches. An extension of this 'biomimicry technology plus local materials' philosophy could be revolutionary for people living in rural areas.



88. 3D-printed ceramic by Olivier van Herpt showing the beauty and precision with which relatively crude materials like mud and clay can be assembled

Plastics

Plastics can be made out of plant resins and, if toxic additives or coatings are avoided, then the material can be returned to the soil as biological nutrients.[96] One of the most interesting examples of this is a plastic developed by Javier Fernandez and Donald Ingber called 'shrilk' which combines certain properties of both shrimp shell and spider silk to create a composite that is strong, durable and biodegradable.[97] An alternative option is that plastics are made from agricultural waste and then endlessly recycled. In the C2C model this would be an example of a material originating in the biological cycle and then being treated as part of the technical cycle. It is tempting to think that this could be another drawdown technology, but this aspiration needs to be tempered by the current reality that most crop production involves considerable quantities of oil-based fuels and agro-chemicals. Consequently, it would not make sense to grow plants specifically for the purposes of plastics production (it would be better to use oil to make plastics directly) but it would certainly be worth using agricultural waste. Another possibility, with huge drawdown potential, would be large-scale seaweed farming, which could produce both fertilisers and raw materials for bioplastics.

Adhesives

Nature has evolved intriguing solutions to adhesion, none of which involve toxins. Studies into the dry adhesion characteristics of geckos' feet and the way that mussels attach themselves to rocks have led to a glue called 'Geckel'. This innovative glue works on both wet and dry surfaces and is also reversible – handy when it comes to dismantling. Sandcastle worms (*Phragmatopoma californica*) have evolved a direct equivalent to two-part epoxy adhesive, which can set underwater in 30 seconds. The worms use it to build colonies of protective homes from fragments of shell and grains of sand, strong enough to withstand battering waves. Scientists at the University of California, Santa Barbara are working on an alternative to medical-grade cyanoacrylate (superglue) based on the sandcastle worm's adhesive.

The biodegradability of biological adhesives is hugely advantageous from a C2C perspective because it allows many small elements to be assembled into, for instance, large panels, while still ensuring that all the materials can remain within the biological cycle. It is conceivable that we could make whole buildings by gluing together elements with the same elegance as the sandcastle worm (though it may be a while before commercial housebuilders take up the idea!).

Integrated approaches

Some of the most thorough explorations into biomimetic architecture in recent years have been carried out at the Institute for Computational Design (ICD), in collaboration with the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart.[98] Much of this work has emerged from the realisation that almost all load-bearing structures in biology are fibrous composites and their performance is substantially determined by the way in which the fibres are aligned. Interesting examples are to be found in arthropods, such as crustaceans and insects, which have exoskeletons made up of layers of bundled fibres in an arrangement similar to plywood (fig. 89).

Menges' team built a lightweight Research Pavilion in 2013–14. They studied a wide range of different biological fibre-composite structures and settled on beetle wing covers (otherwise known as 'elytra' – the hardened forewings that protect the much more delicate flying wings) as offering the greatest combination of lightness and strength (fig. 90). The team's research included scanning electron microscopy in order to develop detailed three-dimensional models of the fibre structure and alignment inside the elytra, guiding the design.

Mimicking a complex biological arrangement of fibres required the kind of techniques that have only recently become possible with the benefits of computational design and fabrication. A system was developed using two robots that wound resin-coated glass fibres together to form large-scale double-layer components without the need for a mould. Comprehensive analysis of the global structure informed the precise fibre layout at the local level.

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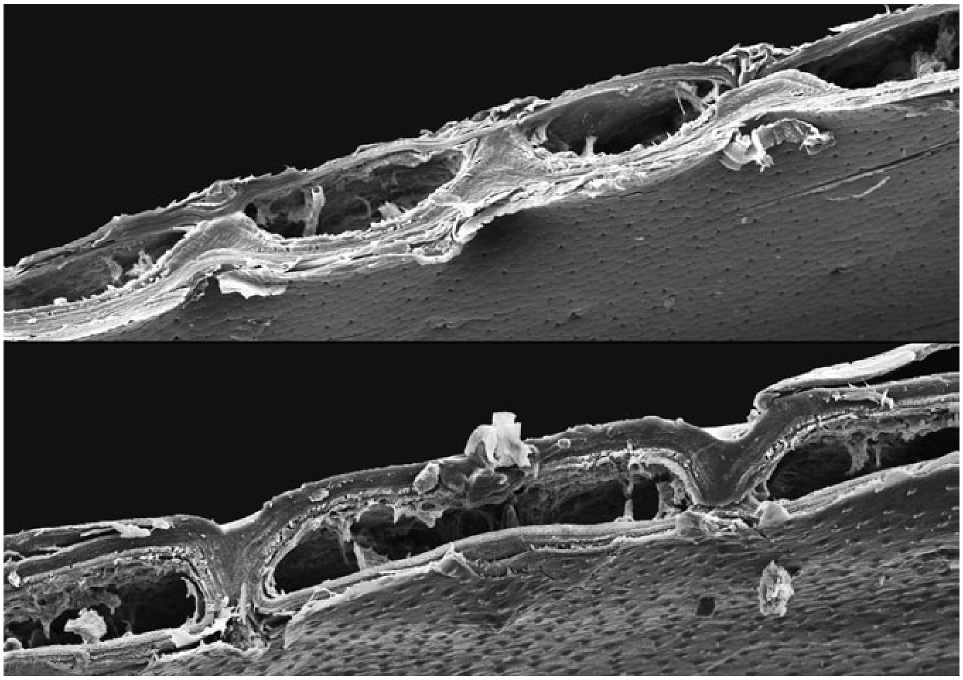
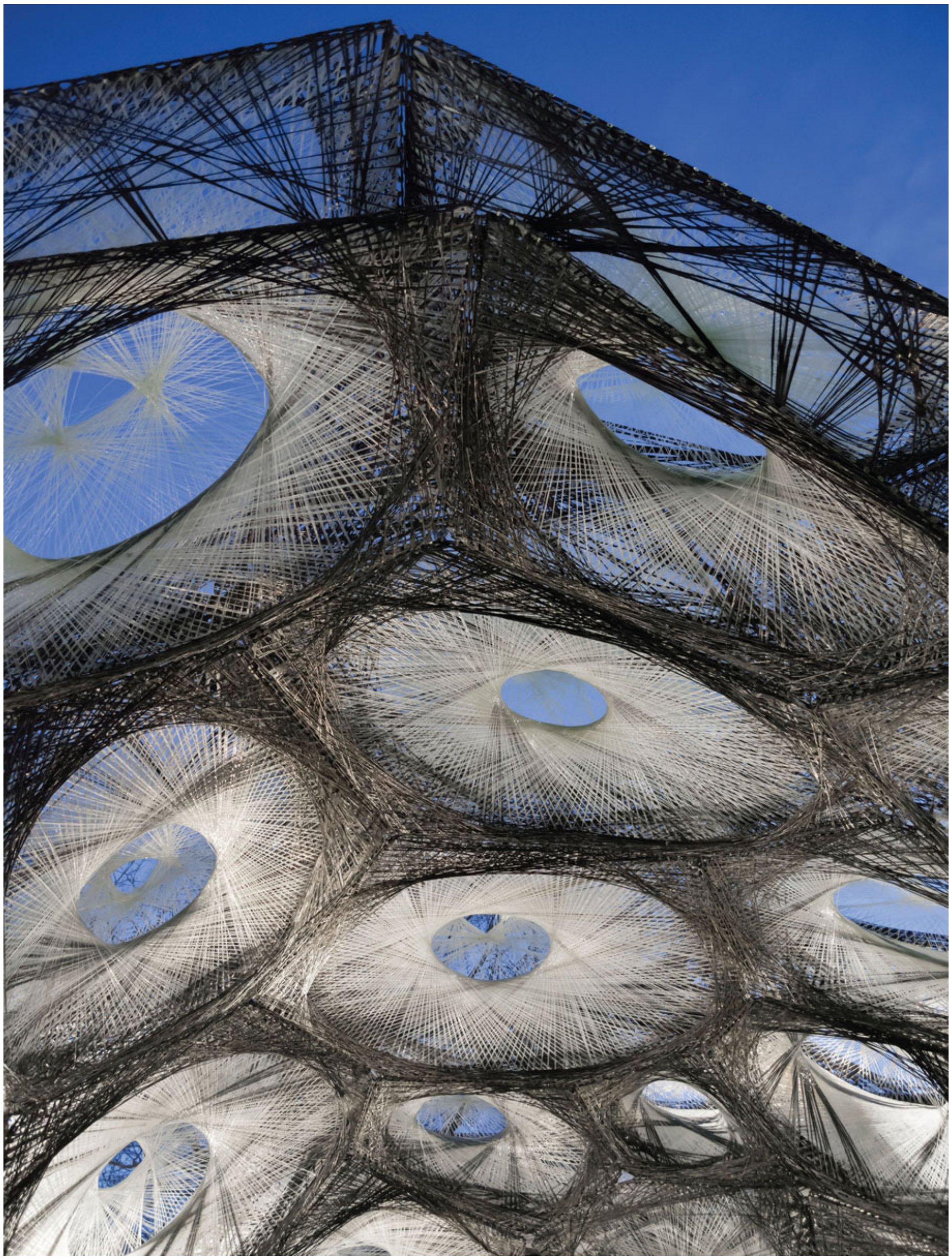


90. Beetle shells studied by Professor Achim Menges' team during the design of the ICD/ITKE Research Pavilion

91. The ICD/ITKE Research Pavilion at the University of Stuttgart, made from robotically woven fibres based on a detailed understanding of the morphology of beetle shells



92. The ICD/ITKE Research Pavilion at the University of Stuttgart, made from robotically woven fibres based on a detailed understanding of the morphology of beetle shells

The result is a spectacular pavilion that shows what can be achieved from a deep dive into biomimetics (figs 91 & 92). A detailed understanding of biological material morphology has resulted in a generative design approach, innovative construction methods and a highly distinctive work of architecture. The weight of the pavilion works out to be less than 6 kg/m^2 –

a comfortable factor-10 saving over more conventional approaches – which gives a further example of the resource efficiency that could be delivered in future applications of biomimicry. Clearly, the project would form an even more satisfying conclusion to this chapter if, instead of resin-coated fibreglass, it was made from biological fibres or materials that follow C2C principles – but that development will hopefully emerge from the Institute's ongoing work.

Conclusions

If we can steadily increase our use of biological raw materials and technical materials whose manufacturing absorbs rather than emits carbon dioxide, then, with these drawdown technologies, the construction industry can move into a new environmental paradigm that goes beyond mitigating negatives to deliver a positive and regenerative approach. While architecture faces the limits of what materials are available, science and bioengineering are pushing ahead with research and development: changes are under way. Computational design and fabrication are allowing us to edge steadily closer to the precisely structured materials found in biology. Applying the 'more design, less material' approach is becoming increasingly plausible.

It is readily conceivable that making construction elements using biological polymers in rapid manufacturing could achieve factor-100 savings in energy compared to conventional approaches.[99]

Providing a good quality of life for the likely future global population of nine billion will be far less challenging if such radical increases in resource efficiency can become commonplace.

It is promising that biomimicry doesn't always need to rely on high technology. As we saw with the 3D clay printer, biomimetic approaches can be low tech – giving people the tools and solutions to transform locally available materials with the resource of human ingenuity. Similarly, Guastavino vaulting can be developed with straightforward biomimetic approaches to span further using basic materials (and less of them).

Where biomimicry can be a particularly powerful design tool is in identifying ideals towards which we can strive. The goals of growth by adaptive accretion, self-assembly, non-toxicity, self-repair and the many other characteristics of biological materials may not all be achievable within our current constraints but they are worthy aims that will deliver multiple benefits.

A biomimetic approach to materials can facilitate the shift from a linear, wasteful and polluting way of using resources to a closed-loop model – one of the essential transformations necessary to arrive at truly sustainable architecture and a good quality of life for all the world's inhabitants.

Notions of closed-loop stewardship of resources and biomimetic manufacturing are inextricably linked, as Julian Vincent has neatly summarised:

> *Our materials are rendered biologically inert through the introduction of high energy bonds (necessarily using high temperatures). Biological materials have evolved to be recycled, and their molecules are stabilised by bonds that are only just strong enough for the expected conditions of temperature and mechanical function.* [100]

Considering how nature makes things leads us to consider systems, and how we can rethink human-made systems to mimic the remarkable efficiencies of ecosystems.

Chapter Three

How will we create zero-waste systems?

93. *Schizophyllum commune* fungi. The renowned mycologist Paul Stamets has described fungi as ‘the grand molecular disassemblers of nature’[101]

Biological systems have evolved to thrive in closed loops, in which the concept of waste does not exist: everything is nutrient. Ecosystems are regenerative, resilient and run entirely on solar energy. We could do the same with our buildings and cities. This chapter explores how natural systems operate, and what we can learn from them in order to rethink our own systems. This shift from a linear, polluting way of using resources to a closed-loop model is one of the most important transformations that we need to bring about.

The way nature integrates structure and materials inextricably, as explored in Chapters 1 and 2, opens up a vista in which the skin, structure and materials of a building can be seen as a cohesive system. But, at the edges of a building project, are bigger systems: ecosystems. In normal practice, interrogating the brief is standard operating procedure. Can system boundaries also be interrogated, to maximise the value of the project and minimise every kind of waste? Biomimicry offers defined strategies for taking opportunities to create a closed-loop system in the built environment. Ecosystems thinking can create regenerative contexts which maximise human value in the system, and the social and economic benefits of preventing the waste of human capability. The prospect exists to derive far more value from the same resources while moving towards zero-waste ways of operating.

Waste?

The whole subject of waste is characterised by contradictions. It is unglamorous, yet offers huge potential to achieve very desirable closed-loop systems. It is largely ignored by designers, yet projects that explore this area demonstrate wonderful ingenuity. It employs the word ‘waste’ that is, by one reading, dismissive (worthless material) and, by another interpretation, revealing of its possibility (a lost opportunity).

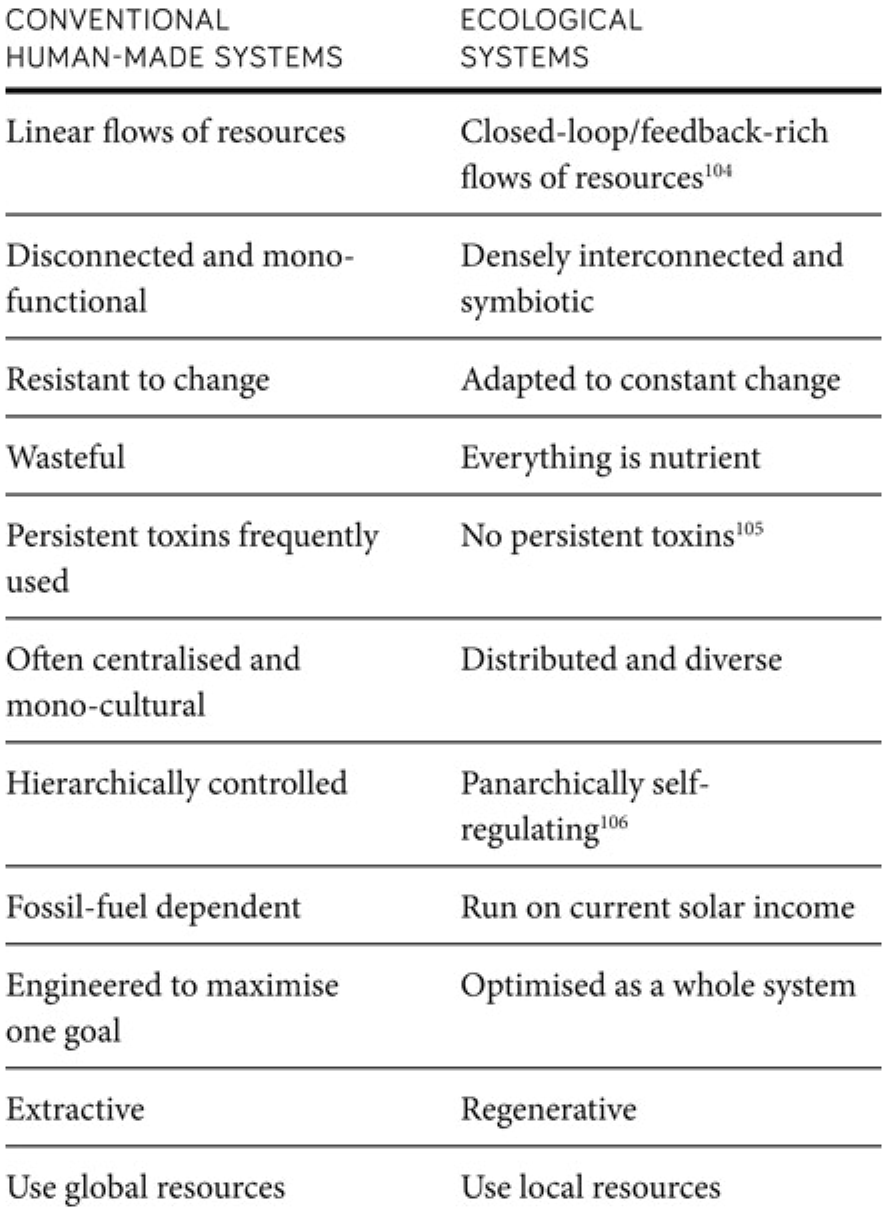
The history of sewage illuminates the key issues. The sewage disposal system devised by Joseph Bazalgette in 1859 was a huge breakthrough in public health and sanitation. But his contemporary, chemist Justus von Liebig, had studied the Roman sewers and their efficiency in transferring vast quantities of minerals from the soils, via the collective digestive system of the Roman Empire, out into the Mediterranean. Liebig urged the British Prime Minister to adopt a system that returned the nutrients to the fields of Britain, remarking that the equilibrium in the fertility of the soils is destroyed by this incessant removal of phosphates.[102] Despite this correct prediction that the system would precipitate the biggest loss of nutrients in the history of civilisation, the disposal model won the day. Two different views of the same thing – one in which sewage is future nutrient, and the other in which it is a public health hazard – have led to far-reaching consequences. Our consumption habits show the same magnitude of effect. Amory Lovins describes how, in the US, the quantity of materials per person mobilised into the economy every day is twenty times the average citizen's body weight and, of that, only 1 per cent is still in use six months later.[103]

From one perspective this appears ridiculous or even tragic, but from an ecosystems view it represents an enormous opportunity. Much more value can be made from the same resources, while moving towards zero waste. Biological systems teach us to see waste as an opportunity: a vital lesson. This applies equally to the resources that flow through our cities, as well as the materials from which they are made.

Ecosystems: basic biomimetic principles

What is an ecosystem in nature, and how can this be translated into the built environment? The underlying organisation of life is principally through cycles of carbon, nitrogen and water. Plants photosynthesise atmospheric carbon dioxide into sugars and, with the addition of other elements taken up through their roots, are able to grow and form the basis of most food webs. Nitrogen is fixed into the soils by particular plants that have evolved a symbiotic relationship with bacteria called *Rhizobium*. When plants die, drop leaves or are digested and excreted by animals and micro-organisms, the carbon, nitrogen and other elements are returned to the soil. Water, the universal solvent for nearly all biological reactions, is also cycled through these processes and ultimately evaporated into the air to be returned as rainfall. While this seems a complex description, a system is, at its simplest, **elements** and **interconnections**, harnessed to a **function** or **purpose**.

Mapping the key differences between conventional human-made systems and ecological systems can guide how to think in this way:



CONVENTIONAL HUMAN-MADE SYSTEMS	ECOLOGICAL SYSTEMS
Linear flows of resources	Closed-loop/feedback-rich flows of resources[104]
Disconnected and mono-functional	Densely interconnected and symbiotic
Resistant to change	Adapted to constant change
Wasteful	Everything is nutrient
Persistent toxins frequently used	No persistent toxins[105]
Often centralised and mono-cultural	Distributed and diverse
Hierarchically controlled	Panarchically self-regulating[106]
Fossil-fuel dependent	Run on current solar income
Engineered to maximise one goal	Optimised as a whole system
Extractive	Regenerative
Use global resources	Use local resources

All the principles of ecosystems can, and I argue should, be applied to architecture and cities.

How are ecosystems thinking and architecture connected?

When using biomimicry, in a given situation some biological models are more appropriate than others for the function or system that you intend to re-imagine. Recent use of the term ‘urban metabolism’ exemplifies the problems of adopting the wrong scale or system: Marc Weissburg, Professor of Environmental Science and Technology at Georgia Institute of Technology suggests that this is not the right model because describing a city in terms of a single organism implies a very high degree of centralised control, which is not the case.[107] Ecosystem principles can be applied at various scales, as we will now explore.

Cities

Applying ecosystem models to cities, or parts of cities, is a much more appropriate starting point than the metabolism of a single organism because the source is one that comprises a wide variety of different actors with a high degree of interdependence and operates in a state of dynamic equilibrium. Ecosystems have the further advantage that they have evolved to minimise the amount of energy and resources they have to draw from elsewhere and to minimise the amount that are lost. Clearly, there are exceptions to the characteristics described in the human systems versus biological systems comparison, but the general characteristics hold true in many cases and often the distinctions become more marked as human-made systems mature. In biological systems, there are millions of contributors to the system, no unemployment and numerous opportunities for nature’s equivalent of entrepreneurship – species that evolve to fill a wide variety of ecological niches. In human-made systems, large multinationals often dominate, power resides with a few individuals, a degree of unemployment is deemed necessary and creative entrepreneurship is limited.

Cities involve vast resource flows and in a linear system these become waste or they build up as stocks which, in the absence of good design, will ultimately become waste as well. Ecosystems point to a different paradigm, in which all flows are nutrients that can be endlessly cycled within the city or between the city and its hinterland. Ecosystem models also deliver strong resilience benefits, which are discussed further below.

Perhaps one of the most important contrasts between human-made systems and ecosystems is that ours are generally extractive whereas ecosystems are regenerative. Janine Benyus summarises this neatly: ‘life creates conditions conducive to life’[108] – the more ecosystems mature, the more they enhance their environment and allow for greater diversity. We should also remain mindful of the limits of biomimetic models. Cities are, of course, far more than networks of actors and resource flows; they have profound social and cultural dimensions. The challenge is how to address these areas simultaneously – an approach that Susannah Hagan describes as ‘ecological urbanism’. She observes that:

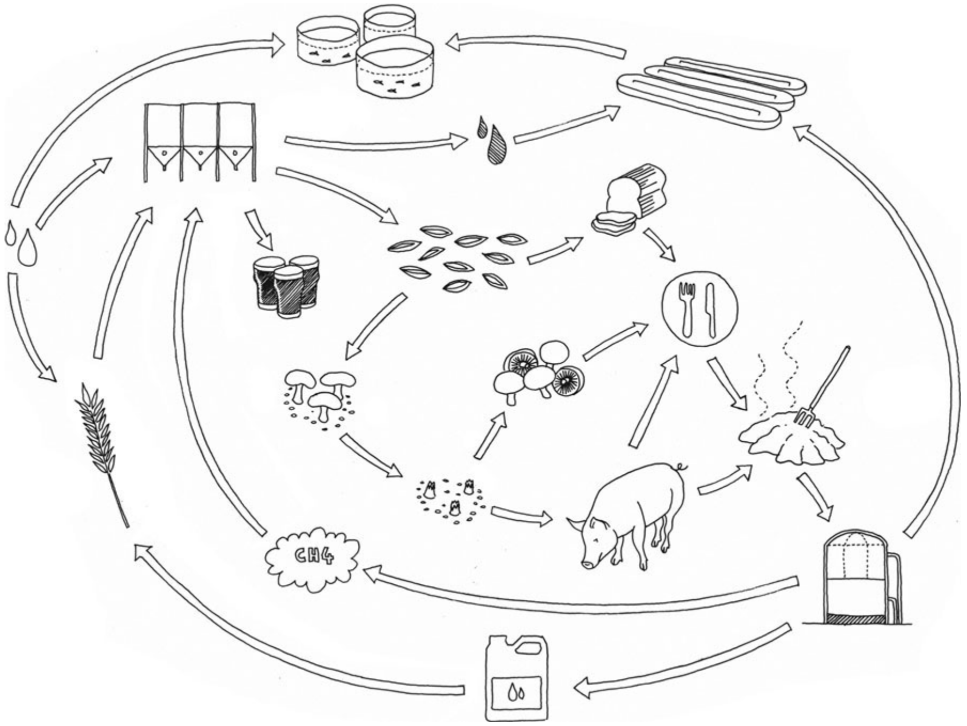
> *In one way, Ecological Urbanism is simply a late entry into a line of ecological subfields that engage literally or figuratively with the built environment. In another way, it has the potential to be a new bridgehead between urbanism and ecology, one that projects and defends design as a vital element in the necessary transformations of our cities.* [109]

We will return to the subject of biomimicry applied to cities in Chapter 8.

Infrastructure and industry

To make real progress with the big transformations identified at the beginning of this book, we need buildings and industries to be integrated into a wider system of biomimetic infrastructure. An essential part of this will be the widespread adoption of ecosystem models – sometimes referred to as ‘industrial ecology’ or, in terms of its manifestations, as ‘eco-industrial parks’ (EIPs). EIPs are networks of industrial processes that function like ecosystems in the way that they share resources and, by doing so, radically increase the amount of useful outputs from the same inputs. An early example of this is Kalundborg Eco-Industrial Park, an industrial complex in Denmark, which is estimated to have saved 240,000 tonnes of carbon dioxide emissions and 264 million gallons of water each year, amongst other resource savings. While Kalundborg involved the co-location of a power plant, chemical works and other processes, there have since been a number of schemes in which all the core elements are compatible with natural systems.

Two realised projects encapsulate the power and promise of ecosystems thinking at the scale of individual projects and businesses. Civil engineer George Chan pioneered an ecosystem approach in the development of a sorghum brewery in Tsumeb, Namibia (fig. 94). He promised 'Good beer, no pollution, more sales, and more jobs'.[110] Breweries conventionally use large quantities of water and grains, of which only a fraction remains in the finished product. Often, the alkaline waste water, which contains low levels of biological contamination, undergoes expensive chemical treatment before disposal and the spent grains are given away as cattle feed. The grains are too fibrous to be effective cattle feed and this results in the cattle producing more methane (one of the most potent greenhouse gases). Chan approached both of these problems as opportunities to add elements to the system that create more value from exactly the same inputs.

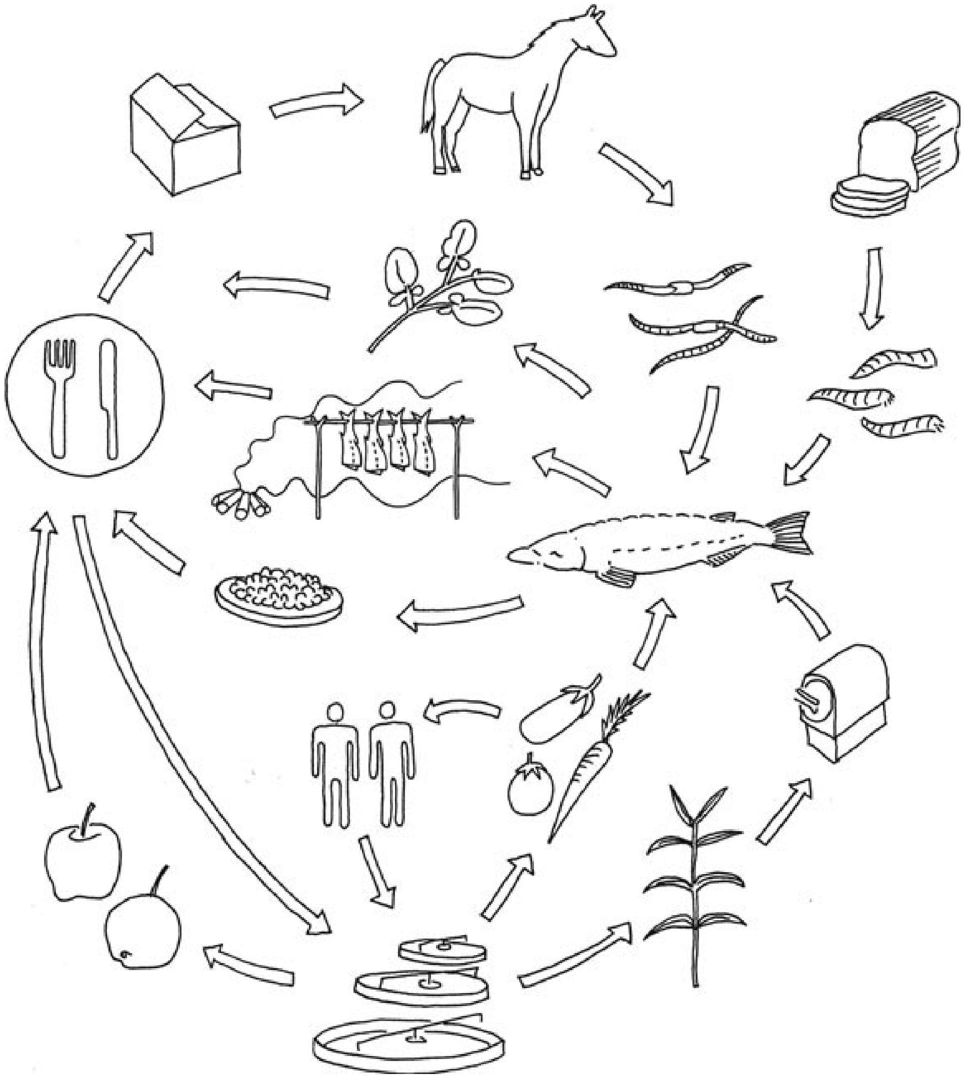


94. Tunweni Brewery, showing how industrial systems can be conceived in ecosystem terms and represented as food webs, in which the output from one part of the system becomes the input for something else

The waste water was used for cultivating *Spirulina* algae, rich in protein and micronutrients and therefore effective at combating malnutrition. The water was then used for fish-farming to produce further sources of protein. The large water bodies with a diversity of aquatic life ensured that the water cycle was closed and secondary benefits of recharging groundwater were achieved. The spent grains were an ideal substrate for growing mushrooms, as up to one tonne of fungi can be produced from four tonnes of grain. After mushroom cultivation, the substrate was then more suitable as animal feed or for earthworm composting. The earthworms were used to feed chickens and the manure went to an anaerobic digester, which produced gas for the brewery.

The end result was a system that produced 12 products instead of just one, seven times as much food, fuel and fertiliser, four times as many jobs as a conventional approach and a fraction of the waste.

The Cardboard to Caviar Project (also known as the ‘ABLE Project’) is an inspired example of how linear, wasteful systems can be transformed into closed-loop systems that produce no waste and yield much greater productivity (fig. 95). Conceived by Graham Wiles of the Green Business Network (GBN) in Kirklees and Calderdale, northern England, the scheme started as a way of involving people with disabilities in a recycling initiative. Waste cardboard was collected from shops and restaurants and was shredded for sale to equestrian centres as horse bedding. The second stage was to compost the used bedding through vermiculture. Initially, the idea was to sell the surplus worms to a fishing-bait supplier. At the eleventh hour the supplier backed out, so Graham Wiles, not being one to give up easily, decided to cut out the middle man and set up his own fish farm.



95. Food web diagram for the Cardboard to Caviar Project, which evolved over time to follow nearly all the key principles of ecosystems thinking

Working now with recovering heroin addicts, Wiles established a fish farm to raise Siberian sturgeon. He noticed that many of the youngsters were coming to the site each day with junk food, so he decided to involve them in growing vegetables and learning about healthier eating. Allotments were created nearby and vegetable waste was used to supplement the worms' food and reduce dependence on commercial fish food. It became clear that the rate of fish growth slowed during winter because the water was too cold. Yorkshire Water, who ran the adjacent sewage works, agreed to give a further 10 hectares of former industrial land to the project, as well as treated sewage pellet fertiliser. The team set about planting short-rotation willow to feed a biomass boiler.

One of the supervisors on the project had experience of fish farming in developing countries and redesigned the proprietary filtration system using reclaimed water storage tanks. Excess nitrates and phosphates were removed by passing the filtered water through tanks planted with watercress, creating another food product, as well as clean water, for the fish tanks. The sludge from the new system was fed into worm-composting beds and some was put into buckets of water to attract mosquitoes in order to create a regular supply of larvae for the fish hatchlings.

Food production was extended by planting more of the available land with fruit trees. Clover provided ground cover, nitrogen fixation for the soil and pollen for a thriving colony of bees. The site was transformed from a degraded industrial site into a haven for biodiversity. The production of caviar from the sturgeon demonstrated the potential to turn a waste material into a high-value product while yielding social, economic and environmental benefits. The caviar could be sold back to the restaurants that supplied the cardboard to close a particularly satisfying and alchemical loop.

The project continued to evolve. New types of fish, tilapia and carp, were raised to supply anticipated demand from local south-east Asian and Polish communities. A maggot farm, using another waste stream, mouldy bread (which produces none of the smells of meat-based production), was set up to enrich the fishes' diet and eliminate the need for any supplementary fish food. A fish smoker was then built to create higher-value products, and this time Wiles worked with ex-service personnel. Soldiers often return from conflict zones with severe disabilities and post-traumatic stress disorder and find it very difficult to fit into civilian life, which frequently leads to homelessness and crime.

If we refer to the list above that compared human-made systems with biological systems, we can see that the Cardboard to Caviar Project fits very clearly into the right-hand column. It has developed into a complex system of interdependent activities and there is a sense in which, just as with ecological succession, the more the project grows, the more the possibilities expand. It transformed a number of waste streams into valuable products and re-engaged what is arguably the most deplorable form of waste – under-utilised human resources with great skills to offer and a desire to be involved.[111]

96. The Mobius Project – a scheme that brings together cycles of food, energy, water and waste in synergistic ways (CGI by Filippo Privitali)

Buildings

The Mobius Project by Exploration co-locates and integrates food, energy, water and waste in synergistic cycles[112] (fig. 96). Partly inspired by the Tunweni Brewery and the Cardboard to Caviar Project, the scheme incorporates a restaurant, food production (fish, vegetables and mushrooms), waste handling (anaerobic digestion), water treatment and energy production. By bringing these cycles together, it is possible for the output of one part of the system to become an input to another. The building can handle much of the biodegradable waste from a local urban area using anaerobic digestion and the methane derived can be used to generate electricity and heat for the greenhouse. The restaurant, apart from being supplied with fruit, vegetables and fish from the greenhouse, which cuts down on food miles, can operate at close to zero waste, as food waste can be fed to fish or composted. Fertiliser from the various forms of waste handling can be used in the greenhouse and the significant surplus can help to remediate brownfield land on the outskirts of the city. Just as Graham Wiles steadily improved the Cardboard to Caviar Project by transforming weak links, under-utilised resources or system leaks (such as money used to buy what was missing from the system), the Mobius Project could benefit from the same refinement. For instance, flue gases from the methane combustion can be captured through accelerated carbonation and turned into building materials.

The Mobius Project could play an important role in generating a sense of community and reconnecting people with food, while addressing many of the infrastructural requirements of sustainable living in urban areas. Delivering these benefits realistically relies on scaling the individual elements, in terms of both economic viability and functional constraints.[113] But this can be done most effectively by making explicit measurable aspects, which are normally excluded from economic calculations as ‘externalities’, including pollution, nutrient loss and urban deprivation, and forming new indicators by which to judge projects and their success. The potential exists, with schemes like the Mobius Project, to reverse this flawed paradigm – to convert our problematic, linear systems into closed-loop solutions while addressing the food, energy, water and waste challenges of sustainable urbanism.

Systems that value human resources and social capital

The possibilities that these projects offer, to become virtuous circles, promise to address two massive concerns: human and social value. What do we mean by these terms? How can they be characterised sufficiently to use them as workable biomimetic principles? Human values are considered at an individual level (equity, skills, knowledge, ability to travel, safety, health, happiness) and social values are collective concerns (participation, cohesion, regulation, development, cultural heritage, crime). Different aspects of human and social value will be appropriate to different contexts, but thinking of them in a defined way makes them easier to consider as components of an ecosystem.

The Cardboard to Caviar Project was extremely successful in getting addicts off drugs and into more constructive pursuits. Whereas the local authority rehabilitation programmes were often costing £100,000 per addict per year (not counting other costs, such as crime and policing) and experiencing a 95 per cent failure rate, the Cardboard to Caviar Project had an 80 per cent success rate. The scheme also reintegrated two other, often marginalised, groups: people with disabilities and ex-service personnel.

An inspired example of mobilising underutilised human skills while transforming physical waste and delivering social value can be found in the work of Rural Studio in Hale County, Alabama. The architects and students there have created some exceptional buildings and worked with the local population, whose resources often militate against them building homes, thereby diminishing their equity. They use waste resources with great ingenuity – carpet tiles, vehicle licence plates, truck windscreens (fig. 97) and a whole range of other locally available resources have been transformed into architecture. Their methods involve the active involvement of poor communities in Alabama, delivering dignity through the process and all the social cohesion benefits of participatory involvement.

97. The architects at Rural Studio have demonstrated great ingenuity in transforming waste into value – sometimes using vehicle windshields as glazing, stacked carpet tiles as walls or licence plates as shingles

As an urbanised society, we have become increasingly disconnected from food. Carolyn Steele articulates clearly in *Hungry City* the way that food used to be something that richly animated public spaces in towns and cities.[114] Food had social value. Creating interconnected systems of growing food, producing building materials and dealing creatively with waste would re-establish a connection with food while creating resilient and vibrant places to live.

Designing a sustainable built environment is not only about the design or economics of single buildings. It is also about strategic planning and infrastructure that embraces food, transport and energy as well as health and well-being. Pooran Desai of Bioregional champions the point in *One Planet Communities* that ecosystems thinking can help to make the shift from an economic model in which 'resources, energy and capital investments flow through the economy, becoming waste, to closed-loop processes where wastes become inputs for new processes'.[115] Economists such as E. F. Schumacher and Richard Douthwaite have argued convincingly for the benefits of local economic development and the 'multiplier effect' of money being spent numerous times before it leaves the local economy. The UK Sustainable Development Commission estimates that for each £10 spent on local organic food, £25 of value is created in the local economy, whereas the same £10 spent in a supermarket generates only £14 of value.[116]

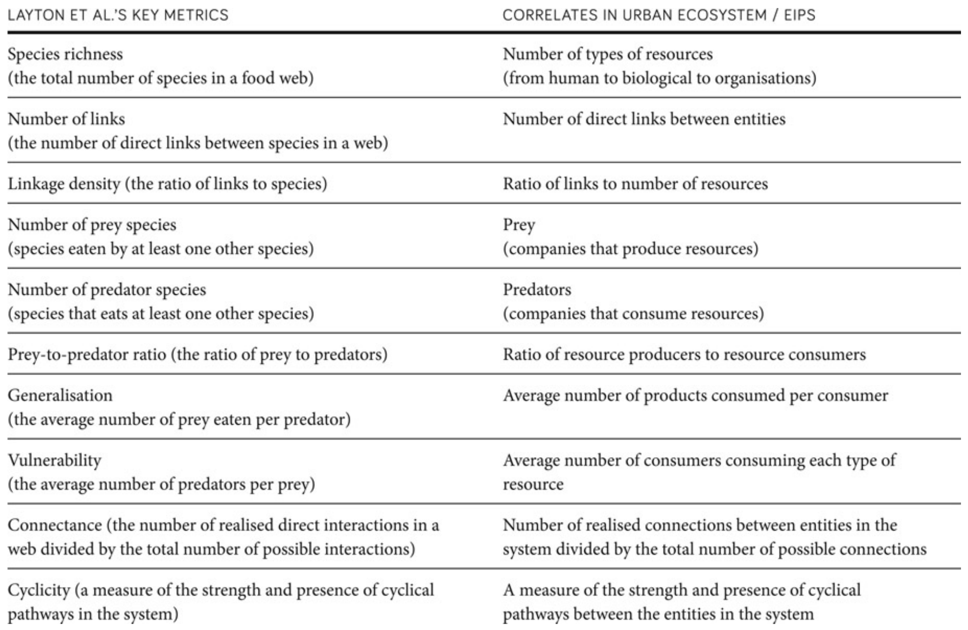
Resilience

Food webs often have four different species that are able to perform the same function – a characteristic referred to as 'redundancy'. Donella Meadows observed that 'A diverse system with multiple pathways and redundancies is more stable and less vulnerable to external shock than a uniform system with little diversity'.[117]

This touches on the whole subject of resilience, which has attracted a lot of interest in recent years – in no small part due to the work of the Rockefeller Foundation and their '100 Resilient Cities' initiative. Judith Rodin defines resilience as 'the capacity of any entity – an individual, a community, an organization, or a natural system – to prepare for disruptions, to recover from shocks and stresses, and to adapt and grow from a disruptive experience'.[118] Rodin goes on to define five characteristics of resilient systems as being 'aware, diverse, integrated, self-regulating and adaptive'.[119] We can see all of these at play in biological systems. Complex and densely interconnected systems are generally more resilient than simple disconnected ones because, in the former, there is a multiplicity (and therefore a healthy degree of redundancy) of entities and flows that can continue to operate and take up the slack if one part of the system is interrupted. Similarly, self-regulating systems are more resilient than hierarchical ones and the adaptability of ecosystems means that they are much better able to respond to change than less flexible systems. Others have included within the definition of resilience the capacity of systems to take advantage of opportunities that arise from disturbance. A city modelled on ecosystems with a wide variety of different entities would be able to achieve the equivalent.

Extending biomimetic principles

The examples discussed above use ecosystems as high-level models to deliver substantial resource savings and regenerative benefits to the people involved and their physical environment. Now there is an opportunity to extend this model by applying deeper principles of ecosystems to analyse and identify improvements to EIPs and even cities. Ecological Network Analysis (ENA) is a method usually applied to food webs which has been adapted by Layton *et al.* to apply to industrial ecology.[120] Food webs – similar to the diagram for the Tunweni Brewery above – can be used to describe EIPs. Each industrial element is analogous to a species, and the exchange of resources between them is equivalent to predator/prey relationships. The following list describes the key metrics used by Layton *et al.* to analyse food webs and EIPs.



LAYTON ET AL.'S KEY METRICS	CORRELATES IN URBAN ECOSYSTEM / EIPS
Species richness (the total number of species in a food web)	Number of types of resources (from human to biological to organisations)
Number of links (the number of direct links between species in a web)	Number of direct links between entities
Linkage density (the ratio of links to species)	Ratio of links to number of resources
Number of prey species (species eaten by at least one other species)	Prey (companies that produce resources)
Number of predator species (species that eats at least one other species)	Predators (companies that consume resources)
Prey-to-predator ratio (the ratio of prey to predators)	Ratio of resource producers to resource consumers
Generalisation (the average number of prey eaten per predator)	Average number of products consumed per consumer
Vulnerability (the average number of predators per prey)	Average number of consumers consuming each type of resource
Connectance (the number of realised direct interactions in a web divided by the total number of possible interactions)	Number of realised connections between entities in the system divided by the total number of possible connections
Cyclicity (a measure of the strength and presence of cyclical pathways in the system)	A measure of the strength and presence of cyclical pathways between the entities in the system

While they discovered, unsurprisingly, that EIPs are far less complex than biological food webs, it is worth understanding where differences lie. EIPs are smaller networks, there is a lower degree of cyclicity, each predator exploits less prey and prey are consumed by fewer predators. Generally, in EIPs there are more companies that use resources (predators) than there are companies that provide resources (prey). An important area to exploit from both a biomimetic and a business perspective is the lack of 'detritivores' in EIPs, compared to their biological counterparts. Detritivores are organisms, such as earthworms, fungi and bacteria, that feed on dead organic matter, but they are also, as a group, 'fundamentally different from any other functional group present – they allow energy to flow unrestricted to any location in the system and process a large percentage of the total energy'.[121] This is an obvious underdeveloped potential, and the equivalent in an EIP would be waste treatment, agriculture and forms of recovery or recycling. The metrics referred to above tell us a lot about how effectively resources can be moved around within the system.

It was clear from the Cardboard to Caviar Project that the scheme had huge potential for growth (through expanding the number of 'species' as well as the scale of each operation) and it is tempting to think that the more an EIP grows, the better it will be in terms of performance, but the study referred to above suggests that we need to be a little more circumspect than that. If biology is the model to be mimicked, then we need to ensure that there are numerous forms of detritivore, that there is a high degree of cyclicity (so, not just connections but as many loops as possible) and that there is the right balance between predators and prey. Much can be gained by achieving 'starter' levels of connectance and cyclicity and, as knowledge and capabilities grow, we will produce densely woven, resilient projects and urban ecosystems.

The final piece of the puzzle is information flows. Predator/prey relationships are self-regulating in ecosystems, essentially because of feedback, and the potential exists for EIPs to do the same – each linkage is not just a resource flow but also an information flow (communicating levels of supply and demand between entities). It is in this way that schemes modelled on ecosystems become increasingly self-regulating (panarchic as opposed to top-down, hierarchically controlled). These principles can inform a new way to design. In biological systems, the death of an organism is a transition point rather than an end point, for the materials. The equivalent can be achieved for buildings if information flows are managed properly. This is a crucial aim if we are to create architecture whose physical expression is fully biomimetic, allowing buildings to be completely integrated into a circular economy. From a materials perspective, waste is simply material without an information strategy.[122] Turntoo's Liander building in the Netherlands is a large-scale built project aiming to enact a circular economy principle. The architects implemented a thorough information strategy for materials. They started by first reusing 80 per cent of on-site materials, and created a finished building in which 80 per cent of the materials could be used again. Full documentation of the 'depot of materials' in the new Liander head offices has been created, which should enable more effective maintenance, redevelopment and value maximisation in the future.

Integrated approaches

We have seen that there is a clear connection between the previous chapter and this one: we need to rethink the way we make things if we are to create comprehensive, zero-waste systems for cities. The ideal scenario would combine a circular model for materials (as pioneered by McDonough and Braungart and developed further by the Ellen MacArthur Foundation) with the food web-type network of EIPs. One scheme that has come close to realising this is the Park 20/20 project by developer Delta Development Group and architects William McDonough + Partners (fig. 98).

98. Park 20/20 by Delta Development Group and William McDonough + Partners. The buildings have been re-imagined as 'materials banks' for long-term material cyclicity, which requires new design approaches and new business models

Situated near Schiphol Airport in Amsterdam, the development comprises 92,000 m^2 of office space and demonstrates a radical departure from conventional development, in which capital cost is the primary driver and little attention is paid to materials at the end of the building's life. At Park 20/20 all the buildings have been designed for disassembly so that, as far as possible, components can be re-used in their existing state rather than recycling (with all the related energy and other impacts involved). Instead of conventional finished products, the buildings have been re-imagined as 'materials banks' in which resources are 'stored' and their value is retained. This represents a significantly longer-term perspective on value than is conventional, so the relationship between Delta and their investors is critical. It is testament to the persuasiveness of the model and the team's leadership that they have been so successful at innovating in a conservative industry. Contracts with product suppliers include reverse logistic agreements. This incentivises the suppliers to make their products in a Cradle to Cradle way and ensures that material recovery will occur at the end of the product's life. Some of the elements, such as the lighting, are incorporated on a leasing basis, which provides similar incentives for effective resource stewardship, as well as the potential for regular upgrades as product technology improves. The system of feedback-rich flows of information initially establishes detailed information about materials, and then allows them to be tracked over time.[123] In addition to extending the C2C model to a building scale, the project incorporates many other elements that contribute to system cyclicity and human well-being. All the buildings are connected to a site-wide water strategy involving rainwater harvesting (to provide for WCs and irrigation), storm-water management (managing all predicted flows within the boundaries of the site) and water features that benefit biodiversity as well as being attractive amenities. Adjacent to the water feature is the Biological Nutrient Pavilion (fig. 99), containing a restaurant supplied with food partly grown on site.

Currently, the development is predominantly office buildings (due to tight zoning regulations in the Netherlands) but the next phase will include a greater diversity of building types. This equivalent to greater 'species richness' offers the potential for enhanced cyclicity of resource flows and associated resource efficiencies.

Conclusions

Conventionally built structures have tended to draw down on natural capital and degrade their context, whereas ecosystems thinking provides an opportunity to do the opposite. Many of the best examples of mimicking ecosystems are indeed based on food production, rather than processing building materials, but this boundary exists mainly because of the manufacturing situation explored in Chapter 2. Generally, we manufacture materials with high-energy bonds, which makes them difficult to integrate into systems modelled on biology. If buildings, cities and products were made from stuff like natural polymers, with low-energy bonds, then there could be a perfect fit and we would see more building materials featured in these cycles. This shift in materials is already under way, so the wider system context becomes not only possible but essential to address.

99. The Biological Nutrient Pavilion at Park 20/20, providing fresh food (partly grown on site) as part of the biological cycle for the site, as well as benefitting from the visual amenity of a creatively designed water cycle

An interesting question concerning the models, such as the Cardboard to Caviar Project, we have discussed in this chapter is: are they biomimicry or bio-utilisation? The answer is both. Many of the individual elements in these systems would best be described by the latter term, in that they directly implement a biological process for human benefit. However, the way that these are deliberately brought together in synergistic systems is very definitely biomimetic. This synergy is a critical part of a regenerative approach.

Models based on ecosystems involve complex interactions between different processes that require design input if they are to be optimised. Architects can meet this need for a new type of building and a new type of urbanism. New building types will emerge from the transition to a zero-waste society: the potential exists to celebrate these as great works of architecture.

> *What kind of practice – and discourse – might result if urban design became environmentally literate and environmental engineering became culturally literate remains to be seen, but the time has come when the two have to be suspended in the same solution.*
> SUSANNAH HAGAN [124]

If waste is seen as future nutrients or as an underutilised resource, then a new economic paradigm emerges and wealth can be created while consuming *less*; in stark contrast with the current assumption based on creating wealth by consuming *more*. What is clear from even a cursory look at our conventional industrial, agricultural and urban systems is that the way in which resources flow through our economies represents a huge opportunity. If we contemplate the fact that, in many cases, the unused portion of those resources will have caused expensive disposal problems, which are likely to become even more costly in the future, then the potential offered by ecosystems thinking becomes even more pronounced.

Underutilised resources often include people – as brilliantly demonstrated by the Cardboard to Caviar Project – and can also include spare capacity in existing systems or infrastructure.[125] While the evolution of ecosystems has rewarded nature's equivalent of entrepreneurs (the organisms that have evolved to fill new ecological niches), the same opportunities exist in human-made versions of ecosystems: rewarding those who can turn waste into value and jobs. The significance of these pioneering projects should not be underestimated. Traditional economics are based on liquidating natural capital into financial and physical capital, often at the expense of social capital. The importance of natural capital is increasingly apparent, as is the need to provide livelihoods for a growing number of people. Many of the examples based on ecosystems thinking reflect exactly those values, being restorative to the immediate environment and helping to build local resilience through re-engaging marginalised groups of people.

There will be an urgent need in future for designers to work more closely with industrialists and biologists to create forms of industrial symbiosis that are integrated into mixed-use communities with the benefits that arise from combining residential and employment areas. Instead of the inherent risk involved in basing communities around mono-functional industries, models based on ecosystems thinking would involve a diversity of functions.

Working with ecosystem models does not require high technology or large budgets – it can even be easier with low technology. If you are working in a context that already has a lot of built elements, then there is much that can be achieved by simply connecting compatible inputs and outputs. If you do have a substantially blank sheet of paper, as is the case in new cities in developing countries, then there is a great opportunity to co-locate activities with strong synergies and, ideally, do it in a way that connects at a cultural level as well. Development anthropologists can offer crucial insights into these contexts, finding synergies that are fitted to the social, spatial and cultural context of projects in other geographies, ensuring the persistence of new projects by valuing the human differences between cultural settings. The ecosystem view opens out both the challenges and the possibilities of biomimetic architecture.

Chapter Four

How will we manage water?

100. The skin of the thorny devil has a network of capillary grooves that transfer water to the lizard’s mouth from damp ground or from droplets of water that condense onto spines

Water is becoming an increasingly contentious topic, both environmentally and politically, as climate change has become indisputable. Until now, we have managed to feed the world’s growing population, in large part due to the achievements of the ‘green revolution’ in high-yielding seed varieties, pioneered by the agronomist Norman Borlaug. The increases in crop yields achieved from these technological advances were impressive, but they are looking increasingly fragile because they are dependent on large quantities of irrigation and synthetic fertiliser. Recent history has shown that there is a very direct link between water shortages and armed conflict. Even a ten-year extrapolation of existing trends in climate change, water supplies and population growth raises some alarming possibilities.

The consensus amongst climate scientists predicts that much of the developing world in tropical latitudes will experience a substantial loss of agricultural productivity due to temperature increases and a reduction in rainfall. Other parts of the world, generally temperate regions, are likely to experience increased precipitation, both in terms of quantity and intensity, which, unless managed, will increase the risk of flooding. Agriculture will change under these pressures. Rethinking our waste-water treatment methods could help to restore the fertility of our soils and re-plumbing buildings and cities with energy-optimised systems could deliver further increases in resource efficiency.

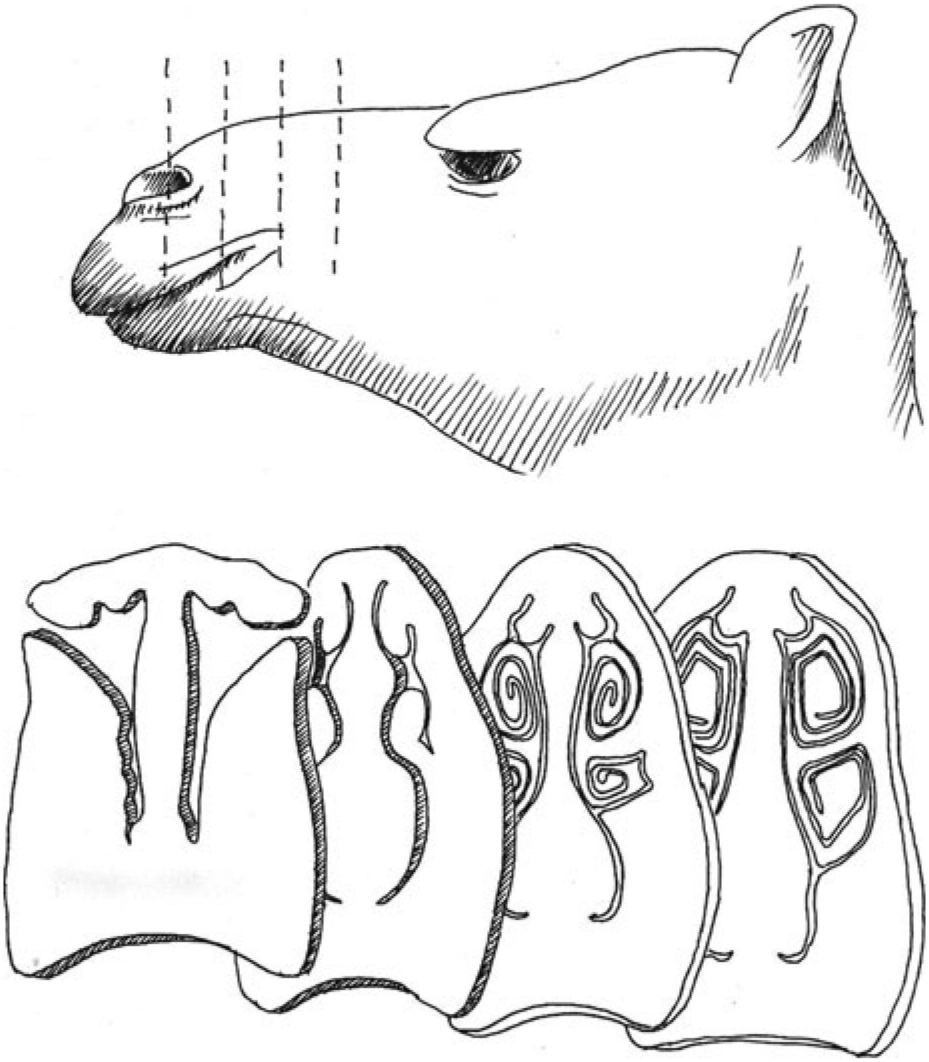
This new context should be viewed as a challenge to design: we can ameliorate both lack of water and its excess using biomimetic design. The good news is that many comparable problems have already been solved by organisms that have had to adapt to environments in which water is scarce, intermittent or excessive. Some species have evolved ways to harvest water from the air in deserts, store water for periods of scarcity or thrive in locations with as much as 11 m of rainfall per annum. These examples show how biomimicry can deliver radical increases in water efficiency.

Minimising water loss

All creatures adapted to living in arid conditions have some means of reducing water loss. This often involves using non-living matter to create shade, trapping a layer of air next to the organism's surface to reduce the evaporative gradient, or a combination of the two. Some birds that live in deserts have black plumage, which might seem like a bizarre strategy but the feathers are protein structures (made from non-living keratin and containing UV-absorbing melanin) that, through their opacity, prevent most of the sun's heat reaching the birds' skin and consequently reduce water loss. Numerous species of cacti are covered in fine white filaments, which not only reflect the sun but also help to trap humid air next to the living tissue so that the exchange of gases necessary for photosynthesis can continue while water loss is minimised. The umbrella thorn tree (*Vachellia tortilis*) retains large amounts of dead branches, which appear to serve no function other than to provide shade for the living tissue and for the soil beneath so that the need for evaporative cooling is reduced.

Similar strategies could be used more extensively for buildings in hot climates: opaque or reflective structures that provide shade and could, as we will see below, double as water collectors. Increasing shade around such schemes could also help to hold a layer of cooler air at ground level and provide comfortable conditions for people while reducing evaporation from the soil.

Camels have highly intricate nasal structures, known as turbinates, which are made from spongy bone covered with richly vascular tissue. As the camel breathes in, the tissue is cooled by the evaporation of water into the dry air. During exhalation, the humid air from the lungs passes this large area of cool surface and much of the humidity condenses to allow reabsorption (fig. 101). The intricacy of the turbinates results in very small distances between the surfaces and the centre of the air stream, which increases the potential for heat and moisture transfer. Inevitably, during the heat of the day, a certain amount of water is lost and the cooling created by this process is transferred by blood capillaries to the brain – in extreme conditions keeping this vital organ 6 °C cooler than the rest of the camel's body.[126] Turbinates in camels and other mammals could inspire the design of better water-recovery heat exchangers.



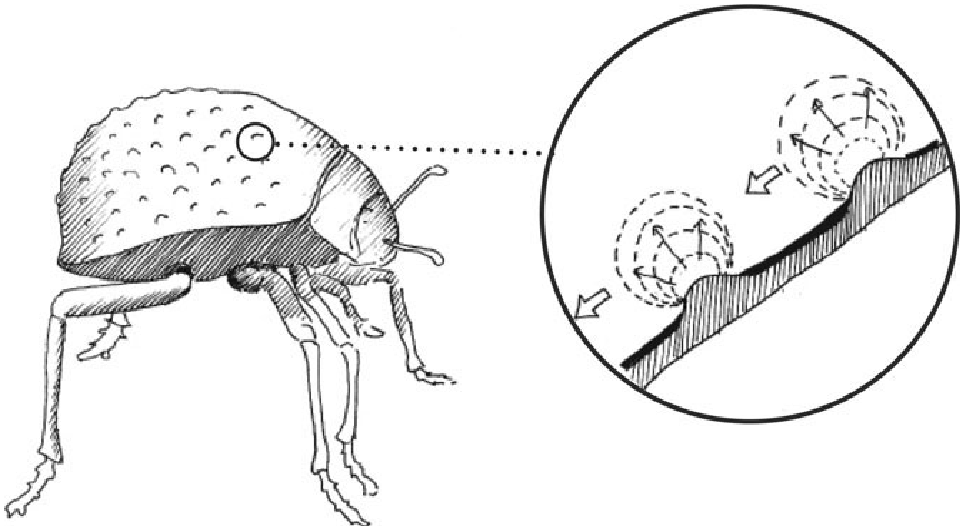
101. Camels have been maligned as 'a horse designed by committee' but actually they are phenomenally well adapted. Their nostrils are miracles of water recovery and evaporative cooling

Water storage

Some habitats are characterised by intermittent rainfall with, in extreme cases, the whole year's meagre precipitation falling in a few hours. The cacti's ribbed stems, which resemble concertinas, respond to this situation. These structures can absorb large quantities of water very quickly without any significant new growth – simply by expansion.

Other plants have adapted by storing their water below ground in large, swollen roots. An extreme example of this is the elephant foot – a species of yam that can grow tubers that weigh as much as 300 kg. What does this suggest for architecture? Water storage in buildings is, almost without exception, in the form of rigid tanks, often built underground, with considerable cost and embodied carbon. There could be potential for expandable storage vessels made from lightweight membranes to be incorporated into walls or landscape features. This would allow buildings to harvest a far larger proportion of the rain that falls during the infrequent rainstorms that characterise some arid climates. Such a strategy could make sense for remote sites that would otherwise require expensive infrastructure to connect to mains water. The chances of flash-flooding caused by rainwater discharged from roofs would also be reduced.

Camels accumulate body fat (much of it in their humps), which can be metabolised when needed, producing a certain amount of water as a by-product. Are there forms of energy we could use in buildings that would do the same? Hydrogen fuel cells produce approximately 0.3 litres of pure water per kWh of electricity which, based on average household energy consumption, would provide more than enough drinking water for the occupants.[127] Whether or not fuel cells will ever be a significant part of our electricity production infrastructure remains to be seen but, where implemented, it would certainly be worth capturing the water.



102. The Namibian fog-basking beetle – a biomimicry hero that harvests water from the air in deserts

Water harvesting (with gravity)

It would be hard to find a better example of what biomimicry can offer than the Namibian fog-basking beetle (*Onymacris unguicularis*) (fig. 102). This creature has evolved a way of harvesting its own fresh water in a desert. The way it does this is by climbing, at night, to the top of a sand dune and, because it is matt black, it is able to radiate heat to the night sky (the heat sink is actually outer space which is at a temperature of −273 °C) and become slightly cooler than its surroundings. When the moist breeze blows in off the sea, droplets of water form on the beetle's back. Then, just before sunrise, it tips its shell up, the water runs down to its mouth, it has a good drink and goes off and hides for the rest of the day. The effectiveness of this beetle's adaptation goes even further because it has a series of bumps on its shell that are hydrophilic and between them is a waxy finish that is hydrophobic. The effect of this combination is that, as the droplets form on the bumps, they stay in tight spherical form, which means that they are much more mobile than a film of water over the whole beetle's shell would be. So, even when there is only a small amount of moisture in the air, the beetle is still able to harvest it effectively. It's a remarkable adaptation to a resource-constrained environment and, consequently, very relevant to the kind of challenges we are going to be facing over the next few decades.

The fog-basking beetle has been studied in detail by biologist Andrew Parker,[128] who collaborated with the firm QinetiQ to produce a type of plastic with the same combination of hydrophilic and hydrophobic surfaces to enhance condensation. In 2015, a group of scientists at King Abdullah University of Science and Technology claimed to have developed a low-cost approach to making a water-harvesting surface, based on *Onymacris*, that achieves significantly higher fog-collection efficiency than uniformly hydrophilic or hydrophobic surfaces.[129] In a busy year for the beetle, 2015 also saw technology start-up company NBD Nanotechnologies secure $750,000 of funding to further develop their enhanced condensation innovations. One of NBD's work areas is using their hydrophobic coatings to improve the effectiveness of fog-nets. Fog-capture devices have been in use for centuries in parts of the world such as Chile and the Canary Islands[130] – generally locations where cold ocean currents run alongside steep landforms that force air to rise. Air temperatures drop approximately 1 °C with each 100 m increase in elevation, which in turn increases the relative humidity, so in these locations air quickly reaches saturation point. Biomimicry takes these traditions further, using technology to widen their application.

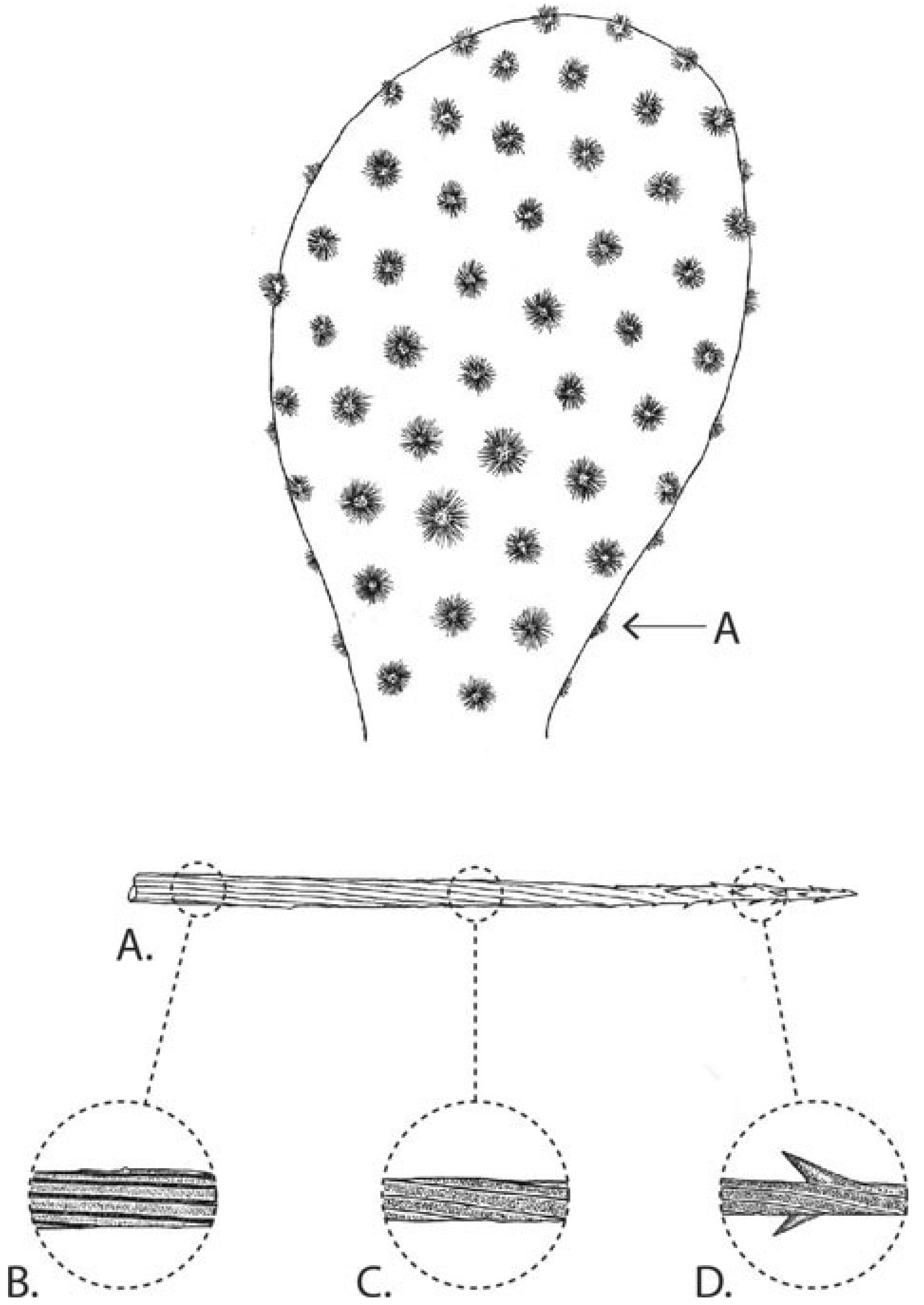
Many biological organisms besides the beetle have evolved to capture moisture. A species of laurel (*Ocotea foetens*) that grows on El Hierro in the Canary Islands does this to such an effective degree that one particular specimen achieved sacred status. According to legend, during the sixteenth century a mature example, known as the Garoé laurel tree or the fountain tree, provided enough water to supply the local population during periods of siege.

Desert rhubarb *(Rheum palaestinum*) grows in parts of Jordan and Israel, where precipitation is as low as 75 mm per year. Its large, round leaves have a distinctive texture that resembles a miniature mountain range over the whole leaf surface. This appears to be an evolved water-collection surface that channels water towards the centre of the plant to create a water regime equivalent to many times the annual precipitation.[131]

Water harvesting (against gravity)

Another supreme example of adaptation to scarcity is the thorny devil lizard (*Moloch horridus*), which is able to harvest water in two ways: using its feet and the spikes on its back. Its skin is covered with fine capillary grooves so that, if it stands on a damp patch of ground, the water tracks up its feet and towards its mouth by capillary action. When conditions are favourable, droplets of water form on the spikes and then track along the same network of grooves. The thorny devil shares this adaptation with a number of other lizards, including the Arabian toad-headed agama (*Phrynocephalus arabicus*) and the multi-talented horned lizard (*Phrynosoma*), which can also spit blood from the edges of its eyeballs to deter predators.

The Chihuahua Desert cactus (*Opuntia microdasys*) has evolved water-harvesting clusters of very fine conical spines (fig. 103). Its success relies on two physical phenomena: first, a gradient of Laplace pressure and, second, a gradient of surface-free energy.[132] Laplace pressure refers to the pressure difference (between inside and outside) created within bubbles. When a droplet of water forms on the end of the conical spine, it forms asymmetrically – wider at the tip of the spine. The result is a pressure gradient that drives the droplet along the spine (even against gravity) towards the wider part of the cone. The effect is enhanced by microgrooves along the spine, which widen towards the base, creating another means by which the droplet is driven along the spine towards the base (referred to as a gradient of surface-free energy). The spines all converge at the base into a structure where the droplets of water are absorbed. The rest of the cactus leaf is waxy to reduce water loss. It should only be a matter of time before human manufacturing can create equivalent structures that could form the walls of buildings to harvest water.



103. Some of the most remarkable adaptations to managing water are found where water is at its scarcest. The spines of *Opuntia* cacti are able to harvest water from the air and conduct it into the body of the plant

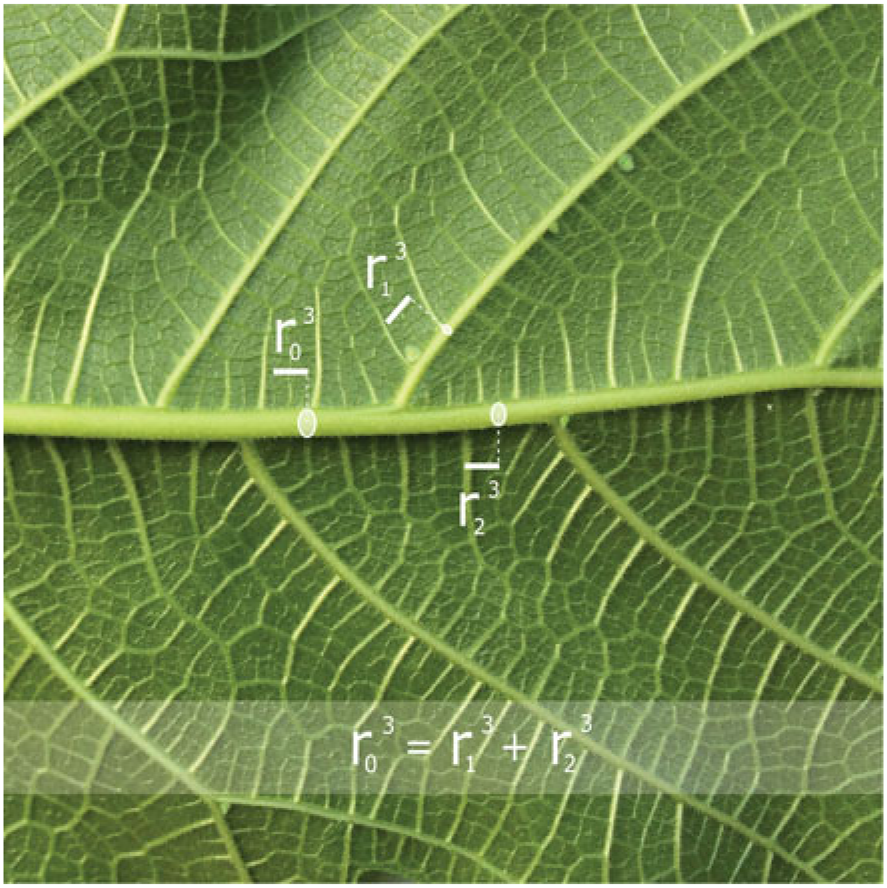
Water transport: helices

It may seem obvious that a straight line is the most efficient way to connect two points: but ‘flow in nature is helical’,[133] Emeritus Professor Colin Caro at Imperial College London discovered. He has studied the flow characteristics in human arteries and demonstrated that a damaged artery fitted with a helical stent is subject to far less deposition of fatty substances than a straight stent. Deposits occur where flow stagnates, which a helical stent minimises. A spin-out company is now commercialising the use of helical tubing, focusing on specialist applications where an even flow rate is needed. As the manufacturing cost of helical pipework decreases, more widespread application of the idea in the construction industry is likely to follow, with the potential for significant energy savings and reduced maintenance.

Spiral flow patterns have also inspired Jay Harman,[134] whose company Pax Scientific learned from marine molluscs’ geometry to manufacture a range of fans and impellers. Based on extensive research, they boast substantial performance improvements over more conventional versions (fig. 104).

104. High-efficiency impeller developed by Pax Scientific, based on spiral flows in biology

Transporting fluids around a large organism’s body can use around one-sixth of its resting metabolic energy,[135] so the process of evolution has refined these systems intensely. Biologist Cecil Murray developed a formula, Murray’s law, which describes the relative diameters of branching vessels. This formula appears to hold true for most circulatory and respiratory systems in animals, and the branching of xylem in plants. Murray’s law (fig. 105) states that the cube of the radius of a parent vessel that branches symmetrically into two daughter vessels will equal the sum of the cube of the radii of the daughter vessels. Recent studies of Murrays law[136] reveal remarkably consistent angles between bifurcating vessels: around 77 °. This may also represent a minimum-energy solution, where flatness overrides the helical flow patterns described above. Leaves illustrate this clearly. Substantial savings could be achieved in designing pipework and ductwork installations to follow the formulae found in biology, rather than those taught in schools of mechanical engineering.



105. The biologist C. D. Murray found that the relative diameters of branching vessels in animals and plants, and the angles formed by the junctions, follow consistent mathematical formulae which suggest a minimum-energy system. Architects and engineers could apply the same principles to duct and pipework systems

Principles in practice

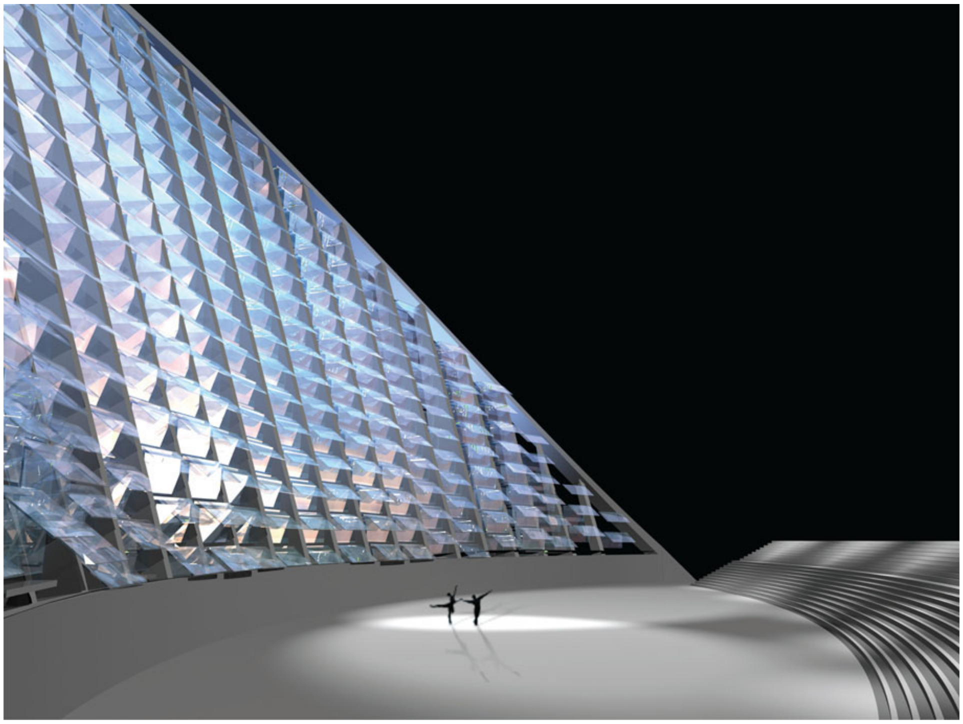
A number of projects have translated biological forms of water harvesting into building proposals, principally those of the fog-basking beetle (see the Sahara Forest Project in Chapter 8). The Seawater Greenhouse (figs 106 & 107) is an invention by Charlie Paton that uses the evaporation of seawater to achieve factor-8 savings in irrigation. Wind drives air over evaporators at the front of the greenhouse, creating a cool and humid growing environment for crops in arid regions, while the plants inside benefit from lower temperatures and the high humidity, reducing their transpiration rates. At the back of the greenhouse a second evaporator, supplied with hot seawater from black pipes in the roof, raises the temperature and absolute humidity of the air. This hot, saturated air then passes a series of vertical polythene pipes, which are supplied with cool seawater from the front evaporators. The polythene pipes are equivalent to a large area of beetle's shell, and form a condensation surface for the humidity. Droplets of water form on the surface of the pipes and run down to a tank for irrigating the crops. The building essentially mimics and enhances the conditions in which the beetle harvests water. Saline water is turned into fresh water using just the sun, the wind and a small amount of pumping energy.

Biological examples of direct desalination, such as penguins and mangrove trees, could inspire other approaches. These may lead to improvements in membrane-based desalination, such as aquaporins, where protein molecules act as channels for water transfer across cell membranes, which are now being developed to compete with more energy-intensive reverse osmosis or forward osmosis.

The Las Palmas Water Theatre (fig. 108) proposed for Gran Canaria in the Canary Islands by Grimshaw demonstrates how the challenges of water shortages can be transformed into creative solutions. The island's declining annual precipitation has fostered dependence on desalinated water brought in from mainland Spain. This is highly carbon-intensive, combining fossil-fuelled desalination and inefficient transportation (compared to piped water). Fortunately, the biology and geography offered numerous opportunities for the design team. Home to the Garoé laurel tree, the islands also enjoy a steady wind direction for most of the year. Because of their volcanic origin, the islands have very steep cliffs below sea level. This means that it is economically feasible to install a sea pipe that reaches 1,000 m below the surface, where there is a stable temperature of 8 ℃. Taking as a starting point a system of evaporators and condensers, the proposal was to use solar-heated seawater in the former and

106. The Seawater Greenhouse in Oman as it looked on completion day

107. The Seawater Greenhouse one year later



108. Las Palmas Water Theatre by Grimshaw – using biomimicry to transform infrastructure into architecture

cool seawater in the latter. The enhanced evaporation would create abundant humidity, while the condenser surfaces at 8 °C would greatly increase the amount of fresh water that could be captured. A bold, arching structure, curved on plan, creating the backdrop to an outdoor amphitheatre was designed as the form these simple technologies would take. The team strove to achieve the maximum benefits from the cold seawater so, after passing through the Water Theatre, it could cool mixed-use buildings nearby. Passed through a heat exchanger, the seawater can cool fresh water, feeding fountains in planted courtyards. The sprayed water itself forms a condensation surface for humidity in the air, so that the volume of water would increase, providing irrigation water. Calculations suggested the scheme would produce fresh water using one-tenth of the energy of the existing method of supply.

The result was a dramatic public theatre and landscaped gardens, richly evocative of the Alhambra in Granada, that came with a free desalination plant. This example provides a strong narrative about a precious resource which we, all too often, take for granted.

Managing excess water

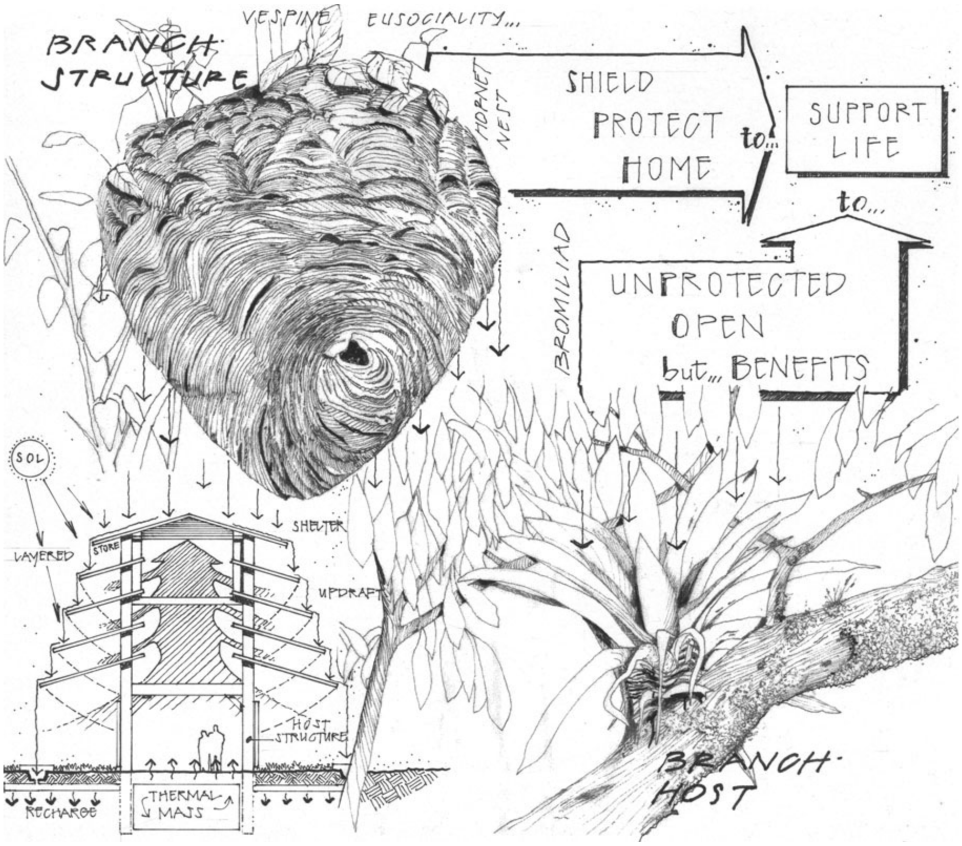
> *To an average civil engineer, water is just cubic metres of nuisance to be taken somewhere else in big concrete pipes.*
> AMORY LOVINS [137]

In most cases there are more imaginative approaches to managing surplus water, offering multiple benefits – lower construction costs, minimising flood risk, creating water habitats rich in biodiversity and recharging groundwater. To build in the Lavasa region of India, which experiences 11 m of rain a year, predominantly within a three-month period, consultancy Biomimicry 3.8, with architects HOK, adopted a holistic and ingenious approach. They studied the local ecology and the way that water flows through it.[138] In the native forest, as much as 30 per cent of the rain that falls remains in the canopy level, evaporating back into the atmosphere. In this way, rainforests often act as atmospheric pumps, where water evaporated from the surface of the sea is carried inland as vapour by the wind, falling multiple times. This process pushes precipitation deep into the continental interior, and this project responded by striving to maintain these natural cycles.

The requirement for maximising evaporation became a significant driver of the architectural form, leading to cascading roof surfaces made from absorbent material. This is the diametric opposite of normal structures. These roofs maximise evaporation, in contrast to the more conventional channelling of rainwater efficiently into gutters and downpipes (fig. 109). The storm-water management design continued into the design of all the urban surfaces in order to limit run-off and enhance infiltration and the recharging of groundwater.

Waste-water treatment

Is waste water genuinely waste? A cool, strategic look at the global cycling of all nutrients, of which water is a major vector, might lead to some significant changes in the way we treat 'waste' water. Over the past half century we lost vast quantities of minerals from the world's soils in the linear flow of nutrients via food, the human gut and our dominant waste-water treatment paradigm (see Chapter 3). Between 1940 and 1991, this translated directly into a drop in the mineral content of food. A comprehensive study showed a drop of 19 per cent in magnesium, a 29 per cent loss in calcium, a 37 per cent loss in iron and a 62 per cent loss in copper.[139] This is alarming, as it suggests that, even with fertiliser, the quality of food cannot be maintained. Current fertiliser production relies very heavily on fossil fuels as a feedstock, and the supplies of compounds such as phosphates are dwindling, so the case for transforming our food and water treatment systems from linear, wasteful, polluting flows to closed-loop solutions is compelling.



109. Sketch of the Lavasa project by architects HOK, showing how locally adapted species, such as the bromeliad, provided a number of sources of design inspiration, including the idea of cascading roof surfaces to catch and evaporate rainfall

This may well lead to buildings with distinct systems for solid and liquid wastes, using source-separating toilets. A fully functioning pioneering scheme has been implemented by the Berlin Water Competence Centre. An existing office and a residential building sewage system were comprehensively redesigned to use a multi-loop process, where grey and black water were turned into fertiliser and biogas within the buildings, and the remaining fluid was purified using constructed wetland outside. On the agricultural side, urine had the same effectiveness as mineral fertilisers.[140] While the dominant waste disposal paradigm encourages a prejudice against more local processing of waste water, successful projects can overcome this barrier.

Plant systems can also be introduced inside buildings. The US company L3C has various implementations for both options. Their Living Machine® (fig. 110) uses a complex ecosystem of plants and micro-organisms cultivated in wetland beds to treat sewage or industrial waste-water to a level that allows it to be re-used locally for toilet flushing or irrigation, or reintroduced into the environment. The idea of using versions of wetland ecosystems to treat waste water was first conceived by biologist Dr Käthe Seidel at the Max Planck Institute in the early 1950s. Where waste-water treatment usually involves heavy infrastructure and complicated 'end-of-pipe' solutions, Living Machines® avoid long-distance transportation and often unnecessarily high standards of treatment (when the end-use may not be human consumption). The systems are so effective at controlling pathogens, odour and other nuisances often associated with waste water that several Living Machines® have been installed in reception areas of commercial buildings. These systems, available now, are the antithesis of a centralised approach and come much closer to the local and resilient ways in which water is cycled in nature.

110. A Living Machine®, at the Adam Joseph Lewis Center for Environmental Studies, Oberlin College by William McDonough + Partners, that uses plants and micro-organisms to treat waste water

Integrated approaches

An integrated biomimetic approach to managing water would bring together a number of the strands exhibited by the projects described above. As Biomimicry 3.8 advocate, the design process would begin by studying the organisms and systems that have adapted to the particular conditions of the ecosystem and would almost certainly provide clues to solving the biggest challenges. A finished scheme would harvest all the water it needs for the occupants, have features that absorb or retain storm water, treat all its own used water with systems that enhance biodiversity and, for schemes that involve significant flows of water, might well have distribution systems modelled on helical flow and Murray's law. For parts of the world where comfort cooling is required, the water strategy may even be integrated with the designs for thermoregulation – examples of which we will see in the next chapter.

Conclusions

Just as with our use of fossil fuels, many of our standard approaches to water have an inherent technological laziness to them that has developed from the same assumptions of limitless supply that characterised our attitude to resources at the start of the Industrial Revolution.

Studying adaptations in biology can reveal solutions to some of the most intractable problems, like harvesting water in the desert. The biological examples shown work without pumping energy; some even gathering water against the force of gravity by using subtle pressure gradients. The architectural examples show how, with imagination, these ideas can be translated into inspiring buildings, like the Las Palmas Water Theatre, which contribute to the character of their settings. Nature's remarkable solutions to water shortages should provoke us into thinking of more ingenious ways to meet our needs than energy-intensive desalination. Similarly, designing with biomimicry to manage excess water flows can lead to more locally attuned solutions that also benefit biodiversity. Just as plants and animals have evolved minimum-energy ways of conducting fluids, we could use the same principles to design far more efficient water transportation systems in buildings and cities. The potential exists to design with water in a way that produces better cities, which are less prone to flooding, using less energy and regenerating biodiversity.

The examples of biological approaches to treating waste water brought another crucial aspect into focus: managing waste water is inseparably connected with nutrient flows. Rethinking our water treatment systems is vital to restoring the fertility of our soils and providing long-term food security, particularly in those areas that will be suffering from declining rainfall due to climate change.

Chapter Five

How will we control our thermal environment?

111. The Himalayan rhubarb (*Rheum nobile*) – probably the closest biology comes to a greenhouse. The adaptation has given the plant a substantial advantage over others in the same habitat

Homeostasis – the tendency for living organisms to maintain steady conditions – is one of the features that most closely link the buildings we create with biology. Where the similarities break down is that animals tend to continually modify their structures or their behaviour in order to make use of freely available energy (such as the wind), whereas we use large amounts of energy to pump heating or cooling around. In terms of physical control, biological solutions are often complex, multi-functional and highly responsive, whereas ours tend to be simple and relatively unresponsive, and the range of necessary functions are generally handled separately by mono-functional elements.

In this chapter we will be focusing primarily on one aspect of homeostasis: thermoregulation. For convenience we will divide this into ‘keeping warm’ and ‘keeping cool’. Of course, many organisms have evolved ways to do both, sometimes using the same biological structures. For instance, fossil records of the plate-like structures on the backs of dinosaurs (such as *Stegosaurus*) show that they were richly vascular and may have been used for both absorbing and shedding heat, depending on whether the creature positioned itself side on to the sun or to face the wind. In other cases, the characteristics of the habitat to which an organism has adapted have resulted in one strategy being more pronounced than the other.

Some animals, known as homeotherms, generate heat from within and keep their bodies at a steady temperature, while poikilotherms absorb heat from their environment and allow their body temperature to vary quite widely. The history of environmental engineering shows that humans have been growing increasingly demanding in terms of what we regard as a comfortable temperature band in our buildings. This can reach levels of absurdity when, in certain parts of the world, office buildings are heated to 24 ℃ in winter and cooled to 19 ℃ in summer. The energy implications of this are huge, so reversing this shift and encouraging clients to tolerate a wider thermal comfort envelope is a critical first stage in designing a low-energy building. This can normally be done with thermal-modelling exercises rather than trying to persuade clients to evolve into poikilotherms or thermophiles.[141]

Keeping warm

The two main sources of heat for organisms are both based on solar energy: first, indirectly through metabolising food and, second, through direct solar gain.

The continual generation of heat from metabolism results in many biological solutions to keeping warm being based on reducing heat loss. Insulation, a familiar strategy in buildings, could find new modes of action from nature here. For land mammals in temperate regions there are two main physiological ways in which this is achieved: a subcutaneous layer of insulating fat and a dense layer of fur. Those like the polar bear and the reindeer that live in colder regions have further adaptations, such as hollow hair fibres for added insulation. Polar bear fur inspired an initial biomimetic response, a wall system, which turned out to be based on faulty scientific understanding (the hair filaments were thought to conduct sunlight down to the animal's dark skin). This comes closer to biomythologically-inspired design than biomimicry, but as long as we continue to adapt to new scientific knowledge then we are acting as scientists do themselves. New discoveries change existing knowledge and can lead to different avenues of discovery but do not, by definition, devalue existing viable solutions. Reindeer fur includes a very dense underlayer of fur that traps air against the skin to reduce convection loss, while longer guard hairs minimise wind chill by repelling water. Penguins have evolved feathers that allow them to respond to two very different conditions. While swimming, the bird's feathers are held flat against the body for optimum streamlining; on land, the penguin lifts its feathers so that the mass of downy filaments at the base of each form millions of pockets of trapped air for effective insulation. The bird is able to maintain a temperature difference of 60 °C between its body and the exterior with just a 20 mm thick layer of feathers. There are also some examples of insulation found in the plant kingdom, such as the groundsel trees that grow on the slopes of Mount Kenya. They accumulate a thick layer of dead leaves from previous years that provide insulation to the trunk and prevent water within the vascular tissues from freezing.

Turning to direct solar gain, perhaps some of the most elegant examples of trapping solar energy in biology are found in the communal nests built from multiple layers of silk by eastern tent caterpillars (*Malacosoma americanum*) that face south-east to capture the morning sun. The combination of insulation and solar orientation maintains the temperature inside at least 4 ℃ above ambient.[142] The Himalayan rhubarb (*Rheum nobile*) towers above the other plants in its habitat by growing a vertical greenhouse of translucent leaves that results in ‘internal’ temperatures being as much as 10 ℃ higher than outside.[143] The warmer conditions aid both survival and reproduction. Termite mounds, often built in areas with widely varying temperatures, effectively stay warm and cool but have mainly inspired solutions for cooling buildings, so we will turn to these later in the chapter. Interestingly, these examples all show a tendency to adapt the wider microclimate, rather than the individual organism.

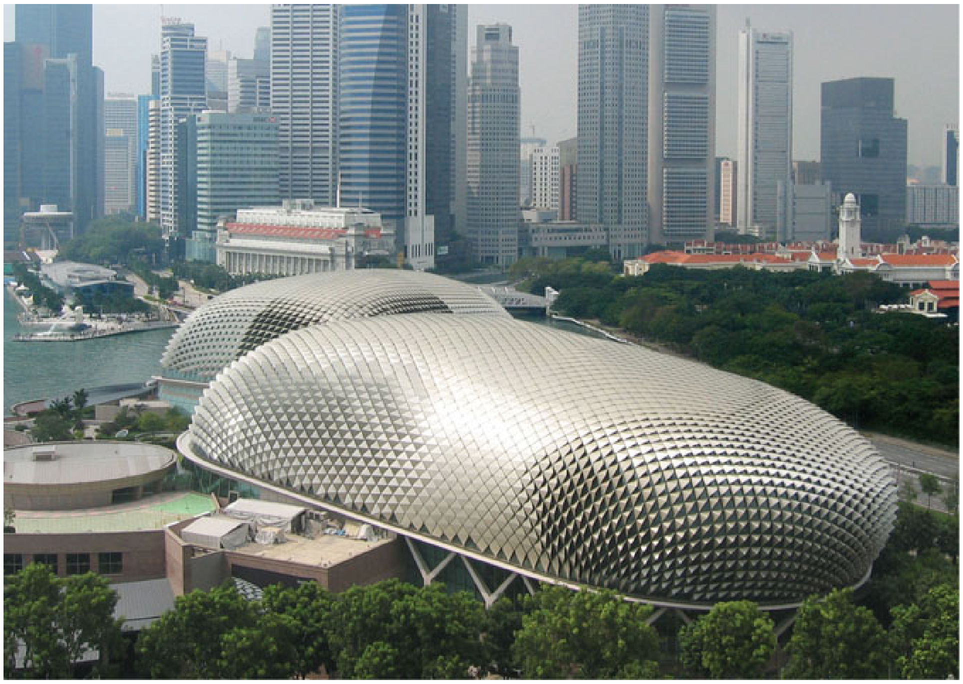
Penguins show us strategies of groups and arrangement to adapt to the different conditions they face. Our building skins tend to stay the same, regardless of whether there is blazing sun or a night-time blizzard. Penguins huddle together in large groups to minimise their effective surface area, and we could apply similar principles to groups of buildings by connecting them with atria that can be opened in summer to increase ventilation or closed in winter to reduce heat loss. The translation of ideas is more one of analogy than technology, but valid nevertheless.

What we need to see is adaptive technologies spreading from niche applications to mass-market ones, as is now happening with climate-adaptive building skins (CABS),[144] discussed later in this chapter. If we could dramatically reduce heat loss from buildings, then we could increasingly implement what has been achieved in some Passivhaus projects, in which the heating system has been completely ‘designed out’ by getting the internal heat gains from the occupants' metabolism and equipment in the building (analogous to metabolism) to balance the heat losses through the skin. Reaching these points of whole-systems optimisation is often where quantum changes in energy performance can be achieved.

The oriental hornet (*Vespa orientalis*) has a distinctive thermoregulation strategy, which doubles as solar energy harvesting. Inside their nest, the pupal cells (in the familiar hexagonal honeycomb structure) are covered with silk caps. These caps insulate the pupa from outside air, and also act as a thermostatic regulator. The silk's thermoelectric properties can store daytime heat in the form of electric charge. As the temperature falls, this charge is released in the form of an electric current, providing heating. The pupal cells are further cooled by evaporation of excess water. As the ambient temperature falls, the silk absorbs moisture and regains its earlier level of humidity, retaining this by distributing the water throughout the cocoon. The local storage of electric current, for local re-use as a thermoregulation strategy rather than for the purposes of generating electricity, is a different way to consider the role that electricity plays in thermoregulation in buildings.

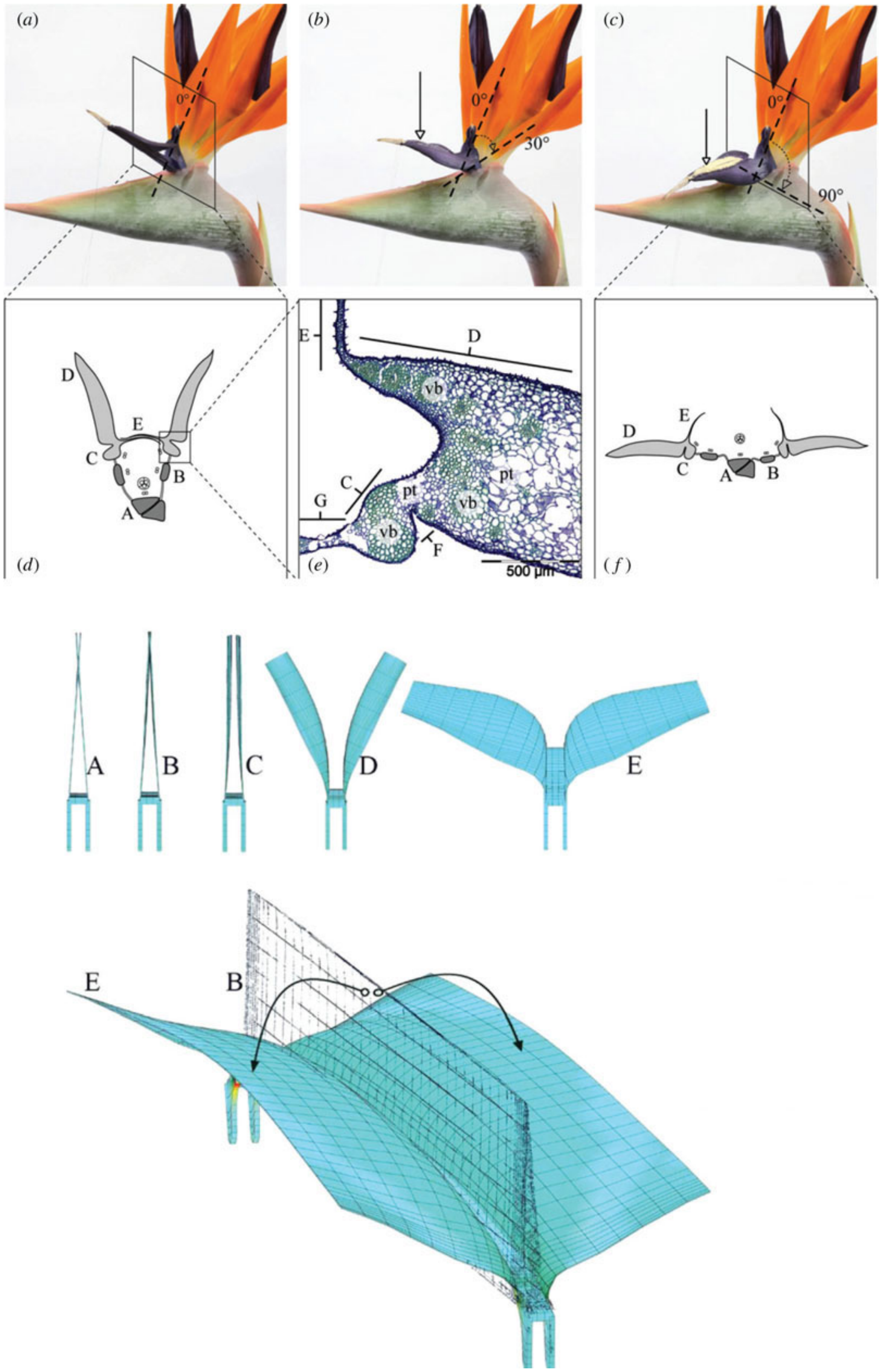
Keeping cool

112. Cabo Llanos Tower masterplan in Santa Cruz de Tenerife, Spain, by Foreign Office Architects – with palm-leaf inspired shading fins that follow the movement of the sun



113. The Singapore Arts Centre, designed by Atelier One, Atelier Ten and Michael Wilford & Partners, showing what can be achieved with shading systems based on plants

Heat is transferred in four ways: radiation, evaporation, conduction and convection. Many organisms that live in hot regions go to great lengths to avoid picking up heat. Some of them avoid radiative gain by staying out of the sun altogether or skipping across the sand rapidly to minimise absorbing heat through conduction. Applying the same logic to architecture would lead to the conclusion that avoiding heat gain should be the first priority when trying to keep a building cool. In spite of the obviousness of this statement, solar shading has not been exploited anywhere near as widely in late twentieth-century architecture as it could be. Schemes such as the Cabo Llanos Tower in Santa Cruz de Tenerife, Spain, by Foreign Office Architects (fig. 112), and the Singapore Arts Centre by Michael Wilford & Partners with Atelier One and Atelier Ten (fig. 113), both loosely based on plants,[145] give a sense of what can



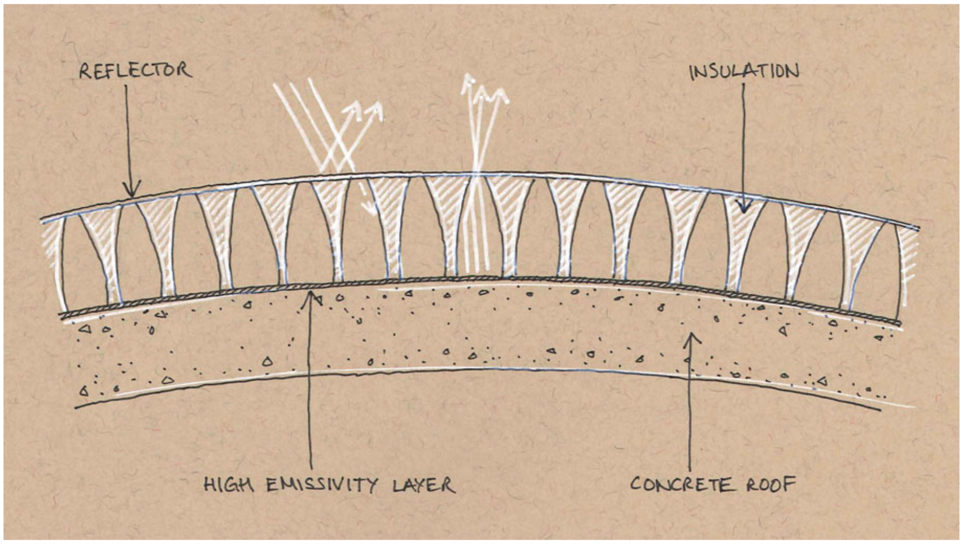
[114](). Flectofin shading system inspired by the way that the *Strelitzia* flower changes its geometry when a pollinator lands on it

be achieved. The work of Chuck Hoberman in the field of deployable shading structures also shows the beauty of adaptive approaches to solar shading. As I argued in the previous section, we have to develop buildings that adapt to changing conditions if we are to truly mimic the low-energy ways in which biology works.

115. Thematic Pavilion by soma, using a kinematic facade inspired by early research on the flectofin as a dynamic part of the facade that controls solar gain

The Plant Biomechanics Group at the University of Freiburg are renowned for their work in developing biomimetic solutions (we met them in Chapter 2 when discussing self-repair systems) and their Flectofin shading product, developed with ITKE and the Institute for Textile Technologies, is an elegant solution inspired by the Bird of Paradise (*Strelitzia reginae*) flower.[146] The group explored a wide range of deployable structures in plants and pursued *Strelitzia* because of the way that a small movement produced a substantial change in geometry.[147] The *Strelitzia* flower has a kind of perch for the birds that pollinate it and, when they land, the perch bends and the petals flap outwards to expose the anthers, which dust the bird's feet with pollen (fig. 114). The principle that they extracted from this understanding of the flower was the idea of a flap that could be moved through 90 ° – a very useful characteristic for solar shading on buildings where the ideal solution is a shade that provides minimal obstruction to the view when shading is not required and full protection when the sun comes out. After several prototype stages, a version of Flectofin was realised as a large-scale shading system on the Thematic Pavilion by architectural practice soma at the 2012 Expo in Yeosu, South Korea (fig. 115).[148]

The shading examples described above are intended to keep buildings cool by minimising radiative heat gains from the sun; however, there is another approach to keeping cool that involves maximising radiative losses to outer space. Radiation is the process by which heat diffuses from a warm body to a relatively colder one and, on a clear night, it is possible to get a matt black surface to radiate to outer space. The temperature of outer space is absolute zero (-273 °C), which is hard to beat as a heat sink and explains why clear winter nights are much colder than cloudy ones – on a clear night there is nothing to stop the ground radiating to outer space. The ancient Persians used this principle to make ice in the desert by making shallow ceramic trays, with a matt black glaze, that could hold a layer of water. These were put out on clear nights on top of a bed of straw to minimise heat conduction from the ground and the radiative temperature loss was enough to make the water freeze. The ice was gathered before sunrise and used to make sherbet. This is the same process by which the fog-basking beetle loses heat and, by doing so, becomes an effective condensation surface.



116. Roof system designed by Salmaan Craig using BioTRIZ. Most sunlight is reflected during the day and at night the structure is able to lose heat by radiation to the night sky

One particularly inventive approach to keeping buildings cool using radiation loss has been devised by engineer Salmaan Craig using a powerful problem-solving methodology known as BioTRIZ. The forerunner of this technique was TRIZ (a Russian acronym for 'Theory of Inventive Problem Solving') developed by Genrich Altshuller (1926–98). Any problem can be defined in terms of 'I want A, but it is prevented by B', which is similar to the German philosopher Hegel's concept of thesis, antithesis and synthesis. The resolution, in Hegel's terms, was something that managed to combine thesis and antithesis. Altshuller analysed thousands of patents and distilled from these 40 inventive principles, each of which has the potential to be a synthesis (in Hegel's terms). Julian Vincent and his colleagues, Drs Olga and Nikolay Bogatyrev, extended Altshuller's work by studying roughly 2,500 examples of how problems are solved in biology and producing a refined matrix of inventive principles based on their conclusions.[149] The thesis/antithesis defined by Salmaan Craig was a roof that was insulated against the sun but that allowed infra-red heat to radiate at night. Whereas conventional technology would often have pointed towards manipulating energy in some way (such as air-conditioning) to solve the problem, BioTRIZ indicated that the synthesis found in biology would most commonly involve modifications to structure. This led to a method of structuring a layer of insulation on top of a concrete roof that blocked most of the sunlight while funnelling the long-wave radiation using reflectors towards transparent apertures (fig. 116). Test panels demonstrated that the roof temperature could drop as much as 13 °C below ambient by entirely passive means. The concrete would act as a heat store so that it would radiate this coolness to the rooms below during the day. Craig estimates that the biomimetic roof would maintain the concrete at an average of 4.5 °C cooler than a standard roof in Riyadh, Saudi Arabia.

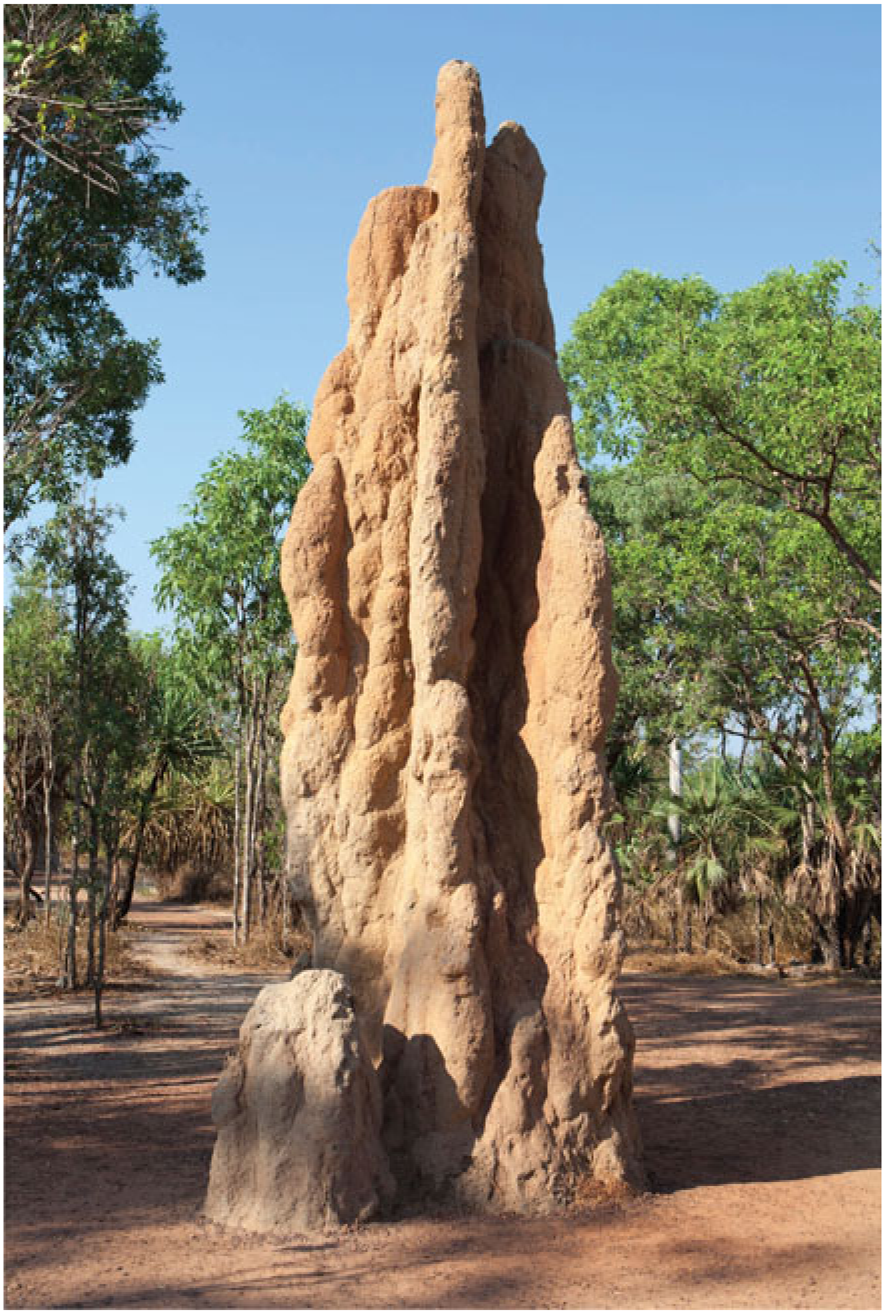
Evaporation is an extremely effective means of cooling because water's specific heat capacity is relatively high and therefore large amounts of heat can be dissipated with small amounts of water. The microscopic pores (stomata) on plant leaves control the rate of evaporation and the exchange of gases involved in photosynthesis. When temperatures increase, the stomata open wider, which causes more water to evaporate and allows the plant to stay cooler than its surroundings. In extreme cases the leaves wilt, which has the effect of reducing the amount of leaf surface presented to the sun. The water in plants is transported through vascular bundles, driven by osmotic pressure from the roots pushing the water up, transpiration loss from the leaves pulling the water up and, to a lesser degree, capillary action, which relies on edge contact at a free surface to provide the force.

Tate Harmer Architects explored the potential of using transpiration in their IHub competition scheme (fig. 117). The aim was to create a building that cools itself using water but without pumps. If capillary action and an equivalent of transpiration pull could be harnessed to deliver the water, then the rate of evaporation would drive the process. There would also be a close match between the demand for cooling and the rate at which it was supplied, because hotter days would create higher rates of evaporation. The designs show a network of capillary tubes on the southern elevation through which air can be drawn and cooled by evaporation.[150]

117. Entry for the IHub competition designed by Tate Harmer Architects. The scheme explored the idea of a self-cooling building based on transpiration

Apart from the dinosaur back-plates mentioned above, there are various other interesting examples of biological structures used for thermoregulation through radiation and convection. The generously-beaked toco toucan, for instance, has the ability to moderate blood flow to its bill and, by doing so, control the amount of heat dissipated. Elephants employ radiation, convection and evaporation when they use their huge ears to lose heat. The ears are permeated by blood capillaries and elephants enhance heat loss by spraying their ears with water and flapping them. Could buildings have the equivalent of large flapping evaporatively cooled elephant ears? Why not!

The biological form of thermoregulation that has been subjected to most scrutiny by engineers and architects is undoubtedly that of the termite mound. From an architectural perspective, perhaps the purest manifestation is the mound created by compass termites (*Amitermes meridionalis*) in Western Australia (fig. 118). The compass termites' tower forms a flattened almond shape in plan, with the long axis aligned perfectly north–south. The long, flat sides present a large absorbing area which catches the warmth of the morning sun after the cold night, while in the middle of the day the minimum surface area is presented to the midday sun. Ventilation tubes within the walls can be controlled by the termites, so it was hypothesised that, if the temperature inside rises too high, vents can be opened and the warm air rises by stack effect. Some commentators[151] claimed that the temperature in the royal chamber is maintained within one degree of 31 °C, even though the outside temperatures vary by as much as 39 °C between night and day. Recent, very detailed research into termite mounds by Rupert Soar and J. Scott Turner has cast doubt on the previous accounts of exactly how they work.[152] Soar has shown that the internal temperatures are nowhere near as stable as previously thought and that the main source of thermal stabilisation is the ground, rather than induced flow ventilation or evaporative cooling. His studies have suggested that termite mounds exploit the wind in much more complex ways than simple stack effect or wind-induced ventilation. Soar and Turner assert that the network of tubes function more like lungs that facilitate gaseous exchange. It appears that, rather than a simple, unidirectional flow of air through the mounds, the movement is much more one of ebb and flow and is driven by subtle wind pressure and frequency differences.



118. Compass termite mounds – zero-waste construction with solar-powered air-conditioning

Termites were the primary source of inspiration for architect Mick Pearce when he designed the Eastgate Centre in Harare (fig. 119), Zimbabwe, in conjunction with engineers at Arup (completed in 1996). This office building and shopping complex achieves remarkably steady conditions all year round without conventional air-conditioning or heating, and uses only 10 per cent of the energy of a standard approach. Pearce based the design of the ventilation system for the building on the mounds of the *Macrotermes michaelseni* and *Macrotermes subhyalinus* termites, which appeared to use a combination of steady ground temperatures and wind-induced natural ventilation as their means of thermoregulation. As in many locations to which termites are adapted, the night-time temperatures drop sharply in Harare and this cool night air is drawn into a plenum between the first and second floors by fans. The cool air is circulated into large floor voids, which contain a labyrinth of precast concrete elements that maximise heat transfer by having a large surface area. During the day, an induced flow system draws air from these cool voids out into the office space via grilles. The Eastgate Centre has been extremely successful in maintaining the interior temperature at 21 ℃ to 25 ℃, while outside temperatures typically range between 5 ℃ and 33 ℃.

119. The Eastgate Centre by architect Mick Pearce – a building inspired by termite mounds that maintains comfortable conditions close to the equator without mechanical cooling

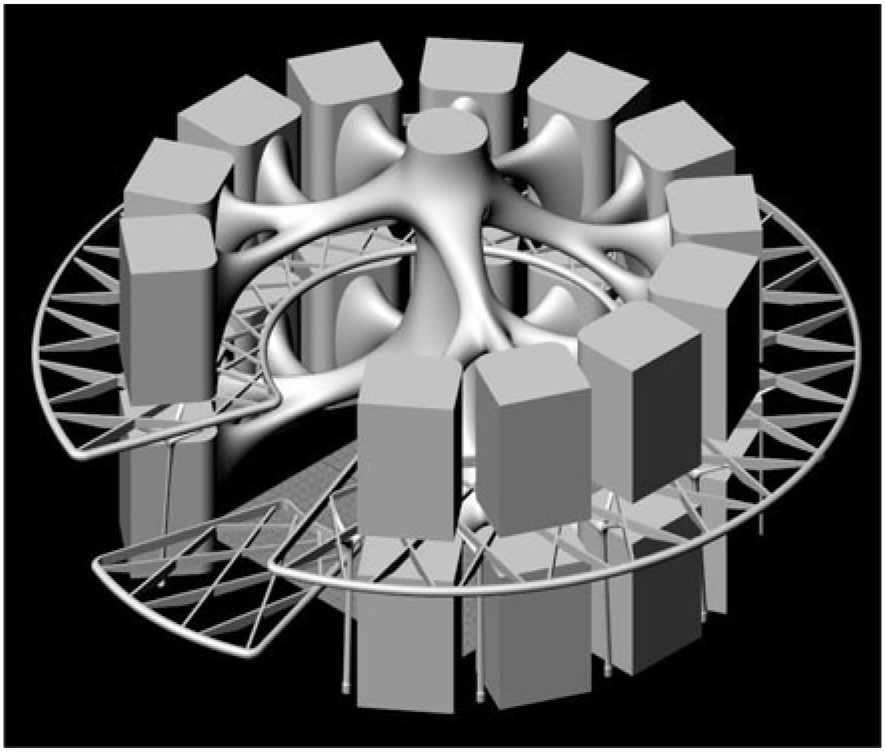
Does this mean that any architectural strategies we have developed from an imperfect understanding of termite mounds are therefore biomythological rather than biomimetic? It is worth maintaining distinctions in order to be clear about how to use biomimicry effectively and continually improve what we do. Perhaps the fairest conclusion to draw is that the Eastgate Centre was a triumph of low-energy design and could, conceivably, be taken even further with the benefit of advances in biological knowledge.

120. The Davis Alpine House at Kew Gardens by Wilkinson Eyre and Atelier Ten. Ideas from termite mounds were employed to create the cool conditions necessary for the collection of alpine plants

Another very successful scheme that fits into the same category is the Davis Alpine House at Kew Gardens (fig. 120) by architects Wilkinson Eyre with environmental engineer and termite expert Patrick Bellew of Atelier Ten. It is common for alpine plant collections to be displayed on refrigerated shelves or in fully air-conditioned enclosures, but the client was keen for the team to generate a more creative solution.

The team designed the building to include a thermal labyrinth which, in layman's terms, is a basement with a network of masonry walls to create a very large area of thermal mass. This mass can be ventilated at night when temperatures are lower to create a store of 'coolth' that can be drawn from during the day by circulating air into the growing area. This approach, sometimes referred to as 'decoupled thermal mass', differs from conventional approaches to exposing heavy wall surfaces within buildings (i.e. 'coupled thermal mass') in that the mass can be cooled to below the temperature required for the space that is being served. This allows effective control so that, similarly to the way that termites appear to open and close vents to control temperature, the source of free cooling can be drawn from as required. The Davis Alpine House includes a deployable sunshade so that solar gain can be controlled. The system has successfully maintained the conditions required for the plants with only minimal inputs of energy to drive the fans. The short payback period of nine years calculated for the cost of the thermal labyrinth, relative to conventional cooling, has reduced further since the project was built, as energy costs have risen faster than predicted.

Many animals adopt a more straightforward strategy to keeping cool – they simply move to somewhere that is cooler. That approach, combined with convective heat transfer,[153] is the basis of the design of the Mountain Data Centre by Exploration (fig. 121). Data centres are often located in, or near to, urban areas and consume a huge amount of energy just in keeping cool. The first design move was to locate the data centre somewhere that was already very cold and rely on high-speed data transmission to get the data to distant customers. The cold location is a mountain that has already been extensively tunnelled and the interior is at a steady temperature of around 5 °C. The challenge identified by the team was how to draw that cool air through the data blocks (the individual parts of the data centre) in the most efficient way and, for this, Murray's law was an obvious choice. Instead of straight lines of data blocks with long lengths of ductwork and multiple right-angled bends, the data blocks were arranged in a circular layout and the ductwork was designed to follow the same principles as branching systems in biology. The combination of free cooling and efficient air-flow is predicted to deliver one of the lowest energy data centres in the world.



121. Mountain Data Centre by Exploration – an ultra low-energy solution based on the mathematical principles of branching systems in biology

Stabilising temperatures

As we have seen with termite mounds, using forms of thermal storage is a particularly effective strategy in locations that experience large diurnal swings in temperature. In this respect, termites could have been discussed under both ‘keeping warm’ and ‘keeping cool’ and I have described them at some length because of their biomimetic celebrity status. Are there other examples that have been left out of the limelight? The stone plants (*Lithops*) that live in deserts are low profile, not just in the physical sense (protruding only a few millimetres above the ground) but also in the extent to which they have been recognised by the design community. Most of the plant is below ground, benefitting from the stable temperatures below the surface, while the translucent surface of the plant allows light into the photosynthetic tissue in the ‘basement’, so to speak. The temperature in some deserts can drop below freezing at night and soar to 50 ℃ in the day, so forms of temperature stabilisation can be very effective. A building in a desert location that mimicked the stone plants, with the addition of smart adaptive solar shading, could well create comfortable internal temperatures with no further energy input. Ground-burrowing mammals do so for reasons of thermal stabilisation, but their efforts look amateurish compared to termites. The vertebrate that digs the deepest burrow is the yellow spotted monitor lizard (*Varanus panoptes*), which excavates as deep as 3 m and, for reasons not yet understood, digs the burrow in a spiral. A team at the University of Newcastle, Australia, is exploring this and the results could reveal further clues about controlling temperatures in extreme environments.

Integrated approaches

122. The facade of the Insitut du Monde Arab by Jean Nouvel – a climate-adaptive building skin that also has cultural references to the mashrabiya of vernacular Middle Eastern architecture

In recent years there has been steadily growing interest, and burgeoning research, in the field of climate-adaptive building skins (CABS). This technology has been defined as having ‘the ability to repeatedly and reversibly change some of its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions, and does this with the aim of improving overall building performance’.[154] Several examples, such as Jean Nouvel’s Institut du Monde Arab in Paris (fig. 122) and the Heliotrope in Freiburg by Rolf Disch, already mimic forms of tropism (growing or turning in response to an environmental stimulus) found in plants. Because sensing and responding is almost universal in biological organisms, there is huge potential for biomimicry to contribute to the development of CABS. We have already seen examples of this in earlier chapters: deployable structures (Chapter 1), that could be used for dynamic control, and meteorosensitive assemblies that can respond directly to changes in the environment without the need for separate control systems. These examples capture the two main forms of CABS: extrinsic (involving sensors, processors and actuators) and intrinsic (self-adjusting). The interest in CABS and the potential offered by biomimicry are likely to accelerate with advances in biomimetic technology and an important shift: the declining cost of sensing systems. The Media-TIC Building (fig. 123) by architects Cloud 9, for instance, contains hundreds of sensors monitoring everything from occupancy, to light, temperature and humidity, and yet the cost of this distributed intelligence was less than 0.01 per cent of the construction budget. The ETFE units incorporate a nitrogen-based fog-filling system, which controls their opacity as required, contributing to the 95 per cent reduction in CO_2 for the building.

If one of our aims is to design buildings that can deliver the same benefits as a healthy ecosystem,[155] then Nikken Sekkei's facade for the Sony Research and Development Centre in Tokyo goes some way towards achieving that goal in terms of thermoregulation.[156] The design was the result of a collaboration between Nikken Sekkei architects and the Nikken Sekkei Research Institute, leading to the development of a scheme that harvests rainwater from the roof and runs it through a series of porous terracotta tubes that can cool the microclimate around the building by 2 °C (fig. 124). The building is a long, rectangular slab and was orientated with its narrow dimension to the wind, allowing the breeze from Tokyo Bay to blow past with minimum hindrance. The main evaporative facade faces north and the southern facade is heavily shaded with photovoltaic panels. The combination of these strategies substantially reduces the need for cooling inside the building and shows how managing water and temperature can be unified. If all buildings in a city harvested rainwater and delivered evaporative cooling from the facade like the Sony building, then it would reduce the risk of flooding as well as counteract the urban heat island effect. There would certainly be scope to use biomimicry to take these ideas further – going beyond biomimicry as metaphor, to perhaps develop a functional solution that delivered water to the evaporative surfaces through the same processes as plants. In the near future we will see solutions that combine energy harvesting with microclimate modification and carbon sequestration, all in the same building element.

123. Nikken Sekkei's BioSkin, which delivers evaporative cooling from harvested rainwater to modify its microclimate

124. Media-TIC by Cloud 9 – using a wide array of sensors and adaptive facades together with renewable energy generation to deliver a near net zero energy building

Conclusions

It is in the area of thermal control that, I would argue, we have lost most in terms of historical intelligence and still have the greatest strides to make in learning from biology. It is precisely the kind of ingenuity, such as that displayed by the ancient Persian art of ice-making, that humans developed prior to the fossil fuel age, that we need to reawaken. So far, fairly limited solutions have been derived from nature but the ones that have been are promising: the self-cooling roof developed using BioTRIZ and the termite-inspired Eastgate Centre that stays cool near the equator without any air-conditioning show the radical potential that is emerging.

We are likely to see building skins evolving into complex systems that increasingly resemble living organisms. As Rupert Soar and J. Scott Turner have argued, the direction in which we need to be heading is ‘toward buildings that are extended organisms, where function and structure meld, and are controlled by the overriding demands of homeostasis’.[157] The flourishing of climate-adaptive design approaches coupled with biomimicry will deliver architecture with similar adaptability to that seen in nature and the associated dramatic improvements in resource efficiency. Increasingly, this will move buildings towards the equivalent of self-sustaining organisms that can derive all the energy they need from their immediate environment.

Chapter Six

What can biology teach us about light?

125. Could buildings one day deliver the same low-energy lighting effects as squid?

Architecture is the masterly, correct and magnificent play of masses brought together in light.
LE CORBUSIER [158]

This quote expresses the view of many architects: that light is fundamental to architectural form. Fewer speak of light as essential to people. Could architecture focus less on manipulating light for the sake of form and more on the masterful manipulation of light for the form's human occupants? It certainly could if we learn some of nature's tricks from the spookfish and the clusterwink snail (not forgetting the bastard hogberry).

We know now far more about the effects of light on human well-being and circadian rhythms than we did when Le Corbusier was writing and there is scope for much greater ingenuity in the way we design for light in buildings. Light acts in three ways on humans: as radiation, through our visual system and on our circadian system.[159] If we focus only on how light operates through our immediate visual perception, then we risk overlooking crucial aspects of light. Some projects have gone to great lengths to design artificial lighting that varies in colour over the course of a day in order to align with human circadian rhythms. Conceptually, a more straightforward approach would be to simply make greater use of daylight. It would also save a colossal amount of energy. In the US, 24 per cent of the electricity consumed in buildings is used for artificial lighting, even though daylight provides ideal colour rendering and wavelengths that are physiologically and psychologically better for the occupants. Controlling light in buildings is often handled by completely distinct systems: clear glass to admit the light, sometimes active elements, such as louvres, to control sunlight and passive elements, such as light shelves, to bounce light deeper into the building. Active systems on the outside of buildings can present maintenance problems and passive systems, by their nature, do not respond to the dynamic characteristics of daylight.

Returning to the common concern of bringing light to the human visual system in buildings, biomimicry can offer a plethora of solutions. Considering light also includes considering colour: nature often resolves these two aspects together. There is extensive work under way to unlock the secrets of how biological organisms have evolved to manage light in various ways – gathering, distributing, focusing, diffusing, reflecting and refracting. There is a huge gulf between what technology can currently deliver and what an organism like a squid can do. For example, coloured finishes often involve toxic pigments and generally deliver results that are nowhere near as striking as colour effects like peacock feathers or butterfly wings. But this can inspire us to innovate better solutions. Increasingly, this knowledge will deliver breakthroughs in architecture, allowing us to create buildings that are healthier for people, use less energy and, one day, put on displays worthy of a peacock.

Gathering and focusing light

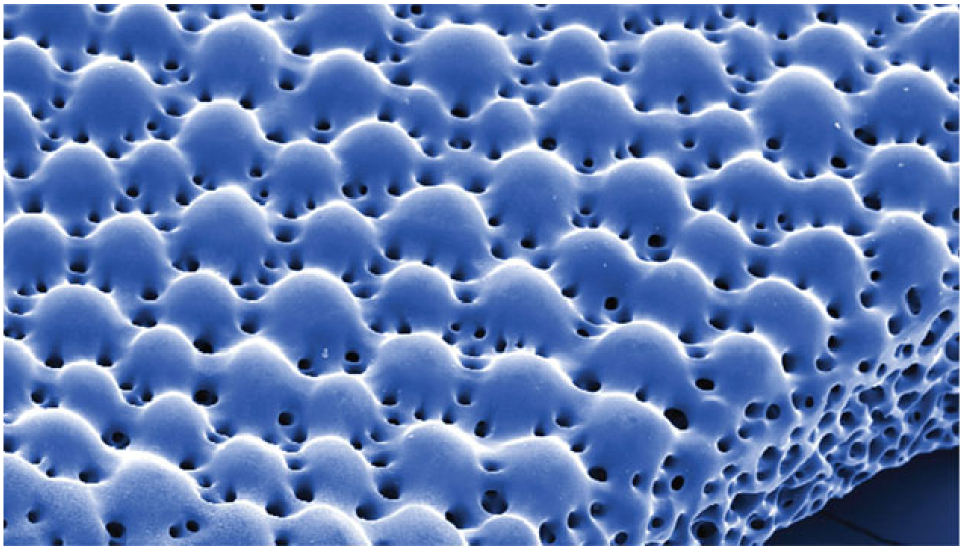
A building's skin acts as armour, as the moderator of light, and sometimes skin can also be structure. Can we consider merging these roles, detailing them with the strategies seen in nature? Brittlestars, such as *Ophiocoma wendtii*, have a covering of calcite crystals that function as effective armour as well as near optically perfect lenses (fig. 126). These focus light onto receptors below, so that the whole body works like a compound eye. Additionally, the brittlestars are able to control the amount of light coming in by means of chromatophores (pigment-filled cells) and adaptively tune the focusing of the lenses.[160] Could we create facades with an equivalent level of sophistication – controlling the amount of light entering the building and even redirecting the light to penetrate deeper into the occupied spaces?

It is often organisms that live in the lowest light conditions that demonstrate the most interesting adaptations, and provide inspiration for architecture. The rainforest plant *Anthurium warocqueanum* has evolved a covering of cells whose diameter, shapes and spatial layout create lenses over its leaf surfaces, which appear to be able to concentrate diffuse light onto a group of chloroplasts, aligned at the point of highest concentration. This strategy ameliorates the basic disadvantage of its growth habit: it receives no direct light because it lives near the forest floor, under the shadow of the dense canopy above.

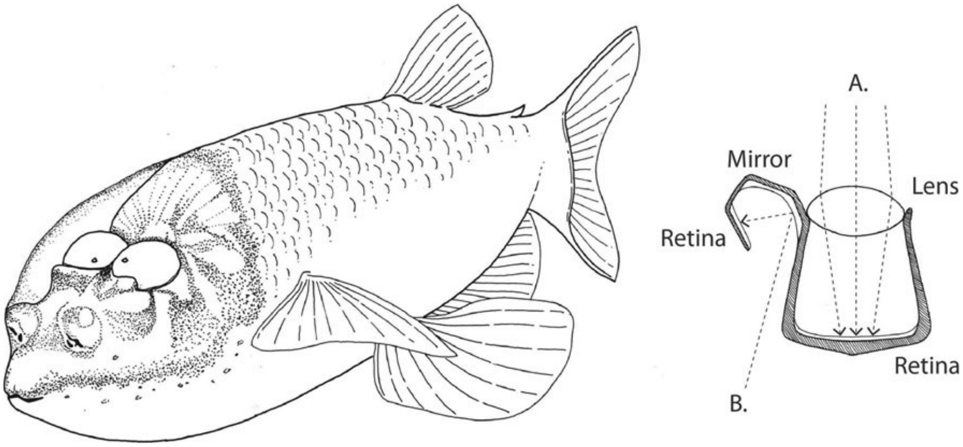
Another solution is evident in giant clams. They have a dull-coloured shell and dazzling iridescent 'lips' that point upwards. The iridescence comes from cells called iridocytes, which reflect non-useful wavelengths of light and accurately distribute the useful light onto vertically arranged columns of microalgae.[161] The algae exist symbiotically and photosynthesise to produce nutrition for the clam, representing a significant part of the mollusc's energy budget. Looking for symbiotic lighting solutions, where crossovers between systems improve the overall performance, is a suggestive starting point.

Spookfish (*Opisthoproctidae*) split the problem of dealing with different types of light, with 'diverticular' eyes (fig. 127). These specialised, bizarre creatures seem unique: their heads resemble the transparent cockpit of a submarine designed by Tin Tin's Professor Calculus and they are the only vertebrate known to use a mirror to focus images. Each eye is split into two connected parts: one part pointing upwards towards daylight and one part pointing downwards, with a mirror to focus the lower intensity light coming from bioluminescence.[162]

Both *Anthurium warocqueanum* and the spookfish were sources of inspiration for Exploration and Julian Vincent when working on the Biomimetic Office. One of the aims was to make the building fully naturally lit – partly to reduce energy consumption but mainly for the well-being benefits offered to the occupants.



126. The brittlestar has evolved near optically perfect lenses over its skin, which function like a compound eye



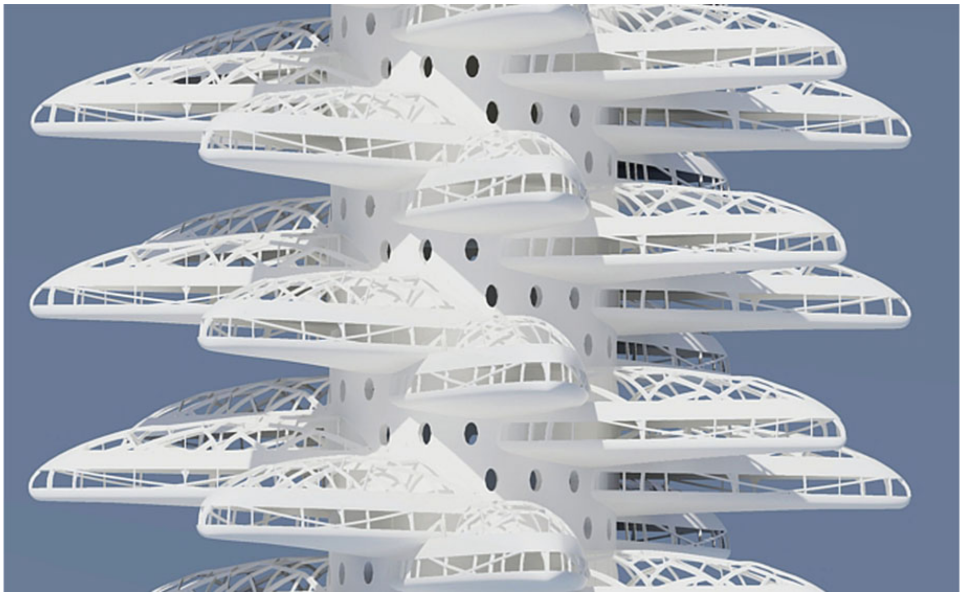
127. The spookfish with diverticular eyes – who the heck designed that?

128. The Biomimetic Office by Exploration – inspired by a wide range of light-gathering examples in biology

The building was designed to ensure that every inhabitable part of the office floors was within 6 m of the nearest windows. This optimisation also included stair/lift/WC cores and a desire for full-width spaces, that are considered essential to allow larger clusters of people to work in creative groups. The glazing system optimised light transmission and minimised heat transfer by using transparent insulation above and below those parts of the window needed to provide views out. This led to a new form of glazing, using very thin curved panes that could deliver a 50 per cent material saving in glass. The most difficult challenge was how to get natural light into the lower floors. *Anthurium* led to the idea of lenses on the roof that could concentrate diffuse light into fibre optic tubes so that daylight could be conducted around the building to where it was needed – much like any other service. There are some products similar to this already on the market, but they all depend on the parallel rays of direct sunlight for their focusing.

This is less appealing because, when there is direct sunlight, general illuminance levels are higher and getting light into the building is less of a problem – *Anthurium* offers the more interesting prospect of gathering light in diffuse conditions. The idea is now progressing as an independent research project. The spookfish led to the idea of incorporating a symmetrical pair of large-scale mirrors in the atrium to reflect light into the ground-floor and first-floor levels. The space under the mirrors presented an opportunity to create a dramatic auditorium that would add value to the building (fig. 128).

Minimising self-shading



129. Phyllotactic tower by Saleh Masoumi, based on the geometry of plants, which optimises access to light by minimising self-shading between leaves

A simple principle seen in plants, phyllotactic geometry (see Chapter 1), has been used to develop a building whose entire form is designed to harness light in a truly profound way. The repeating spiral, whose ratio is normally based on the Fibonacci sequence, has been used to great effect by architect

Saleh Masoumi. He proposes phyllotactic towers, which meet the natural human desire for a private garden space for each home, and also maximise the possible solar gain, which could be harvested for energy (fig. 129). The phyllotactic arrangement means that, as in plants, each unit shades the other units from light and air to the minimum possible extent. Light, air and private outside space are crucial human requirements in high-density housing design and it could be that biology's equivalent solutions could inspire very valuable innovations in this area.

Creating light and colour effects

Turning to how nature creates light and colour, the irrepressible glass sponge features again, in reliably spectacular form. Towards the base, the sponge has a large number of long fibres that anchor it to the sea bed. Many of these are fibre optic tubes (grown at ambient temperature and pressure) with optical quality comparable to, and much greater flexibility than, the relatively fragile human-made versions (manufactured with high temperatures).[163] Some of the tubes terminate in the sea bed with a prong structure comprising an array of lenses. The glass sponge has evolved a symbiotic relationship with a mating pair of bioluminescent shrimp that remain trapped within the structure for their whole life[164] and it is speculated that the glass fibres either transmit light from the shrimp out into their surroundings or light from bioluminescent bacteria in the sea bed up the structure of the sponge. Whichever version is correct, it is thought likely that the lighting scheme attracts food for the shrimp (they can't exactly go foraging) and that the glass sponge benefits from the leftovers.[165] The glass sponge is a paragon for architects to aspire to in terms of structural, material and lighting sophistication.

Bioluminescence (the production of light by living organisms) is found in a large number of marine organisms, certain fungi, some bacteria and terrestrial animals such as fireflies. The last of these has already resulted in improvements to the design of light-emitting diodes (LEDs).[166] The clusterwink snail (*Hinea brasiliana*) produces bright flashes of light, which are amplified and diffused throughout its protective shell.[167] This could inspire the design of structural elements that also diffuse light, or simply more effective light fittings. There is intense speculation about the potential for synthetic biology to engineer bioluminescent organisms into elements of the built environment. This intriguing proposition may be challenged by the relatively very low levels of illuminance generated from bioluminescent organisms – spectacular in an otherwise pitch-black ocean but which would be virtually invisible in an averagely well-lit contemporary city.

Adaptive or stable structural colour

Cephalopods, such as squid and octopuses, extend their exceptional light manipulation attributes with shape-shifting camouflage.[168] Biologist Tamsin Woolley-Barker observes that 'octopuses not only have a centralised light perception system (the extraordinary cephalopod eye), but they also have a decentralised system of light sensors distributed throughout the skin. The entire body of the squid is, in fact, a series of cameras, sensing light from every direction. The combination of powerful eyes and distributed light sensors allows the octopus to detect and match its background completely.'[169] Cephalopod skin contains a range of cells that manipulate ambient light passively, requiring much less energy than actively producing light. It is this characteristic that could lead to new forms of display screen that could cover the whole facade of a building and still use very little energy. Conceivably, buildings could dynamically blend into their surroundings as the colour of the light changes over the course of a day, and as the plants change over the course of a year.

Many striking colour effects in biology are examples of structural colour. Whereas most of the colour in synthetic surfaces is the result of reflection from pigmented material, structural colour is produced by the diffraction of different wavelengths of light from a nanosurface.[170] Nanosurfaces in nature show both structural hierarchy and 3D spatial arrangements at a scale smaller than an atom. While the practicalities of creating a biomimetic nanosurface are challenging, the prize is a much more dynamic colour effect with little or no energy and no pigments. To address the practicalities, self-assembly techniques have been successfully trialled[171] by the biomimetic research group led by Professor Aizenberg to create nanostructures that resemble the architecture of the bright-green wing scales of the butterfly, *Parides sesostris*. They have also been inspired by the bastard hogberry's fruit, with its dazzling colour effects. How this species got its name remains something of a mystery, since its Latinate name (*Margaritaria nobilis*) translates as 'noble pearl'. What has been demystified is how to replicate its colour effects. Its iridescent blue is the result of a multiple layered cylindrical structure within each cell on the surface. This nanostructure produces light interference patterns, resulting in the reflection of vibrant (mainly) blue light. The scientists have managed to produce a fibre based on the maligned berry that changes colour when stretched, displaying all the colours of the rainbow.[172]

Integrated approaches

The skins of biological organisms are directly analogous to the external walls of buildings: both perform multiple functions. The key challenge, I would argue, is to learn from the levels of integration and performance that can be seen in biological examples and combine that with the best that human ingenuity can deliver.

Two different integrated biomimetic approaches are currently being explored by a multi-disciplinary team involving the Harvard Graduate School of Design and the Wyss Institute for Biologically Inspired Engineering. The first proposal, put simply, is to combine all the required functional performance within a single glazed unit.[173] The Dynamic Daylight Control System (DDCS) combines millimetre-scale transparent light reflectors, that can be moved according to the sun's angle, and the channels between them, through which fluid can be passed to reduce heat transfer (fig. 130). The light reflectors are made from flexible, transparent polydimethylsiloxane (PDMS), bonded to outer sheets of clear material so that, by moving the sheets relative to each other, all the reflectors move elastically – an elegant solution with minimal mechanical movement. Furthermore, the fluid can be controlled, such that it can be completely clear when desired or pigmented to reduce light transmission. The biological inspiration came from a profound understanding of how light is controlled in biology and from the way that blood vessels can transfer heat to, or away from, skin.[174] Prototypes have demonstrated impressive results: reduced glare, improved light penetration, reduced heat transfer and, by matching the refractive indexes, the reflectors are almost indistinguishable from the fluid.

The second solution, now in development, also by the Wyss/Harvard team,[175] pursues another strategy for adaptively tuning light and temperature simultaneously, and is also based on human vasculature and on the idea of adjustable optical properties seen in nature. But this solution utilises microfluidics for its operation. A clear microfluidic silicone skin, layered onto glass, can heat or cool the interior temperature according to how much fluid fills its microscopic channels. Astonishing ongoing developments show that this technology can be applied not only to window glass but also to solar photovoltaic panels. On windows, the thermal benefits do not affect the visual openness of the glass, something that is also important for solar panels, for operational rather than visual reasons: the sun needs to reach the panel, yet lowering the temperature makes the panel far more efficient at producing energy. From an architect's perspective, it is important that the glass can appear perfectly clear, or its aesthetics can be altered by changing the properties of the fluid: particularly colour or reflectance.

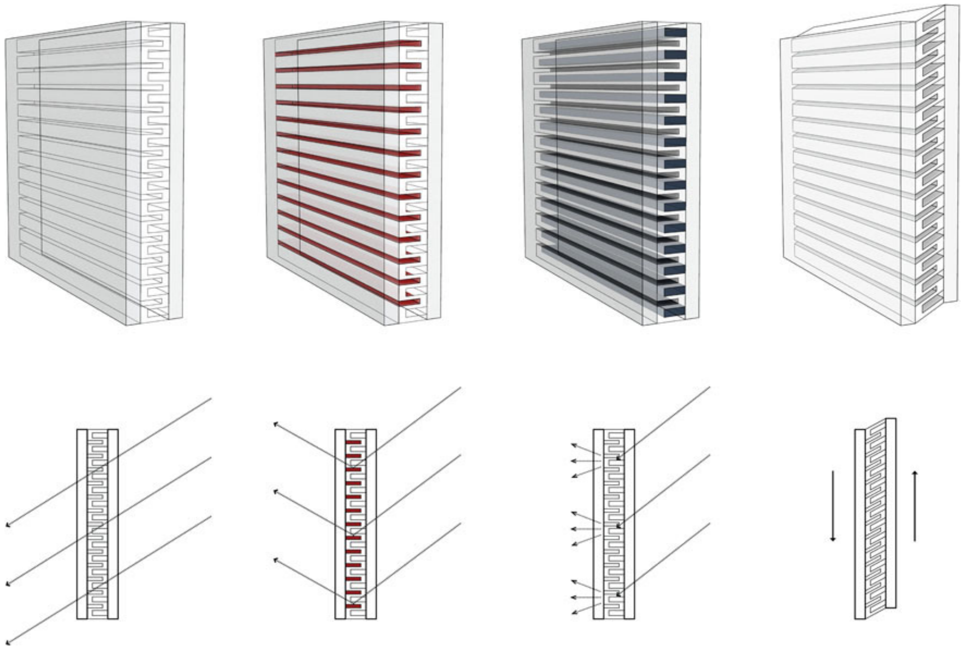
A similar research project at a whole-building scale, led by Maria Paz Gutierrez at the University of California, Berkeley Department of Architecture, aims to integrate not just light control but also temperature and humidity control. The Self-Activated Building Envelope Regulation System (SABERS) project studies how to incorporate optical and hygrothermal sensor and actuator networks into a thin membrane. Gutierrez's team have successfully experimented with 'pores' made from elastomeric material that can swell, providing more insulation, as temperature decreases. The intention is that the pores will also contain lenses that control light – reducing transmission as external light intensity increases and vice versa.

Conclusions

Light affects humans profoundly and, since so many people spend most of their time indoors, how buildings handle light has a direct influence on health and well-being. But the ability of the skin of a building to address not only the handling of light but the climate, the air and many other qualities is the central message in this chapter, as it is in Chapter 5 on thermoregulation. Ultimately, the skins of our buildings will need to integrate all these functions.

As well as considering the building's skin, we have examined both the microscopic and the whole-building scales. Burgeoning research into the light-emitting and biosensing possibilities of bacteria encourage us to think of architecture in ecosystem terms, as do projects at the scale of buildings designed around light and around quality for inhabitants. The Biomimetic Office translated biomimicry ideas, such as the mirrored eyes of the spookfish, directly into architectural form. Other avenues, like the focusing lenses of *Anthurium warocqueanum*, hold promise for future research and development.

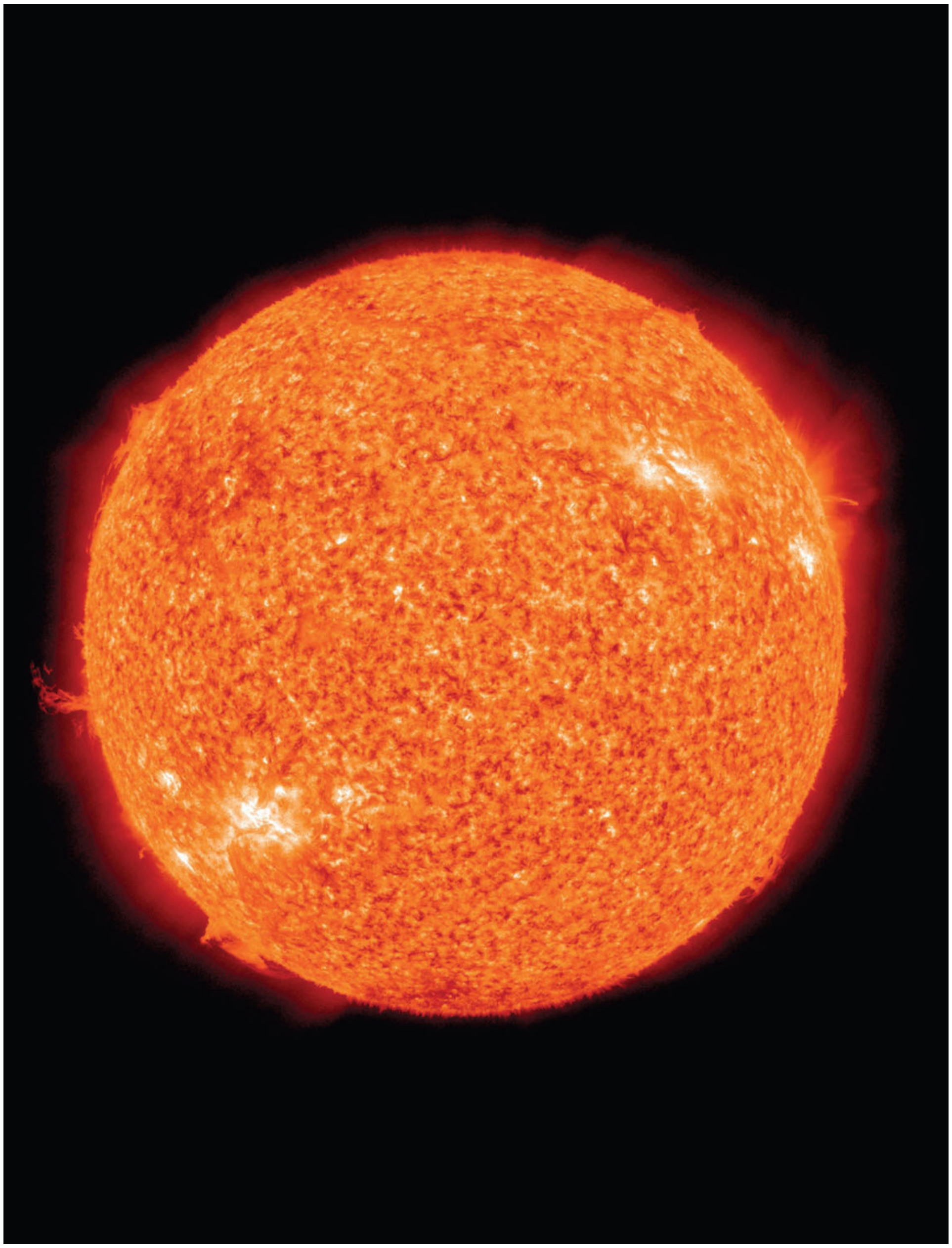
The active academic research communities whose projects have been explored here show enormous promise. In many cases, this foundational work extends to working prototypes, improving the chances and speeding up the process of turning these ideas into products that can be incorporated into buildings. As with all the biological examples we have studied, the evolved adaptations demonstrate what is possible and serve as an inspiring destination to aim for.



130. Dynamic Daylight Control System (DDCS) developed by the Harvard Graduate School of Design and the Wyss Institute for Biologically Inspired Engineering

Chapter Seven

How will we power our buildings?



131. The energy received from the sun every year represents approximately 10,000 times as much as our total annual energy use

Humans tend to tackle problems head-on whereas living organisms, through the process of evolution, have tended to change a problem before resolving it. Nowhere is this more apparent than in the realm of energy. We have generally tried to meet our perceived needs by just creating more and more energy rather than thinking about how we could develop solutions that, just as in nature, need far less energy in the first place.

Energy is one of our greatest challenges, partly due to the increasingly urgent realities of climate change and partly due to a failure of strategic planning. How will we decarbonise our economies over the course of the next few decades? What will this imply for designing buildings and cities?

Energy needs include and exceed the scale of buildings, so this chapter explores how architecture fits into the idea of energy planning. I argue that applying biomimetic principles to energy planning inevitably leads to the solar economy as a critical goal. This has significant implications for architects and urban designers. A 'solar economy' is one in which all our energy needs are met with renewable forms of generation.[176] This shift is of critical importance. It is essential to focus on energy used in buildings, but ignoring where that energy comes from would neglect the benefits that biomimicry can offer. Energy, biomimicry and the built environment will be a crucial part of the bigger transformation to an ecological age.

Ideas about waste and ecosystems thinking are relevant here. The same contrast between human-made systems and biology (Chapters 2 and 3) would suggest four principles for a biomimicry solution to energy:

- demand reduction through radical increases in efficiency as the first priority
- a source of energy that will last indefinitely
- resilience through diversity and distributed networks
- resource flows that are non-toxic and compatible with a wide range of other systems.

Buildings are the front line for demand reduction: itself the first step towards a solar economy. The massive gains that can be made from all the resource-efficient innovations we have seen in previous chapters make improving buildings crucial, as they apply at such scale yet can be implemented by small groups of people. The other three principles underpin larger-scale schemes in masterplanning and urban design, informing the kinds of technologies that are suitable and how they should be integrated. Biomimicry has also been used to design better renewable energy technologies, learning from humpback whales, razor clams and palm trees.

Energy source

Turning first to the most contentious principle: where should our energy come from? If we look at the flows of energy in nature, we find that biological organisms run entirely on current solar income.[177] Could we do the same and transform from a fossil-fuel global economy into a solar economy, rather than a nuclear one? Some might scoff at such an idea, but if one looks at the amount of solar energy available, the possibilities come into perspective.[178] The energy received from the sun every year represents approximately 10,000 times as much as we currently use.[179] This bountiful source of energy has sustained life on earth for billions of years and could supply all of our needs indefinitely. A nuclear-powered future is not our only option.[180] For example, building concentrated solar power plants over roughly 5 per cent of the world's deserts would be enough to provide all of our energy needs.[181]

A solar economy is one that is powered entirely by forms of renewable energy:

- direct solar energy: principally photovoltaics and concentrated solar power
- indirect solar energy: wind, wave and biomass
- related natural-source: tidal and geothermal energy.[182]

These are the principles advocated for here and the rest of this chapter argues the case for this approach.

Resilience

The need for resilience, which is ‘the capacity of any entity … to prepare for disruptions, to recover from shocks and stresses, and to adapt and grow from a disruptive experience’ (see Chapter 3), also applies to energy generation. In nature, systems have evolved resilience through complex interconnected networks and a high degree of diversity, such that critical ecosystem functions can be delivered by a number of organisms. For human energy needs, resilience takes two forms: first, a resilient system would provide the required quantities of energy from a diversity of interconnected generation forms; second, the system would store energy in quantities sufficient to cover any variability inherent in the energy source. Additionally, any system must address the centralisation versus local generation question.

The solar economy starts with the benefit of a constant stream of photons from the sun. The energy available takes predictable forms: between day and night, seasonal variations, the tides and wind patterns. Biological organisms have had to adapt to these same conditions, and all store energy: plants generally store it as sugar, animals as fat. In engineering, the common solutions to variability in power sources are batteries and pumped storage schemes (which pump water from a low-level lake to a high-level one so that it can be released through turbines when required[183]).

The other way in which nature manages fluctuations in energy supply is by simply doing more growing or metabolising when there is energy available, and less when there isn’t. We can apply the same principles by using smart controls that switch equipment off during short-term peaks or varying the cost of electricity to redistribute demand. A good example of this technology is Encycle, which was inspired by ‘swarm logic’. Swarm logic is the way that some systems achieve emergent properties, in which a relatively simple set of rules can result in complex behaviour (similar to that seen in social insects, such as bees and termites). Encycle uses inter-communicating controls on each piece of electrical equipment in a building that ‘cooperate’ to reduce peak loads and increase efficiency. The physicist David MacKay has shown that a combination of managing demand, pumped storage and batteries in stationary electric vehicles (assuming most transport is electrified) would be sufficient to deal with the fluctuations that would arise from a solar economy.

The energy sources for both nuclear (massively centralised large-output stations) and fossil-fuel generation (centralised but in smaller plants) are problematic. Fossil fuel consumption contributes to dangerous climate change and nuclear plants are heavily, although not exclusively, dependent on high-grade uranium, which is only found in a few countries. In resilience terms, a nuclear fission-only energy strategy would create significant geo-political risks: one major incident could conceivably knock out a substantial part of a country's generating capacity. From a systems perspective, much greater resilience can be achieved by a more distributed, diverse and fully interconnected network of energy generation.

To move towards a resilient solar economy, energy transmission is essential for countries where solar potential is insufficient to meet demand. It is now theoretically possible to transmit energy as high-voltage direct current (HVDC) from solar power plants in North Africa to the UK with about the same losses as conventional AC grids. The advantage of a super-grid is that a number of countries with diverse energy sources can be interconnected, and the diversity of generation and storage forms makes it easier to balance the quantity and timing of output. Such interconnection raises the need for negotiation and fair exchange to create a solar economy: one country does not have an automatic right to energy from another. Some of the countries that have the highest levels of solar energy are less politically stable and pundits might raise related geopolitical concerns. Paradoxically, this is where something that is commonly seen as a problem – energy storage – could prove to be a big advantage. The value of the energy, and the fact that it is difficult to store for longer than a few days, means that there would be great financial incentives for countries with huge solar resources to be consistent providers of solar power and very little to be gained from doing the opposite. The solar economy could therefore contribute to long-term job creation and stability.

What is the role of local production and storage in the solar economy? Can local strategies, particularly local generation, have an impact? Consider mobile phones: trivial in number 20 years ago and more than 3 billion now in use. Mobile phones could help to deliver more localised management of renewable energy production and consumption. This technology is promising and its scale in the future may surprise us. In the same way that many developing nations leapfrogged wired landlines to take up mobile phones as the more economic and effective solution, those nations – with plentiful, renewable energy available – may succeed in the solar energy revolution without the expense of building national grids.

System compatibility

Elements of any biomimetic system should be compatible with a wide range of other systems in terms of their local interaction and resource flows. An element that produces long-term toxins would be a clear case of incompatibility.

The resource flows in most renewable energy technologies are very straightforward. In some cases, heat is captured from the sun or a geothermal source to drive a thermal engine; in other cases, kinetic energy from the wind, ocean currents or waves is used to drive a generator. While there are some toxins involved in manufacturing renewable energy technology, the energy is produced without the release of any toxins and, in many cases, renewable energy installations deliver substantial benefits.

Regarding local interaction, a recent scientific study concluded that the bases of offshore wind turbines create new habitats for crustaceans and plants, which can significantly boost numbers of fish.[184] This effect was achieved without any deliberate intention, and consequently could be enhanced by designing bases to incorporate features that promote biological colonisation. The suggestion made above, when discussing Biorock, could push this restorative effect even further by growing the foundations and creating artificial reefs. Then windfarms in coastal waters could function as marine nature reserves as well as energy generators.

Photovoltaic (PV) solar farms and concentrated solar power (CSP) installations will generally be located, for obvious reasons, in regions with high levels of solar intensity, and an intriguing benefit arises. By reducing the amount of direct sunlight that falls on the ground beneath, it makes it possible to grow a range of plants that would not normally survive in the open because of thermal stress and water loss. Grazing animals also benefit from the shade as, in most cases, their natural habitats would have included partial tree cover and they, in turn, can build the fertility of the soil. Photovoltaics offer the potential for the skins of buildings to become much closer to the photosynthetic surfaces of plants – harvesting energy from the sun so that human-made structures could shift from being static consumers of energy to net producers of useful resources. At a simpler level, PVs and CSP could provide dual benefits by shading buildings as well as generating energy. Floating PV systems are now being installed on reservoirs; an approach that reduces land-take as well as reducing evaporative losses.

Cultivating algae for biofuels is still in the early stages of development and many experiments to date have proved to be uneconomic. However, the potential exists for biofuel production to offer valuable by-products. As discussed in Chapter 2 on materials, cellulose can be extracted from algae for use in rapid manufacturing of low-energy materials. Algae cultivation could well prove to be the most effective way of reversing the loss of nutrients from the world's soils – helping to extract minerals from seawater to create micronutrients for human consumption and fertilisers for agriculture. Taking both these secondary benefits into account could make biofuel production far more economically attractive. It is possible that algae production could eventually be deployed on the facades of buildings to provide solar shading and carbon dioxide absorption, but currently the economic viability of this is a long way off.

Demand reduction

Designers can act most directly with regard to demand reduction. The international consulting firm McKinsey's renowned and frequently updated study 'Pathways to a Low Carbon Economy' concludes that **many of the biggest and easiest reductions in greenhouse gas emissions can be found in the built environment**.[185] This applies regardless of whether we pursue a nuclear future or a solar-powered future, because most energy-efficiency improvements are cheaper than adding new generating capacity. The fastest and cheapest path to cutting greenhouse gas emissions, the report states, is a step-change in the energy performance of buildings, and then to supply all remaining needs from low- or zero-carbon sources.

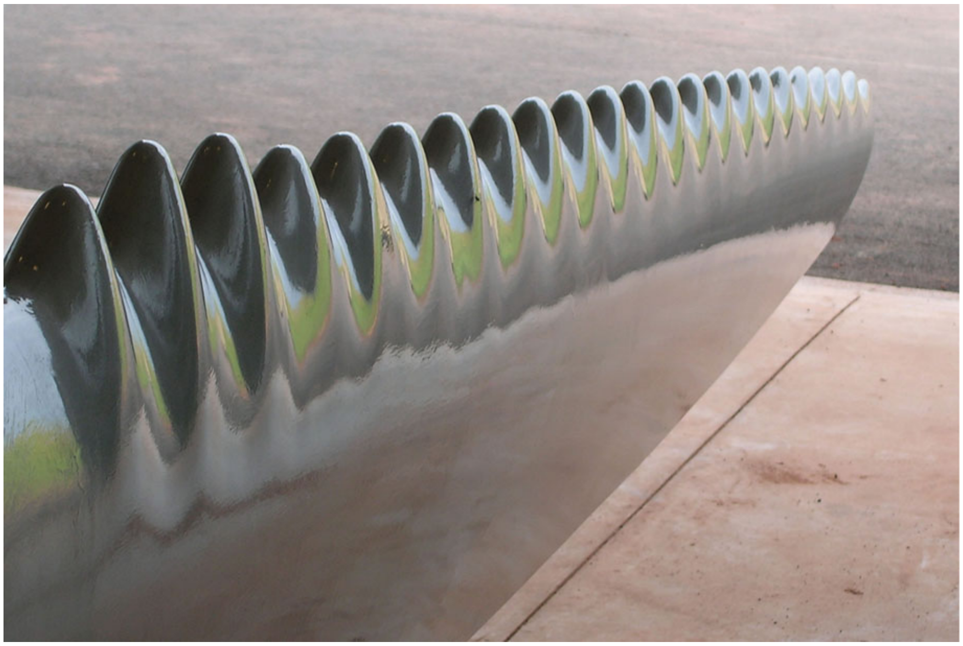
What levels of energy saving are realistically achievable? Using only current technologies and maintaining or improving the average European's quality of life, David MacKay[186] shows that we could reduce our energy demands from 125 kWh per day per person (kWh/d/p) down to 68. Many of these savings involve the built environment.

Demand reduction is one area where biomimicry offers huge potential to realistically reduce this number further. We have seen numerous examples of factor-10 and factor-100 savings in resource use – delivering the same function with a fraction of the resource input. Making materials with a hundredth of the embodied energy of conventional ones and then shaping these into biomimetic, highly efficient structures could deliver the levels of resource efficiency seen in spiders' webs, bird skulls and glass sponges.

Similarly, if we could steward all of our resources in closed loops, design out the whole concept of waste and create buildings that passively thermoregulate, then we could achieve really radical reductions in energy use. Every unit of energy saved will make the overall task of decarbonising our economy easier. All of this innovation is within human and architectural capabilities.

Biomimetic technologies

Biomimicry has been applied to the design of a number of renewable-energy technologies and has delivered similar improvements to those we have seen for building technologies. For instance, a new form of wind-turbine blade, developed by a marine biologist with the engaging name of Dr Frank Fish, was inspired by the tubercles on the flippers of humpback whales (fig. 132). These lumps on the front of the fins induce vortices which create more lift and allow the whale to maintain manoeuvrability at low speeds.[187] Dr Fish's new wind turbine blade incorporates the same idea to produce a wind turbine that will maintain operation at slow speeds. The reason this is of radical importance is that all wind turbines have a minimum speed of operation, below which they will stop turning and only start again once the wind speed has picked up enough to overcome inertia of the turbine. The developers, Whalepower Limited, claim that the blades can improve output by 20 per cent over a year and result in quieter operation.



132. Wind turbine blades that mimic whale tubercles in order to maintain energy generation in lower wind speeds

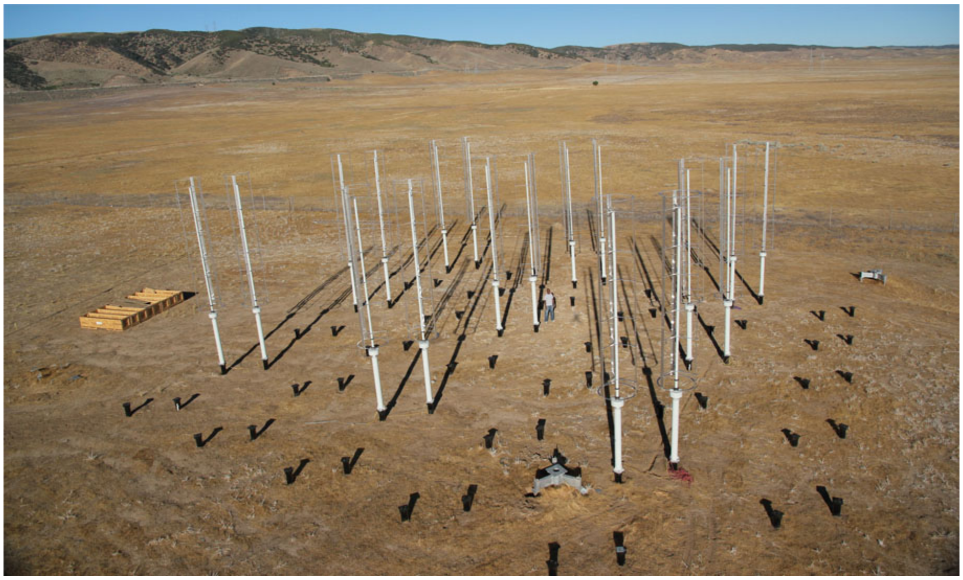
Further solutions from biomimicry could help to address the opposite problem – excessive wind speed, during which less advanced wind turbines are generally taken out of operation with automatic braking systems to prevent damage. Many leaves, for instance, change orientation or roll up in high winds to minimise wind loading on the trunk of the tree.[188] Most new, large-scale wind turbines now have computer-controlled systems that adjust the angle of the blades and, in time, they may be designed to flex either laterally or longitudinally under wind loading, as self-regulating structures, to present less resistance to the wind.

Clearly, this means that a smaller proportion of the available energy would be captured in very strong winds, but the big advantage is that the turbine could keep operating in these conditions. A team in the US recently announced just such a proposal: to develop a turbine, inspired by the way palm trees are swept in the direction of hurricane-force winds to reduce resistance, with blades that bend.[189] The scheme is aiming for the astonishing scale of 50 MW with 200 m long blades, compared to the largest wind turbines currently on the market at an already impressive 8 MW with 80 m long blades. This exemplifies one of the key differences between living organisms and engineering (the former are environmentally responsive while the latter tends not to be) and what can be achieved by following examples from nature.

Scientists at the California Institute of Technology have researched the way that fish swimming in shoals have evolved to optimise the use of vortices created by other fish in front of them.[190] They then applied the same principles to a field trial of vertical-axis wind turbines and found that far more energy per unit of land area can be extracted from the wind (figs 133 & 134).[191]

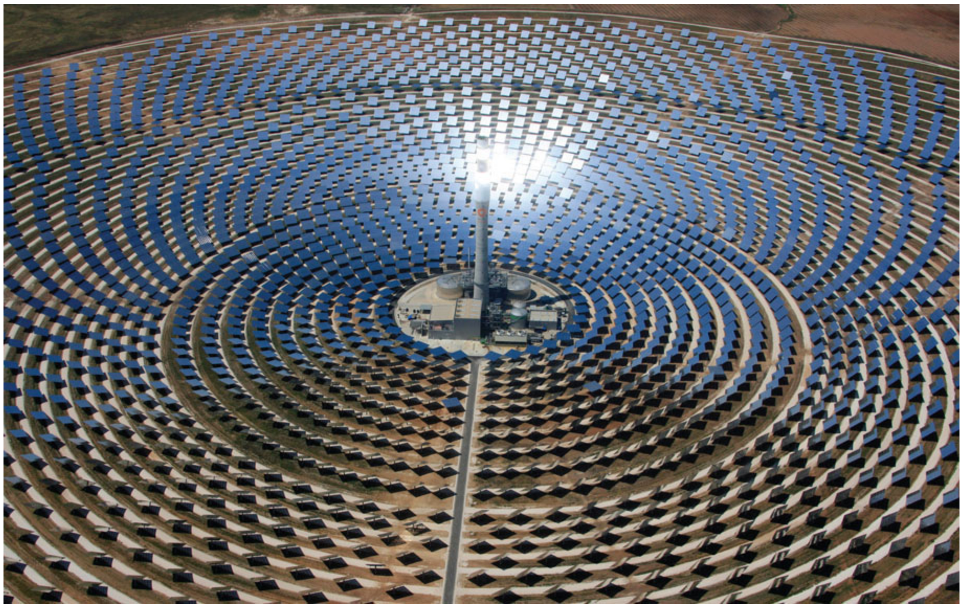
133. Shoaling fish swim in formations that optimise the use of eddy currents

Offshore locations are often favoured for large-scale wind turbines because of the favourable wind conditions, but the installation of the bases represents a major headache for the industry. Recently, a new approach has been adopted that appears to have been inspired by the elegant way that razor clams bury themselves in the sea bed. The clam sucks water into the region immediately under it, which turns the sand into a thixotropic liquid so that it sinks in rapidly, with no undignified scrabbling. The 'suction bucket' foundation for wind turbines works the same way – the upturned bucket-like base is lowered onto the sea bed, then water is pumped out of the top, which draws water and sand in underneath, causing the wind turbine base to steadily 'suck' its way into the sea bed. The technique could potentially be improved by vibrating the bucket as the razor clam does its shell to aid liquefaction of the surrounding sand.



134. Scientists at the California Institute of Technology have applied the same 'shoaling principle' to the spacing of vertical wind turbines and demonstrated a substantial increase in energy generation

Solar technologies have benefitted from biomimetic breakthroughs in lenses and geometrically optimised layouts for mirrors based on sunflowers that increase efficiency and reduce land area requirements (fig. 135).[192] It is highly likely that biomimicry will be used in the near future to solve other challenges, such as self-cleaning surfaces and perhaps scratch-proof coatings for mirrors based on the sand skink, which can swim through sand without suffering abrasions.[193] Artificial photosynthesis is another area of intensive research focus and this will almost certainly lead to further breakthroughs in solar technology.[194]



135. Concentrated solar power (CSP) mirrors laid out with phyllotactic geometry to optimise energy generation. (Gemasolar solar thermal plant, owned by Torresol Energy ©SENER)

Biomimetic windows, which make areas of a building facade into something more closely resembling a leaf or a forest, as they process sunlight from the whole surface area, are an increasingly realistic possibility.[195] The potential of a truly clear solar-energy window has such a broad and large-scale application that it promises the kind of resource gain to be seen if we could widely implement biomimetic concrete.

Integrated approaches

The Green Power Island (fig. 136), designed by architects Gottlieb Paludan, is a speculative but highly realistic proposal that integrates a number of renewable energy technologies and energy storage systems in a symbiotic cluster.

The starting point for the scheme is that many forms of renewable energy are variable in terms of their output and that forms of energy storage are needed in order to create a resilient system. The Green Power Island concept overcomes this problem by creating a large reservoir that can be used in the same way: it can be emptied using excess renewable energy and then generate power when required by allowing the sea to flood back in through turbines. The reservoir has a capacity of 22,000,000 m^3, which gives a generating potential of 2.3 GWh – enough to supply electricity to all the households in Copenhagen for 24 hours.

136. Green Power Island: a good example of how we will increasingly see renewable energy systems deployed in clusters to optimise synergies and deliver regenerative benefits

The project shows how effectively and compatibly a number of renewable energy technologies can be integrated. The flat areas of the island surrounding the reservoir provide ideal conditions for locating wind turbines – straightforward foundations and clear access to wind. The area below the turbines can be used for growing biomass or food crops. Within the reservoir a floating array of photovoltaics is proposed, which offers the benefit of simple solar tracking – the panels can move in one plane only so that their inclination follows the altitude angle of the sun while the floating base can rotate to follow the sun's path from east to west. The outer edges of the island provide breeding grounds for seabirds while the sloping boulder walls below sea level effectively create new rocky shoreline. Whereas flat, rocky sea beds often have relatively low levels of biodiversity, rocky shorelines are amongst the richest habitats that can be found, so this scheme could substantially boost biodiversity and help to rebuild fish stocks.

Most of the world's cities are in coastal locations and some have been extended by land reclamation. The Green Power Island could be built adjacent to such areas and, in the longer term, provide useful protection for low-lying urban areas against sea-level rise. In many low-lying coastal areas, the greatest risk of flooding comes from large waves breaking over the sea defences. Tidal lagoons or versions of the Green Power Island positioned offshore in such locations would prevent large waves hitting the shore and potentially obviate the need for the expensive job of raising sea walls. While the scheme illustrated opposite was designed for Denmark, the architects have proposed similar schemes for sites in the US, Bahrain, India and China, with forms of renewable energy best suited to each.

Conclusions

Handled correctly, addressing our energy challenges could drive the greatest wave of innovation that civilisation has ever seen. Any rational approach to cutting greenhouse gas emissions will require radical increases in efficiency as a first step, and innovations in the built environment offer some of the biggest opportunities.

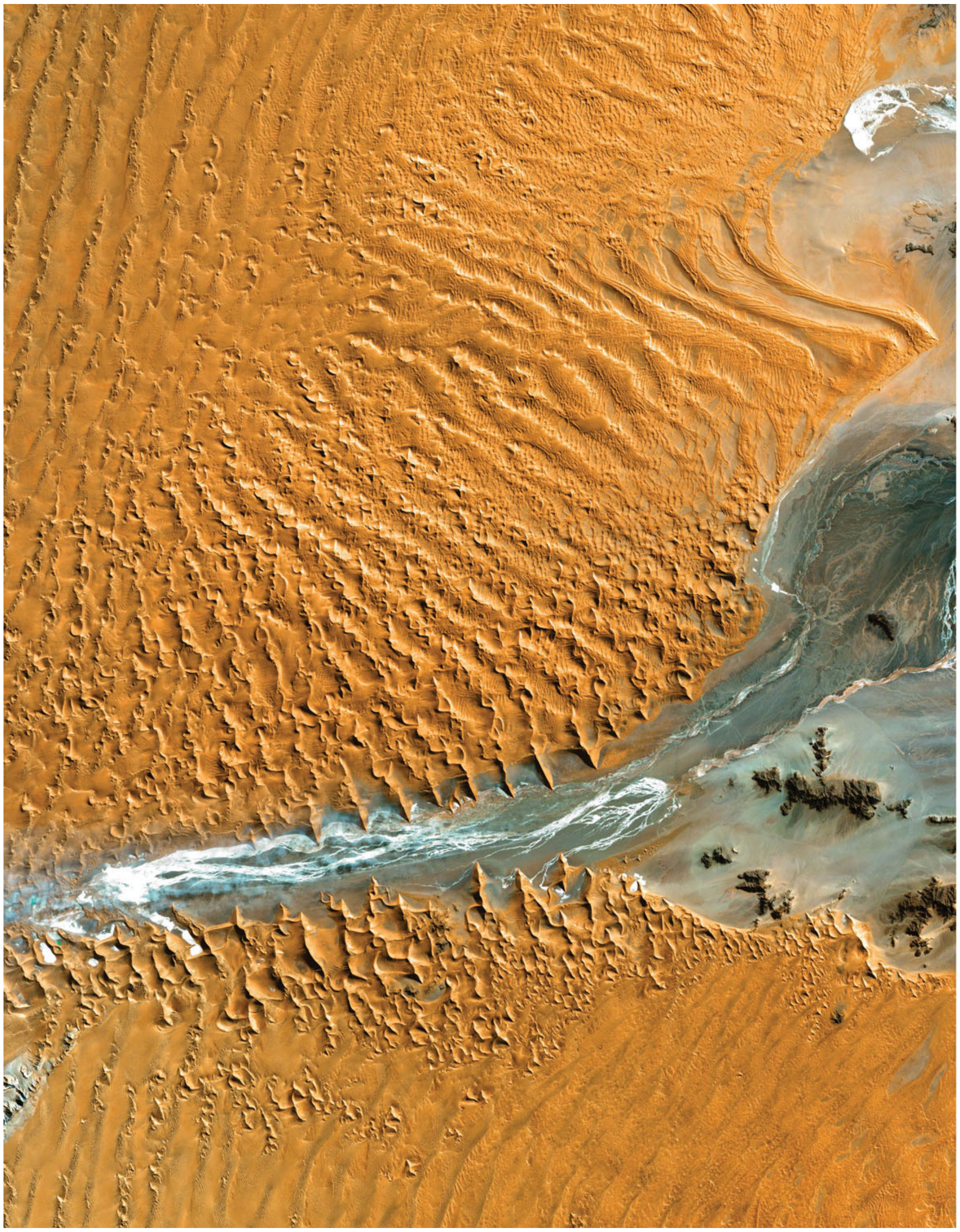
We know from a strategic look at the numbers regarding available energy that it is physically possible to create a solar economy. We also know that there would be major benefits: cleaner air, restored ecosystems with boosted biodiversity and nations connecting to share resources, such that energy becomes an issue that promotes cooperation rather than breeding conflict. A biomimetic solution would be resilient, non-toxic, regenerative and based on an inexhaustible energy source.

Models for a solar economy suggest that we will need roughly 3.6 million wind turbines, 3 billion domestic-sized PV arrays, some large-scale tidal and hydroelectric schemes and about 600,000 km^2 of CSP – all to be built and installed over the next 30 years. These may sound like daunting figures, but they should be compared with some other manufacturing achievements that we have come to accept as perfectly normal. The 3 billion PV arrays could be compared with the 3 billion mobile phones and roughly the same number of personal computers that have come into existence over the past 20 years. Likewise, the quantity of CSP, hydro-electricity and marine renewables could be compared to the 50 million cars that we make every year and the 24.5 million tonnes of new ships produced by the shipbuilding industry every year. Is creating the solar economy really beyond the realm of what modern civilisation has achieved already? The economic viability of this is complicated by a number of factors. We will need to spend large sums anyway on upgrading our creaking grids and power stations. Appropriate investment in research and development, coupled with economies from scaling up manufacturing and deployment of renewable technologies, would radically reduce costs. We also need to consider what costs are externalised from conventional sources of energy (the damage cost of carbon emissions and the cost of oil-related military operations, to name just two) and what benefits are generally overlooked in renewable energy technologies. A full economic assessment would need to take account of all these issues. The obstacles to creating the solar economy are mainly political.

Renewable energy technologies are maturing and coming down in cost at a dramatic rate. I believe we will increasingly see renewable energy in symbiotic clusters – offshore wind turbines with bases that also harvest wave energy and incorporate tidal stream turbines; tidal lagoons with wind turbines on their impoundment walls and wave-energy generation on their seaward sides; CSP installations that also cultivate algae for biofuels and produce methane from waste. If these are to be integrated sensitively into landscapes and cities, then there is a strong case for that being done by architects, engineers and ecologists in collaborative teams. The new infrastructure of the solar economy will present a whole range of design opportunities and we will increasingly see renewables deployed in order to deliver secondary benefits, such as shading buildings and reducing evaporation from reservoirs. Many renewable energy installations will also be regenerative: offshore windfarms with bases that maximise colonisation, tidal lagoons that create new stretches of rocky shoreline and solar installations that help to revegetate deserts.

Although substantial challenges remain, the solar economy is now achievable in practical terms. A vital part of the solution will be solar power installed in the world’s deserts on a massive scale. Also critical to the transformation from fossil fuels to solar energy will be individual buildings and local systems designed to deliver radical increases in resource efficiency.

Chapter Eight
Synthesis



137. It may be hard to believe, but large parts of the world's deserts were vegetated a relatively short time ago. The way we steward water, energy and land in integrated ways over the course of the twenty-first century will have a major bearing on the extent to which our civilisation fails or succeeds

When Peter Smithson was interviewed for the job of running London's Architectural Association in the early 1980s, the idea he pitched to them was as follows. In the first year, the students would redesign the world because when you are 18, you can. In the second year, students would design a city. In the third year, they would design a major public building. In the fourth year, they would design a house, and in the fifth year, they would detail it.[196]

Biomimicry works at all scales of architecture and can even be extended to scales beyond the reach of conventional architecture. It is ultimately a systemic approach. This chapter synthesises, in a way reminiscent of how Smithson structured his teaching, current work in biomimicry applied to a large-scale land reclamation project, eco-cities, a transport terminal, a detail, a company and one of the architectural products that it manufactures and, ultimately, to business more generally. The deliberate breadth intends to convey how widely biomimicry can apply, in design and to the solutions for our common future.

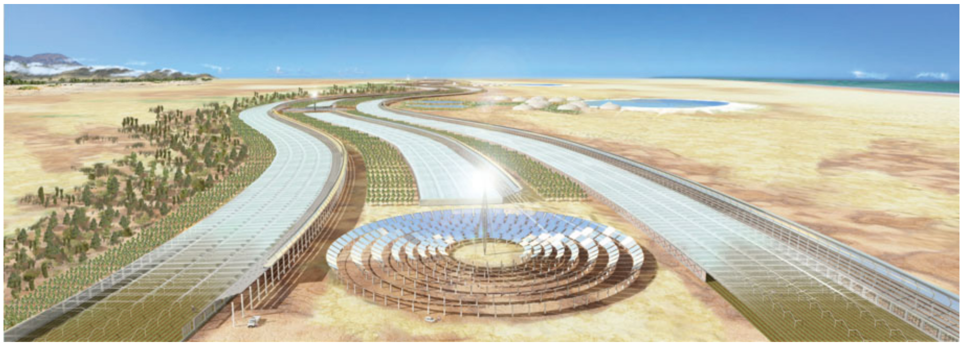
Biomimetic land restoration and energy generation: the Sahara Forest Project

It may surprise some people that many of the world's deserts supported abundant vegetation in recent history. When Julius Caesar arrived in North Africa, what greeted him was a wooded landscape of cedar and cypress trees. Caesar's armies cleared the land to establish farms, and for the next 200 years North Africa supplied the Roman Empire with half a million tonnes of grain a year. Over the years, deforestation, salination and overexploitation of the land took its toll. Productivity dropped and the climate changed.[197] This highly extractive model of land use became the dominant paradigm for the next two millennia.

Promisingly, satellite imagery of global photosynthetic activity shows that the boundaries of growth at the edges of deserts shift back and forth quite dramatically over the course of each year. Can interventions be made at these edges that could halt, or even reverse, desertification? Could biomimetic design create the right conditions?

Often, approaches to environmental challenges tackle individual symptoms, when more could be achieved by addressing the systemic failure. The Sahara Forest Project (SFP) shows how biomimicry can use closed-loop models to address a range of challenges, including creating fresh water, shifting to the solar economy, regenerating land, sequestering carbon in soils, closing nutrient cycles and providing employment to large numbers of people.

Early inspiration for tackling this challenge came from studying the organisms that have already adapted to life in deserts – particularly the Namibian fog-basking beetle (see Chapter 4). The other core biomimicry principle was to combine proven technologies and to explore the potential symbiosis between them.



138. Sahara Forest Project (SFP) – a scheme that integrates horticulture, forms of solar energy and desert revegetation to deliver numerous synergies and secondary benefits

The SFP centres on saltwater-cooled greenhouses in tandem with solar power, together driving desert revegetation through the synergies between these technologies (fig. 138). Together, these components integrate into an ecosystem model (see Chapter 3). Synergistic qualities driving the scheme are based on the way in which these technologies cooperate during operation and also how their waste streams can feed the system, as follows:

- Saltwater-cooled greenhouses and concentrated solar power (CSP) and photovoltaic (PV) systems work well in hot, sunny deserts.
- Saltwater-cooled greenhouses produce demineralised water, which the CSP needs to run the turbines and keep the mirrors clean.
- Greenhouses act as cooling towers for the CSP, shedding excess heat. This makes the CSP as much as 10 per cent more productive in terms of electricity generated.
- A shaded microclimate is created underneath the CSP mirrors and PV panels, making it possible for a range of plants to grow in these new conditions.
- Greenhouses are effective ‘dust scrubbers’, removing particles from the air, which reduces dust build-up on the CSP mirrors and PV panels, so they remain efficient.
- The new outdoor vegetation stabilises soil and reduces dust, so that more sunlight reaches the mirrors of the CSP installation.
- Greenhouses provide a growing and propagation environment for food production.

The Pilot Plant, Qatar

These ideas were put to the test when the SFP team were commissioned to design and build a Pilot Plant (fig. 139) in partnership with two fertiliser companies – Yara International and the Qatar Fertiliser Company. The ecosystem concept of interconnected technologies became the foundation of an even more comprehensive, highly productive system that moves towards zero waste and entirely solar-powered operation. Every underutilised resource was treated as an opportunity to add something to the system that would create more value. The technologies work in a sequence according to the seawater salinity, as follows:[198]

- 4 per cent salinity seawater is supplied to the first three technologies in the sequence: an algae raceway, a pond for growing salt-tolerant plants (halophytes) and a small-scale thermal desalination unit using multi-effect distillation (MED).
- The MED unit (running on high-grade heat from a concentrating solar mirror) produces fresh water to supplement the water produced by the greenhouses. The fresh water is used for crop irrigation and the brine (at 7–8 per cent salinity) from the desalination process goes to cardboard evaporators in the greenhouses. By evaporating more water out of the brine, the greenhouses can be humidified and cooled by up to 15 °C, which creates much better growing conditions for crops in hot, arid regions.

139. The SFP Pilot Plant in Qatar has succeeded in growing crops with half the amount of fresh water of conventional approaches and regenerated biodiversity

- After the evaporation process, the remaining brine is at 12–15 per cent salinity and is piped to external cardboard evaporators. These are located around external growing plots, where further moisture is evaporated from the brine to enhance revegetation.

- After running through the external evaporators, the brine rises to 20–25 per cent salinity and calcium carbonate is deposited on the cardboard. The deposits build up steadily over time and the evaporator can then be replaced with a fresh one and the encrusted one can be used as a lightweight building block.
- The super-concentrated brine then flows to salt ponds, where the sun does the remaining work of drying the brine out to dry salts.
- Waste heat generated during the day from the MED process is stored as hot seawater. The greenhouses have a roof cavity made from two layers of ETFE film, and at night the hot seawater is evaporated into this roof space, where it is condensed as distilled water for irrigation.[199]

Resolving technology synergies

The Pilot Plant was a crucial test-bed for the team to experiment and fine-tune the way in which the technologies were brought together. Issues can be resolved with further biomimetic design thinking.

High night-time humidity in the greenhouse was problematic for the plants. Magnesium chloride, which can be extracted during brine processing, was trialled as a desiccant. Desiccants absorb moisture, reducing the relative humidity in the growing area, and can then be recharged using solar energy during the day.

The sea pipe showed scaling and the design response was: ‘What if we could get the scale to grow on something else and not on the pipe?’ Structural steel wire filigree frameworks, each 2 m long, were made and then ‘grown’ in the salt ponds using Biorock (see Chapter 2). Suspending these frameworks at the inlet of the sea pipe causes calcium carbonate to be deposited on the frames, making the seawater downstream (within the pipe) less alkaline, and thereby reducing or eliminating scale formation in the pipe.

The Biorock structural elements grown in this way become materials to expand the project. Solving these two operational problems using biomimetic and systemic approaches leads to an appealing symmetry: the project grows its own future structural elements.

Regeneration on site

Animal biodiversity was studied by the team for the first nine months of operation.[200] An ecological survey carried out before construction showed that there were negligible levels of biodiversity on site – it was a bare patch of desert. Apart from common flies, the first animals to arrive were house sparrows, which made an appearance the same day that plants were brought to the site. Soon after that, grasshoppers and crickets appeared, and the first butterfly. The variety of birds increased steadily through the course of the project, including wagtails, rufous-tailed shrikes and a hoopoe (an indigenous and colourful bird not seen often in Qatar). When the algae ponds were filled, within a matter of a few days the first dragonfly appeared. There was, briefly, a problem with rats, but this stabilised with the arrival of a feral cat. Subsequently, mouse tracks were found and footprints of the first truly indigenous desert mammal – a jerboa (a hopping, desert rodent, like a tiny kangaroo). This was the effect witnessed in just nine months. Over a longer time period, and if the SFP were to be created at a larger scale, the regenerative design effect would be even more pronounced.

The Pilot Plant succeeded in growing cucumbers throughout the year with 50 per cent of the fresh water used in conventional approaches, while boosting biodiversity and sequestering carbon in various forms (in plant growth, in the soil, in the cardboard evaporators and in the Biorock). It complied with many of the characteristics of ecosystems: densely interconnected, everything is nutrient, no persistent toxins, diverse, run on current solar income, optimised as a whole system and strongly regenerative.

Scaling up: the future

The team completed feasibility studies in Jordan and are about to construct a scheme that is twice the size of the Qatar project. Engineer and founding partner, Bill Watts, is confident that energy consumption can be radically reduced by adopting a simpler approach to fans and pumps. Further experiments will be carried out with technologies such as biochar, which turns agricultural waste into a carbon-rich soil conditioner and, potentially, a large-scale drawdown technology.

When the project advances to larger scales, it should be possible to develop more advanced forms of salt processing to produce fertilisers, construction materials, such as gypsum, and other useful compounds.

The team intends to continue using biomimicry to develop the project. In time, technology may allow improved water capture, based on *Opuntia* spines, and scratch-proof coatings for mirrors could be developed, based on sand skinks. Widening the system boundaries to connect with other processes (such as water treatment facilities) could further increase productivity and enhance the regenerative effects. Developing digital tools based on emergence and swarm logic could help to manage systems that vary dynamically over the course of each day.

Evolving the approach from the Pilot Plant, continuously drawing in fresh technology and redesigning using lessons learned, all contribute to the functional success of applying biomimicry at the scale of reclaiming land. Transforming from an extractive to a regenerative paradigm is possible with biomimetic thinking.

Biomimetic urbanism

Designing cities for the ecological age is, in many ways, the defining challenge of our time. How can biomimicry help us to transform existing cities, and in some cases create new cities, so that all nine billion inhabitants[201] can live happy, healthy lives within the limits of the planet?

Two substantial challenges confront contemporary urban design. One is the resistance of some architects to ecological thinking, the other is ecological experts' lack of experience with the culture of the built environment. Susannah Hagan, in *Ecological Urbanism*, describes the way that some contemporary architects resist ecological limits. They associate the new with limitlessness, and environmentalism as a form of subordination of culture to nature.[202] At the other end of the spectrum are deep-green designers, working in urban environments with a good understanding of ecology, but with little or no sense of how to engage with culture – the thousands of years of history that have made existing cities what they are today. What is required is a synthesis of culture and ecological design, and we have all the tools necessary to deliver this, but few completed examples.

We can imagine creating a completely new city, based on biomimetic principles, integrating a good quality of life for its occupants with clean air, healthy food, access to nature, and so on. We can also see its possible implications: such a city might take decades to develop a strong culture. The most common arena of urban design is adapting existing cities. This could be compared to working on a tapestry that has been added to, repaired and reworked over time. The areas that were reworked maintain a trace of what was there before and the new sections continue key threads from the old. It is clear that this is an organic process rather than a *tabula rasa* approach and, in that sense, might sound inherently more biomimetic.

While it is encouraging that urbanism is now much greener, and that the *avant garde* are achieving much higher standards of sustainability than 20 years ago, the level of ecological transformation that has occurred is nowhere near what the best science of the day demonstrably requires. As Hagan states,

> *The longer architects and architecture schools ignore the politics, economics and science of meaningful change in the built environment, the closer they will come to being what they profess to despise: stylists to the rich and famous. If the worthy can't design, and designers are unequipped, architecture is finished as a profession with any influence on the improved future of cities.* [203]

The tensions involved in reconciling culture and ecological design lie in two key areas. First, it is a serious challenge to design a city to function like an ecosystem when a lot of infrastructure already exists in a form that was never conceived in those terms. Second, there are not enough architects or urban designers trained or willing to synthesise the cultural and the ecological to the extent required.

How can biomimicry address those tensions? Both of these 'macro' issues can be broken down by students and practising architects alike increasing their capacity for biomimetic design. Becoming an informed and competent mimic for both existing and *tabula rasa* contexts is essential to biomimicry fulfilling its potential for the built environment. The first tension will also respond to a systemic change: specifying the metrics which design should strive for. Respected consultants, Biomimicry 3.8, have established Ecological Performance Standards, which specify the key metrics for how a pristine ecosystem in a given location functions (or would have functioned): how much carbon it sequesters; how much oxygen it produces; how much water it stores, filters or evaporates. These metrics then set the standards for what is to be built, so that the city can also be a stable entity within a larger system and can deliver the same ecosystem services. This is a far more stringent set of standards than many building rating systems which require only a basic ecological survey of the site, and allocate points for improvements against that baseline. It is also a practical strategy: using nature as the measure as well as the model for specific projects. In this respect it goes well beyond a metaphorical approach to applying ecosystems models to cities.

Inspiring biomimetic cities: Arup's Dong Tan and Wanzhuang

Architects and urban designers are now making the first tentative and inspiring attempts at generating such cities. Peter Head, who led Arup's urban masterplanning team, sees biomimicry as crucial to facilitating the transition from the industrial age to the ecological age, as crucial as the role of culture in urban design. He began with Janine Benyus' principles from her book *Biomimicry – Design Inspired by Nature*:[204]

> *Organisms in a mature ecosystem:*
>
> - *Use waste as a resource*
> - *Diversify and cooperate to fully use the habitat*
> - *Gather and use energy efficiently*
> - *Optimise rather than maximise*
> - *Use materials sparingly*
> - *Don't foul their nest*
> - *Don't draw down resources*
> - *Remain in balance with the biosphere*
> - *Run on information*
> - *Shop locally.*

These principles were foundational in the design of the first eco-city that Arup worked on, Dong Tan, and carried through to their work on Wanzhuang in China.[205] While the site for Dong Tan – a new and growing area of land formed by silt deposition at the mouth of the Yangtze – was highly unusual and allowed a largely technological response, Wanzhuang was a more complicated, and in many ways more typical, context within which to design a new Chinese city. Wanzhuang is an agricultural area, which includes a series of historic villages and pear orchards that are visited by people from all over China. The client's objective was to create an eco-city extension to the nearest urban area, and a previous team had advocated clearing all the existing land uses and imposing a grid of roads and urban blocks.

Head's team started with a careful analysis, not just of the physical challenges, such as the poor water quality and low agricultural productivity, but also of the culture of the area. They engaged in community consultation and developed a scheme that challenged the conventional *tabula rasa* approach. Arup's aim was to develop a new paradigm in which urbanism could lift the economy and narrow the economic divide between urban rich and rural poor, while allowing the existing farmers to continue farming. The eventual scheme proposed that only 35 per cent of the land would be occupied by buildings, thus preserving 65 per cent of the agricultural land, along with 85 per cent of the historic orchards. The new buildings were proposed as five- and six-storey blocks, concentrated around the existing settlements, so that nearly all of the village fabric was maintained.

'Diversify and cooperate to fully use the habitat'

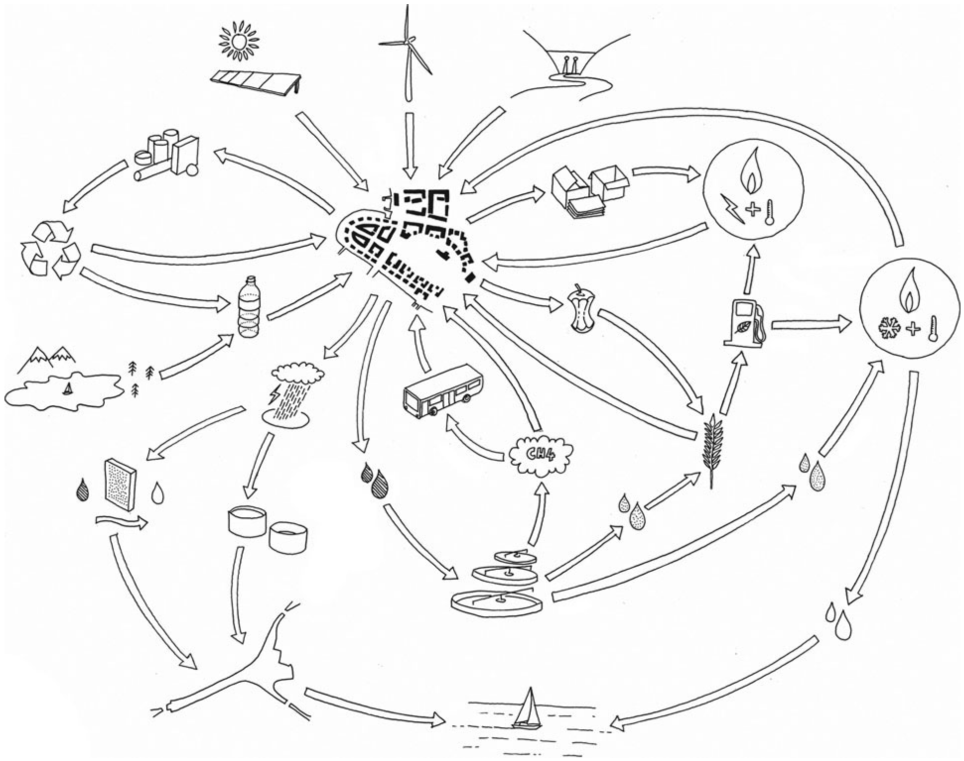
This principle moved the scheme away from sprawling, mono-functional urban zones towards compact mixed-use layouts that allow people to live, work and learn in close proximity, while still allowing immediate access to open spaces for recreation. The resulting concentration of human activities creates vibrant public spaces and makes a range of sustainable transport options viable. New urban developments are often populated with a narrow demographic but Wanzhuang would maintain a diversity of ages, cultures and family groups that provide mutual support systems and enhance community cohesion. Local systems for water, energy and waste management formed symbiotic systems to maximise resource efficiency and 'Use waste as a resource'.

‘Gather and use energy efficiently’; ‘Use materials sparingly’

These principles led Arup to develop transformative approaches to transport. All freight would be handled through consolidation centres at the periphery, allowing goods to be delivered to the central areas in more efficient ways to reduce travel distances and congestion. All vehicles in the urban areas would be either electrically or fuel-cell powered, a far quieter and cleaner option, producing consequent health benefits. The improved environmental conditions would also make it possible to naturally ventilate the commercial buildings, which would typically be air-conditioned. All the new buildings were proposed to be built to high standards of energy efficiency. The result of these measures was that energy demand was projected to be reduced by 80 per cent, which then made the supply from renewable sources much more achievable.

‘Remain in balance with the biosphere’

The discipline of ecological footprinting,[206] which calculates the area of land and sea required to regenerate resources and absorb our wastes, was used by the team to ensure compliance with this principle. Eco-footprinting also revealed the dramatic savings in energy and waste that can be achieved through closed-loop stewardship of resources. The scheme was designed so that only 2 per cent of the waste will go to landfill and, in time, the hope is that the products that make up this unrecyclable remainder will be redesigned along Cradle to Cradle principles. As Peter Head puts it: ‘The benefits that accrue are magnified by mobilising the virtuous cycles that connect the environmental, economic and social performance of different components of the built environment so that change in the design of one can lead to benefits in another’.[207]

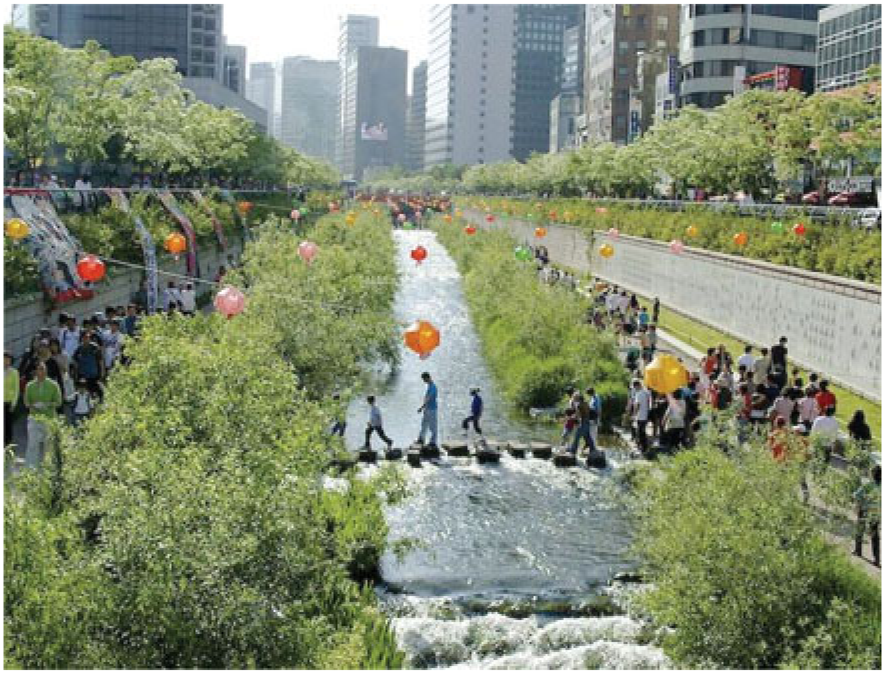


140. Food web diagram for Hammarby Sjostad, Sweden showing how ecosystem principles can be applied to new sections of city to deliver radical increases in resource efficiency

Possible biomimetic futures

Neither Dong Tan nor Wanzhuang were built, so we are left with the question: what forms will the ideal synthesis actually take? They will, in all probability, be an adaptation of an existing city, or an extension to it, that strives for various forms of cultural continuity; designed to match the ecosystem services of a pristine ecosystem in that location, with infrastructure that would create the kind of interconnected, zero-waste resource flows that can be seen in examples like Hammarby Sjostad (fig. 140). Individual buildings designed with biomimicry would contribute to the benefit of the whole city by using resources much more efficiently, cleaning the air, producing energy and being made from materials that make the job of the detritivores (the dismantlers, re-users and recyclers) much easier; most of the rooftops and many of the facades would be planted in order to provide food, manage water, modify microclimate and meet the ecological performance criteria (fig. 141). Circular economy principles would mobilise spare capacity in buildings, transport and infrastructure to meet people's needs far more efficiently;[208] resource flows would be characterised by 'roundput' rather than 'throughput';[209] the city's hinterland would be an area of regeneration rather than extraction.

141. Torre del Bosco by Stefano Boeri Architetti. Cities of the ecological age will need to be designed to deliver the same functions as thriving ecosystems



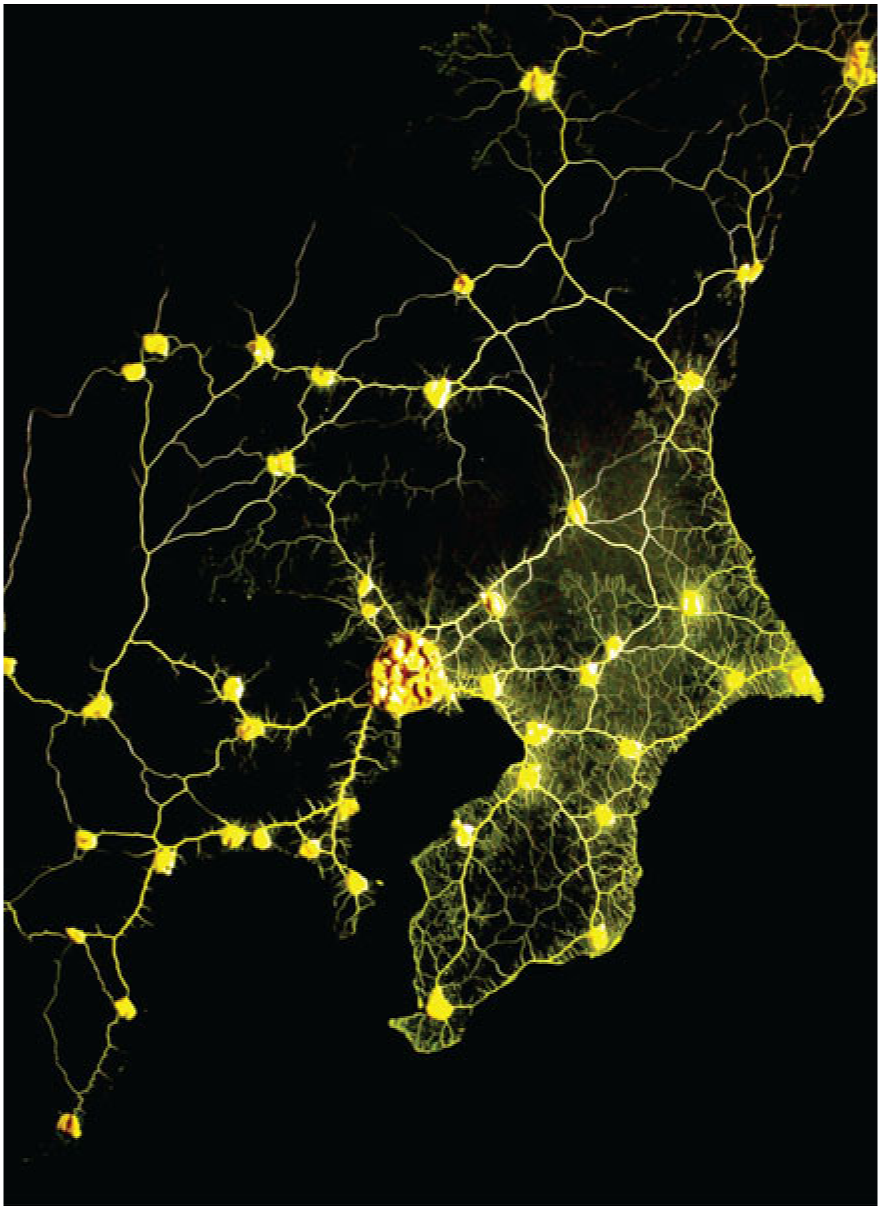
142. Previously covered by a 16-lane motorway, the Cheonggyecheon River park in Seoul is a great example of how industrial-age infrastructure can be replaced with green infrastructure

One of the most obvious differences would be in the 'green infrastructure'. Originally, city streets were designed for large flows of private cars (or smaller flows of horse-drawn carriages, in older cities), which can give way to green infrastructure, as sustainable transport and mobile phones are now more significant determinants of urban form.[210] A striking example of this is the restoration of the Cheonggyecheon River in Seoul (fig. 142). Previously covered by a 16-lane motorway, the river bed is now a linear park that has delivered multiple benefits: improved air quality, a major new amenity and improved microclimate (the immediate environs of the linear park are, on average, 3.6 ℃ cooler than other parts of Seoul).[211]

Biological algorithms will be used in the coming years to resolve complex design challenges into urban forms. The potential of biomimetic computation for urban form is exemplified by a slime mould experiment carried out at Hokkaido University in 2009. Slime moulds are single-celled organisms that form minimum-distance networks between sources of food. Using a map of the region around Tokyo, the scientists put a source of food on each of the surrounding cities and placed a slime mould on Tokyo itself. The slime mould spread out quickly, located all the sources of food and then set about optimising the network to minimise the overall distance between points. When it had finished, the layout was almost identical to the railway network in that part of Japan. But while that network had taken railway engineers thousands of hours to arrive at their optimisation, the slime mould had achieved the same in just 26 hours (fig. 143). This demonstrates a practical way in which biomimicry can be used to help design efficient transportation systems.

Similar optimisation processes can be extended to urban design. Would this be something to fear or embrace? While the slime mould is an example of a mono-functional optimisation, larger organisms and mature ecosystems are the result of much more complex optimisations. With computational algorithms that can process and optimise multiple parameters, we can use equivalent evolutionary processes to help design cities. The parameters can include anything definable, such as dwelling size, desired daylight levels, existing cultural assets, etc. Then millions of design variations can be generated and refined for ‘fitness’. In time, we are likely to see these biological optimisations as being far more reliable, and less arbitrary, than architects’ intuitions alone. We don’t have to be ruled by computers – if we, or our clients (in the fullest sense of the term), don’t like the output, we can change the inputs and rerun the optimisation.

When the creative strengths of urban designers and architects are harnessed to computational technology, biological knowledge and new ecological goals, the result is augmented creativity, not limitation. A coral reef or ancient woodland is a thriving and complex set of interrelationships, which works in balance with the biosphere. We can learn from this to create fully human environments, which share the essential functional qualities of natural systems. This is neither romantic nor nostalgic – it involves a rational understanding of the conditions within which systems can flourish indefinitely. We can use biomimicry to adapt and renew cities by combining the best that nature has to offer and the best that humans can create. While we are late starting, the task defined here is an achievable one. We can mitigate some of the unavoidable climate change impacts already occurring – if we rapidly adopt urban design approaches based on biomimicry. We can remake and build new cities designed for a long future in a sustainable world.



143. Tokyo slime mould experiment demonstrating how biological forms of optimisation could inspire more efficient ways to design transport networks for cities

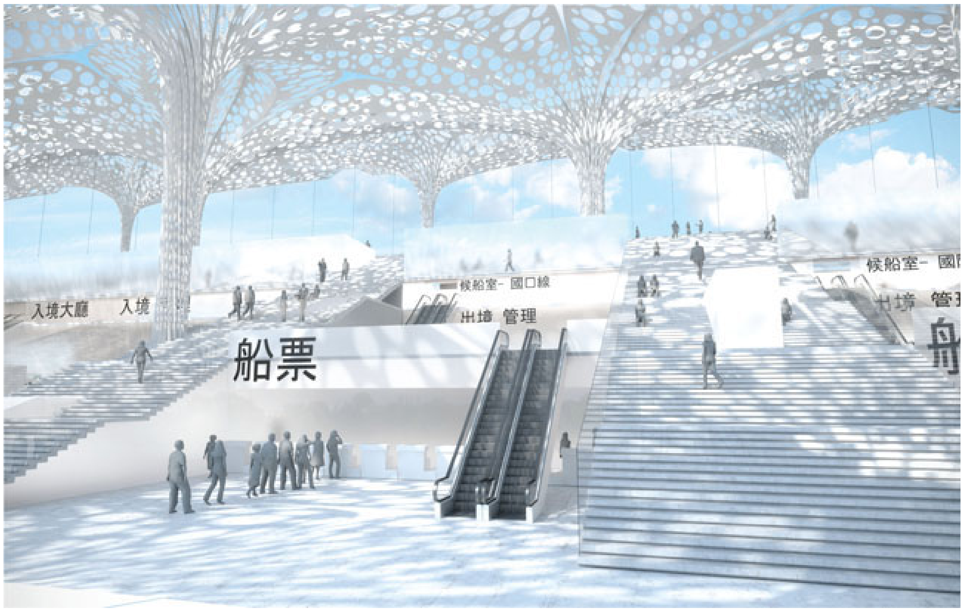
A biomimetic building: ‘Island of Light’ – Kaohsiung Port and Cruise Service Center

Similarly to Wanzhuang, the design of Tonkin Liu’s ‘Island of Light’ (fig. 144) cruise ship terminal in Taiwan has a cultural starting point. The scheme aims to relate to its context by creating the same sense of connection with nature that is captured by many Chinese landscape paintings. Meeting the simple requirements for waiting, ticketing and boarding has been elevated to the level of poetic architecture.

The scheme combines biomimetic and biomorphic design with great sensitivity and skill. There are two main elements to the building: an inclined hill-like base containing all the operational accommodation and a lightweight roof canopy. The roof canopy takes the form of a forest of tree-like columns, providing generous shaded space for the passengers, and whose structural principles are abstracted from the vaulted, folded and twisted forms of shells. The columns are a continuation of Tonkin Liu’s work on shell-lace structures. They describe it as follows:

> *The structural ‘Forest’ makes poetry out of the need to create cool space in a hot climate. By day, a filtered, dappled light fills the hall, covering the surface of the ‘Hill’ and by night the trees glow from within. The steps which form the inclined surface of the hill are always accessible to the public, both in the glazed climatic zone and on the external steps sheltered by a covered colonnade. [Up the steps,] they can experience the relationship between the scale of the city and the scale of the ocean liner … the theatre of arrival and departure.* [212]

Where these poetic dimensions might be a complete description for a ‘normal’ or purely biomorphic project, here the design is also based on clear and rational biomimetic principles. In addition to the structure, biomimetic principles have been used to create comfortable conditions inside by using freely available sources of energy. While conditions in the more transient spaces of the concourses fluctuate considerably, other more static spaces require steadier temperatures and these are set into the hill to benefit from the thermal mass of heavier forms of construction. During the hottest times of the year, additional cooling can be circulated through the structure from another locally available source, seawater, using efficient heat exchangers.



144. Internal view of Tonkin Liu's 'Island of Light' project, showing the filigree quality of the 'shell-lace roof', which provides shelter from the sun, wind and rain while filtering the light and harvesting rainwater

The structural trees perform multiple biomimetic functions. First, with a covering of ETFE pillows, they provide shelter from the sun, wind and rain. Second, they facilitate natural ventilation using rooftop wind-catchers and vents, coupled with low-level vents, which combine to exploit the wind and stack-effect forces to ensure ample flow of fresh air through the space. Third, the trees control the light – filtering sunlight, bringing light down into the solid base and, by incorporating luminaires within the structure, creating a glowing symbol for the city at night. Finally, the roof harvests rainwater to supply the majority of the building's water needs.

Possible futures

How might advances in biomimicry be used to develop the scheme even further? The perforations in the shell-lace structure are a top-down approach to manufacturing – starting with complete sheets and then removing material. With advances in manufacturing technology, it should become easier to adopt bottom-up manufacturing, in which materials are positioned precisely where they need to be when the elements are formed.

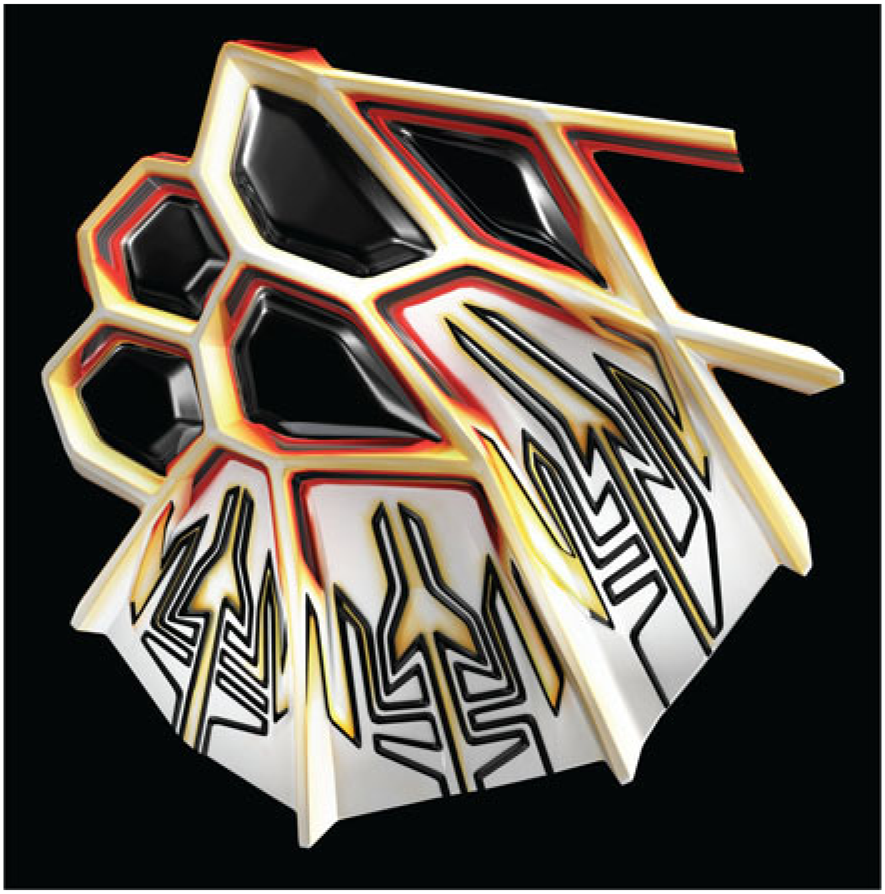
An adaptive structure (see Chapter 1), incorporating sensors and active tension members, could substantially reduce the amount of material, leading to an even more filigreed structure that could 'tense up' when a storm was coming. Whether adaptive structures can respond quickly enough to a gust of wind (as opposed to a more steady accumulation of load) is a major challenge. Perhaps this can be considered a 'sensing' issue, addressed by augmenting buildings with delicate antennae that can give a few additional seconds' warning of wind loading. Finally, the scheme is already designed with ETFE and, if flexible framing could be developed, then the design could pursue an approach of resilience rather than rigidity – swaying in the wind with the same elegance as a grove of natural trees.

A final advance this project could make is in managing information for the materials from which it is built so that the building becomes a full player in the circular economy. Popular new technologies, such as building information modelling (BIM), are already in place to start supporting this strategy. In this model, maintenance, redevelopment and upcycling of the building in the future become the basis of architecture, as a way to store materials rather than the building marking the end of their journey through the materials cycle.

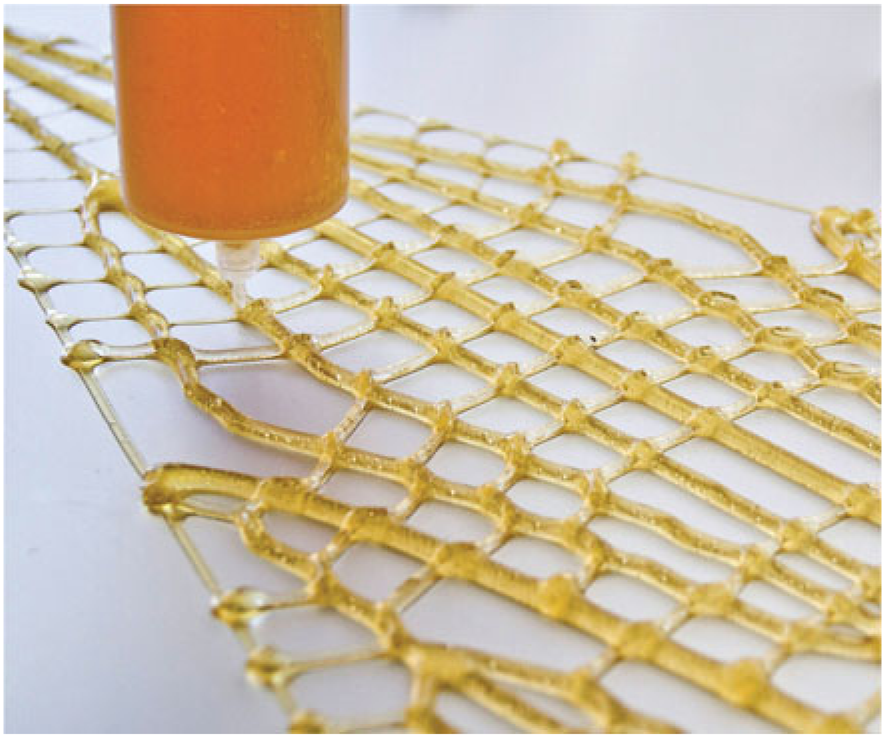
A biomimetic detail: Thermo-Strut

In his 2012 paper, ‘Beyond assemblies: system convergence and multi-materiality’, Tom Wiscombe describes the way that architecture’s development over the past 100 years has been, if anything, towards less integrated systems.[213] The frame is completely distinct from the skin, which is, in turn, separate from many other sub-systems of building services, and the way that buildings are built, in specialist packages, reinforces that disintegration. His office has worked on a number of proposals that aim to rethink this flawed paradigm, using what he describes as ‘ecologies of systems rather than zero-sum optimizations of each system’.[214]

Taking inspiration from prehistoric organisms of the Ediacaran Period (around 600 million years ago), Thermo-Strut is a proposed building element made from a complex folded surface, into which solar energy harvesting, microcapillaries for radiant heating or cooling and even organic LED lighting are fully embedded (fig. 145).



145. Thermo-Strut by Tom Wiscombe. Inspired by organisms from the Ediacaran Period, Thermo-Strut proposes a way in which structure, skin and systems can be truly integrated



146. Chitosan structure by Neri Oxman – making elements of structure with biologically derived raw materials (grown from atmospheric carbon)

New approaches to manufacturing in aerospace industries are facilitating the assembly of composites in which fibres, in the form of bundled carbon-fibre or carbon-fibre tape, can be positioned and orientated to precisely follow paths determined by structural analysis software. As Wiscombe describes it:

> *Winding, taping and wrapping all become a new language of structural and formal articulation, in concert with morphological inflections such as pleating, creasing and crenellation. The ability to resist structural stresses via surface form at the macro scale and gradations in surface composition at the micro scale allows for the tuning of architectural form and structure in a way never before possible.* [215]

This approach explores similar territory to Neri Oxman and her colleagues (see Chapter 2), which progresses the important notion of 'functionally graded materials' – materials that can vary in properties continually rather than abruptly (fig. 146). The gradual transition from, for instance, opaque structure to translucent window is the polar opposite of the 'frame and skin' tectonics that have dominated architecture since its beginning. It is no coincidence that these new developments were initiated in other industries; it is often the case that new approaches to architecture have their origins in industrial sectors with relatively lavish research and development budgets, and where improvements in performance are easier to measure. Wiscombe describes the prevalence of composites in biology and the way that '[t]hese are primarily organic, *non-mineral* composites … with varying tensile strengths, flexibility, weight and transparency'.[216] The non-mineral nature of the composites is, he argues, essential to achieving the variations in material properties (there are no translucent forms of steel), as well as offering the benefits of renewability, in contrast to the more limited nature of materials that have to be extracted from the earth. Currently, most composites used in construction involve resins that are not only toxic but also prevent material recovery. Ideally, the composites we use will move steadily in the direction of biological composites, as shown by Neri Oxman's work using chitin – starting with the right elements and putting them together in the right way.

Thermo-Strut combines a range of biomimetic ideas: surface articulation for enhanced stiffness with minimal resource use ('less materials, more design'), the use of functionally graded materials and the integration of thermoregulatory systems (integrated as nature does), energy-gathering and, conceivably, even self-repair networks. Potentially, the apertures for daylight could open and close or vary their transmittance in response to external conditions. It's a compelling vision of how materials can be put together to provide more performance without sub-assemblies. In time, we will see similar elements, self-assembled with biological polymers grown from atmospheric carbon, as the dominant paradigm and at that point we can truly claim to have moved on from the fossil-fuel era.

A biomimetic company: Interface

In 1994, Interface was a normal, commercially successful company, supplying carpet to clients. The chairman, Ray Anderson, was invited to give a talk about the company's environmental policy. While soul-searching about what to say, a colleague recommended reading Paul Hawken's *The Ecology of Commerce*. Ray Anderson describes the experience as being 'like a spear in the chest'.[217] It struck him that there was 'not an industrial company on earth that is sustainable in the sense of meeting its current needs without, in some measure, depriving future generations of the means of meeting their needs'.[218] Ray Anderson decided to set Interface on course to be the first sustainable corporation and, subsequently, to become the first restorative company.

What followed was an intensive process of engagement with pioneering thinkers, including Janine Benyus, Paul Hawken, Amory and Hunter Lovins and Jonathan Porritt, all of whom helped to re-conceive the company. Perhaps the most fundamental biomimicry principle that drove innovation was the idea of treating waste as an opportunity. The President and COO at the time, Charlie Eitel, defined waste in even more incisive terms as 'every measurable input that does not create customer value'.[219]

From product to service

Traditional approaches to flooring often involved gluing broadloom carpet to office floors, which required all the furniture to be cleared. It also led to a cocktail of off-gassing compounds from the adhesives and fire retardants to be breathed in by the occupants. After a relatively short period of use, the carpet would be worn out in limited areas of intensive use and, consequently, would all be pulled up and thrown into landfill, to be replaced by more carpet in an identical process of disruption, expense and internal pollution. Interface recognised that there were huge advantages to be gained from offering a floor-covering service rather than a product. By developing a durable carpet tile that could be reconditioned almost indefinitely, the company could replace worn carpets out of office hours and provide the client with a better service at lower cost, while achieving radical increases in resource efficiency.

In 2000, Interface worked with Biomimicry 3.8 to answer the question of ‘How would nature make a carpet?’ At the workshop they held, the attendees, mainly designers, were sent outside into the forest to ponder on this issue. Baffled at first, the designers thought they should look for shapes of flowers, natural colours and forms. However, one of the key observations that came back to the workshop was ‘randomness’, particularly the way that no two areas of forest floor are exactly the same and yet it still creates a harmonious appearance. The conclusion of the exercise was a carpet tile design that mimicked this random pattern.

The profound advantages of this idea unfolded gradually. First, it could be laid randomly, so installation waste virtually disappeared. Second, the idea of ‘imperfection’ no longer existed, eliminating a whole category of waste: quality-control rejects. Third, repairs were easier and it became possible to even out wear by rotating carpet tiles, because exact matches were impossible by design. Interface has since developed a whole series of products based on this principle.

Biomimetic innovation continued with gecko-inspired alternatives to conventional adhesives and regenerative design initiatives like ‘Net-Works’, which pays fisherman in developing countries to collect discarded fishing nets from the oceans to supply raw materials for making floor coverings.[220]

Interface has probably applied biomimicry to their whole business culture more comprehensively than any other company and, arguably, has come closer to being a truly sustainable company than any other major industrial player. From 1996 to 2009, the company showed actual reduction of greenhouse gas emissions by 44 per cent from a baseline in 1996, and achieved an 80 per cent reduction in waste sent to landfill.[221]

Mission zero

Their 'mission zero' vision of the sustainable company that they want to become by 2020 is one that very closely follows the principles set out in Janine Benyus' book. It would be a company that runs on sunlight, uses only the energy it needs, does not overdesign, recycles everything, rewards diversity and cooperation, adapts to local conditions and skills, curbs excess, embraces disruptive innovation and accepts failure as a necessary step in evolving better solutions. Other companies might move towards having a positive, as opposed to zero, impact, in the way that they embrace regenerative approaches. One can extend Interface's terminology. 'Mission positive' with biomimicry would involve looking at large-scale drawdown technologies – ways to make floor coverings out of atmospheric carbon. Taking Fuller's assertion that 'Pollution is nothing but the resources we are not harvesting'[222] as inspiration might lead to using blanket weed from eutrophicated water bodies or fibre from invasive species, such as water hyacinth, as raw material inputs. Advances in the technologies described in Chapter 6 might lead to textiles that produce vibrant colour effects without any dyes.

Biomimetic business

> *Successful companies of tomorrow will take their values from their customers, their designs from nature and their discipline from the market place.*
> AMORY LOVINS [223]

Interface demonstrates how one company used biomimicry to transform their operations, while reducing waste and increasing profit. Many of the ideas in this book reinforce this point: the Eden Project Biomes, for instance, were one-third of the cost of a more conventional glazed solution; the Kalundborg Eco-Industrial Park saved 264 million gallons of water per year and reduced carbon dioxide emissions by 240,000 tonnes per year; simple biomimetic approaches that empower people to build with locally available materials can offer low-cost house-building solutions. To put it more succinctly, biomimicry can save energy, increase material efficiency, convert waste into value and transform available resources into cheap building materials.

Other examples, such as the Biomimetic Office (predicted to be one of the lowest-energy office buildings in the world when constructed), have a slightly higher capital cost and much lower running costs. However, to analyse the value proposition in these terms alone would miss the greatest economic benefits that such schemes offer. With the rise of corporate social responsibility (CSR) there has been a significant shift in recent years towards considering less tangible values, such as brand image, the quality of the working environment and the well-being of staff. Millennials, entering the workplace now, have far higher expectations of how businesses should operate in terms of social and environmental responsibility. For a scheme like the Biomimetic Office, the economic benefits for a company of attracting the best staff and enhancing their productivity would exceed the value of the energy savings by several orders of magnitude.

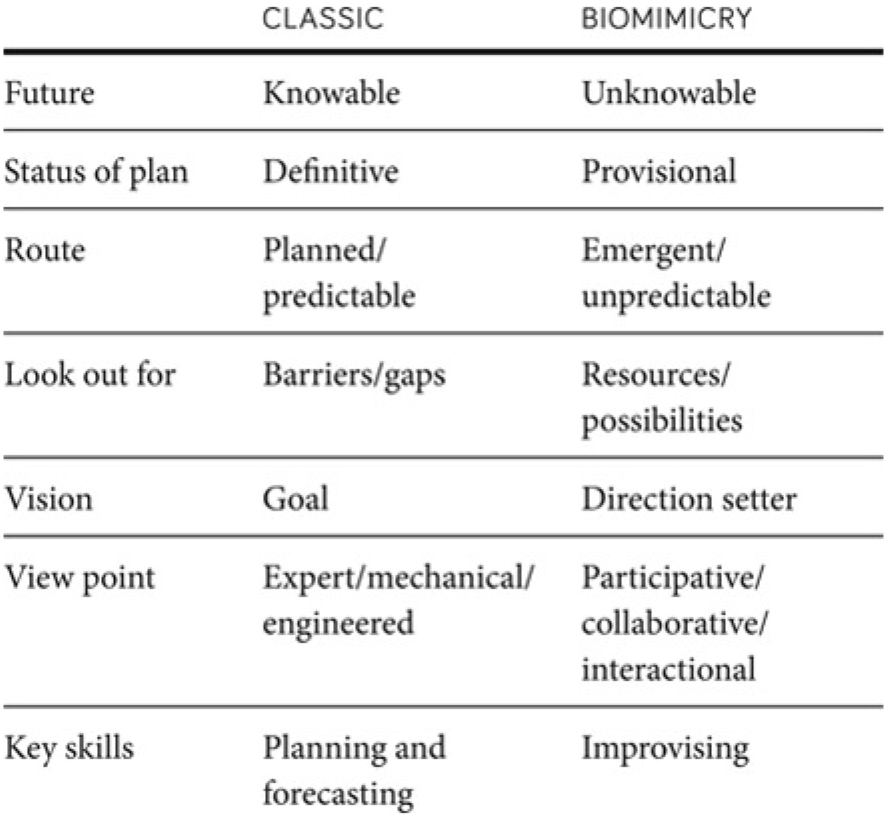
> *Biomimicry has been thought of as being eminently compatible with CSR since the innovations that it produces are supposed to be useful from commercial/economic perspectives as well as being sustainable and/or eco-friendly. Thus, biomimicry has become a concept that is promoted as a way to get corporations to go Green in a profitable manner.* [224]

There are many companies that have pursued CSR with determination. They are likely to have implemented all the obvious improvements and are now wondering where next to turn. Biomimicry can be used to rethink products, processes and buildings and reveal new solutions. Where further investment in machinery efficiency is delivering ever-diminishing returns, the biggest gains are likely to be achieved by widening the system boundary: looking at their wider business ecosystem to form symbiotic relationships with other companies, establishing commercial arrangements for outside parties to make use of spare capacity within the company, perhaps becoming energy entrepreneurs to secure long-term energy security for their operations while selling surplus for profit.

Increasingly, leading companies are ascribing value to CSR initiatives. Google justified the cost of large-scale photovoltaic arrays on its headquarters (long before solar PV was as economically attractive as it is now) as part of creating the image necessary to attract the best staff. Exploration's Zero Waste Textile Factory uses biomimicry and systems thinking to deliver substantial resource savings and an immensely improved working environment. Such measures do cost more than standard approaches but, as the client stated, if an international buyer from one of the major chains walked into the new model factory and placed an average-sized order, the cost of the building would be more than recouped at a single stroke, ignoring the standard calculated payback time for sustainability technologies. For a client, all design projects must make business sense, which often leads to a model based solely on cost – but buildings are more than simple economic assets. For clients that want to demonstrate leadership, buildings can be precisely evolved, competitive organisms that create a profitable and positive future.

For those companies that want to innovate, biomimicry offers new perspectives on familiar problems. Some organisations fear innovation because it can represent a leap into the unknown, but biomimicry has the advantage of drawing on a vast range of solutions that have been refined by 3.8 billion years of research and development. Declining to adapt to a rapidly changing context is a greater source of risk than embracing innovation. As John Cage said, 'I can't understand why people are frightened of new ideas. I'm frightened of the old ones.'[225] Biomimicry does not involve huge intuitive leaps – it's based on ideas that are proven to work.

For businesses wishing to rethink their structure, purpose and planning, it can be illuminating to use biomimetic metaphors. For instance, involving a biomimic to help to translate all the company job titles and key business functions into the nearest biological equivalents can reveal new opportunities for how the company could transform to become better adapted to its environment. Similarly, resilience planning can learn from how biological organisms have evolved to maintain features that are critical for survival in crisis situations. Consultant Paul Z. Jackson uses biomimicry and improvisational techniques to coach businesses in how to manage organisational change. The following table shows the contrasting nature of classic versus biomimicry approaches (and improvisational techniques) in forming a strategic plan:



	CLASSIC	BIOMIMICRY
Future	Knowable	Unknowable
Status of plan	Definitive	Provisional
Route	Planned/ predictable	Emergent/ unpredictable
Look out for	Barriers/gaps	Resources/ possibilities
Vision	Goal	Direction setter
View point	Expert/mechanical/ engineered	Participative/ collaborative/ interactional
Key skills	Planning and forecasting	Improvising

A recent report by the Fermanian Business & Economic Institute estimated that bioinspired innovation could account for approximately $425 billion of the United States' GDP by 2030 (valued in 2013 dollars). According to the

Institute, biomimicry is expected to ‘especially impact the building construction, cement and concrete, chemical manufacturing, and power generation, distribution, and storage industries, providing sizable growth and profit opportunities to developers and investors alike’.[226] Given that level of predicted growth, how many businesses can afford to ignore biomimicry?

Conclusions

What does biomimicry mean for people?

147. The famous biologist E. O. Wilson once opined that 'Destroying rainforest for economic gain is like burning a Renaissance painting to cook a meal.' Can we learn to shape a positive future for which the defining characteristic is one of long-term abundance?

'Saving the planet' is often used as short-hand for environmentalism. But, in reality, the planet is not in danger. What is at stake is whether we can create happy, healthy lives for everyone, or whether we will become embroiled in what several scientists have described as ‘a perfect storm’ of catastrophic climate change, resource wars and ecosystem breakdown.[227]

The substantial extent to which biomimicry could mitigate or avoid that scenario is perhaps the most significant connection between biomimicry and people. There are also many others that have been described in this book and are worth summarising. Biomimetic structures, like Nervi’s Palazzetto dello Sport (fig. 25), have a legibility to them that creates an emotional connection with the user. This enjoyment of beauty and the tangibility of force made manifest in material is something that could be extended even further with mastery of adaptive structures and advanced structural analysis. The Eden Project, in the way that it accommodated the forms of the existing site, creates a more respectful reconciliation between humans and nature. The same could be said of a biomimetic approach to infrastructure: instead of uninspiring industrial behemoths, our cities could include buildings like the Las Palmas Water Theatre (fig. 108), which elevate the mundane to the level of sculpture.

The ‘materials are expensive and shape is cheap’ mantra is something that could put people at the centre of architecture: employing people’s ingenuity with more design input and more physical input in the richly rewarding act of building. While some approaches to biomimicry involve high technology, others involve low-tech or even no-tech approaches. Biomimetic technology, such as the 3D printer using clay, could empower our resourcefulness with cheap and readily available materials. Rethinking linear systems as cyclical systems can be easier to achieve with simple technologies than with sophisticated ones, because what we refer to as high technologies (a disputable phrase when compared to spider silk and glass sponges) often use materials and assemblies that frustrate, rather than facilitate, dismantling. As is evident in the Cardboard to Caviar Project, these low-tech ecosystem models can be regenerative to people, landscapes and economies. An important part of designing ecosystem models is to design out toxins, which not only avoids waste but would make a significant contribution to human health.

Increasingly, over the decades ahead, we are likely to face resource constraints and it is reassuring to know that biology has a wealth of adaptations to many of those constraints. Employing this design ingenuity in dealing with water, food and energy challenges could go a long way towards avoiding resource-based conflicts. Resource constraints can, and need to, stimulate innovation and, quite possibly, lead to the greatest flourishing of human ingenuity since the start of the fossil-fuel age.

While scarcity of some resources will present challenges, I believe the overriding atmosphere of a biomimetic city would be a feeling of abundance: lush vegetation, fresh food, clean air and, at times, even an abundance of energy. A solar economy will result in times when there is an excess of energy (for instance, if all the offshore wind turbines have been at full capacity during extended windy conditions) and cities could put on spectacular lighting displays that do what festivals achieve so successfully: bring people together for large-scale shared experiences.

How can these transformations be accelerated? Often, our first response to a question like this is to think of what would compel change and, while there is a place for legal measures in some circumstances, fiscal measures that reward ingenuity are a surer way to stimulate innovation. Such measures are likely to be more consistent with biomimicry – creating the conditions out of which these transformations would emerge. In the process of evolution, some of the most remarkable adaptations have occurred in response to scarcity or to extreme selective pressure that favoured efficiency. We could stimulate innovation in an equivalent way by shifting taxation away from employment and towards the use of resources. It would also incentivise the kind of ecosystems models we saw in Chapter 3 by rewarding 'waste entrepreneurs'. Making resources more expensive, before they become problematically scarce, would be one of the best ways to ensure that those resources are used more efficiently. Often, governments do the exact opposite in order to provide a quick fix.[228]

I have no doubt that creating a good quality of life for all earth's future nine billion inhabitants is possible, but I am equally convinced that it will not be achieved with conventional economics, which ignores the unmeasurable and externalises the inconvenient. We should perhaps reflect on the derivation of 'economy', which comes from the Greek words *oikos* meaning 'home' and *nomos* meaning 'management'. It shares its etymology with the subject with which it so often seems to be in conflict. 'Ecology' couples *oikos* with *logos* meaning 'knowledge'. Bringing *nomos* and *logos* together, management of our home based on knowledge, surely offers the best chance of creating a positive future.[229] It has long been accepted that exponential, or even continual, growth (which is the *modus operandi* of conventional economics) is not possible on a finite planet. In recent years, there has been considerable discussion about a 'zero-growth economy' or a 'steady-state economy' but, in my opinion, neither of those framings is compelling. A much better model would be biological systems, which exist in a state of dynamic equilibrium with high levels of growth, decay and renewal. Such models have the potential to unify the very worthy causes of the circular economy, championed by the Ellen MacArthur Foundation, the '100 Resilient Cities' movement progressed by the Rockefeller Foundation and the numerous initiatives that are advancing the idea of cities and countries transitioning to run on 100 per cent renewables.

We have seen that the notion of a solar economy could be facilitated through biomimetic invention, both directly, in terms of shaping more efficient renewable energy systems, and in radically reducing our energy use. This transformation could deliver numerous benefits – restoring ecosystems, boosting biodiversity, moderating urban microclimate and reducing evaporative water loss. The solar economy is also entirely consistent with the way that nature works in terms of resilience, compatibility and indefinite supply. This is no coincidence. The sun is the source of energy that has supported all life for billions of years. It is abundantly clear that continuing with the fossil-fuel economy poses huge risks and that a solar economy is the best alternative: promoting cooperation rather than conflict and halting the build-up of carbon dioxide in the atmosphere.

Biomimicry starts with identifying functional challenges and biological organisms or systems that have solved those challenges. Then follows a process by which the potential solutions are translated into solutions that suit human needs, and that process does not have to be limited by what exists in biology; at its best, biomimicry is a synthesis of the best that biology has evolved with the best that humans can devise. Biomimicry can be a very powerful tool for allowing the design conversation to identify the highest ideals and to then come back to something that is achievable within the constraints of the project and existing technology. Design has the flexibility to range from high technology to using local materials and low- to no-tech approaches – if you consider that the human ingenuity powering biomimicry in architecture is ‘no-tech’.

It would be bordering on the evangelical to suggest that nature has the answer to everything. Nature does not make things out of metals, nor does it have high-speed rotating axles or heat engines. But living organisms, because of the ruthless refinement of evolution, are remarkable models from which we can learn to achieve radical increases in resource efficiency: if we multiply the implications of materials made with a factor-100 energy saving by the efficiencies of structures that are ten times higher than conventional approaches, then we glimpse what could be attained. And, if we do it correctly, all of those materials can be cycled permanently in endless transformations. The very notion of waste can be progressively designed out. With new developments in additive manufacturing using biological raw materials and from learning how to replicate bio- and geo-mineralisation, there is real potential to develop large-scale drawdown technologies that reduce levels of carbon dioxide in the atmosphere. Then the construction industry would move comprehensively beyond mitigation to a positive and regenerative paradigm. Much of this may be beyond our current capabilities, but we know that this is not the realm of fantasy because the natural world is living proof of the possibility.

It could be argued that biomimicry is the logical conclusion of a shift in human thought, which has gone from attempting to conquer nature, then trying to preserve it and now striving for reconciliation with nature. With previously unparalleled scientific knowledge, we can use lessons from biology, augmented by human creativity, to retain the many wonderful things that civilisation has developed and rethink the things that have proved to be poorly adapted to the long term. Should we be optimists or pessimists when looking to the future? Hans Rosling argues that we should be neither, as both of those positions imply inevitability. What we should be, he says, is 'possibilists'.[230] We should decide on the future we want and then set about creating it. The ecological age is now a clear enough destination to aim for and I hope this book will help all those who want to make that journey.

Applying biomimicry: practice guide for architects

What skills do you need?

- You need to know enough about other disciplines to ask the right questions (e.g. by understanding how an engineer parses a system and the vocabulary of biology)
- You will need a biologist to be part of the process as early as possible
- The best collaborators are polymaths, able to work across domains; to be a good architect, you have to develop as a polymath too
- Cultivate systems thinking, learning to identify elements, interconnections, overall purposes
- Widen your set of design approaches and familiarise yourself with the two main approaches to biomimicry: top-down (starts with the design problem, identifies how equivalent problems have been solved in biology and then translates that into a solution) and bottom-up (takes biological phenomena as a starting point, identifies the principles and then implements a solution that suits human needs)[231]

How do you start on a project?

- Work with biomimicry to first identify the absolutely ideal solution, and then come back to something achievable within necessary constraints. Never start with reality: always start by identifying the ideal and then compromise as little as necessary[232]

- Prioritise integrating and benefitting from the cultural dimensions to architecture, which needs just as much thought as the areas in which biomimicry can assist
- Analyse the site and establish how a pristine ecosystem works, or would work, in that location. Aim to get as close to those performance targets as possible
- Establish which of the built elements are easy to change and which are best left or adapted

Working with the major principles

- Structures: **less materials**, **more design**, **greater responsiveness**
- Materials and manufacture: **the right elements**, **put together in the right way**
- Ecosystems: **create regenerative closed-loop systems based on solar energy**
- Waste: **everything is nutrient**; **maximise human and material value**

Radically increasing resource efficiency

- Define challenges in functional terms and then see how that function is delivered in biology
- Rethink the problem from first principles and optimise the whole system
- Put the material in the right place (use efficient overall structural forms and individual elements that use shape and hierarchy to

maximum effect)

- Design in a way that is both adapted to the specifics of the location and adaptable to changing conditions
- Look for ‘free’ sources of energy (the steady temperature of the ground, the cool temperature of deep seawater, reliable wind direction, etc.)
- Look for integrated solutions – for instance, solutions to managing water that also assist with thermoregulation and restoring biodiversity

Shifting from linear to closed-loop systems

- Visualise the key elements and flows in your system, as it is only by doing this that you are likely to really see the challenges and opportunities
- Start by identifying existing elements that can be linked to create resource efficiencies
- Consider underutilised resources as an opportunity rather than a problem – add elements to the system that transform waste into value. Similarly, instead of buying in resources, look for opportunities to produce the resources you need by adding something to the system
- Widen the system boundaries and connect with resource flows in adjoining schemes
- Look for synergies between technologies by assessing the inputs and outputs of each
- Test for resilience by seeing how you could sabotage the system – which link, if broken, would cause the system to collapse? Once you know that, you can see where you need greater diversity and multiplicity of connections to create resilience

- Try to be inventive with waste at every level – not just with physical resources but also financial resources and underutilised human resources
- Reconsider conventional approaches to resource ownership and explore opportunities for leasing services rather than purchasing products
- Don't try to optimise something that shouldn't be there in the first place

Shifting from a fossil-fuel economy to a solar economy

- Think about opportunities for buildings to become net producers of energy
- Offset the cost by fully integrating the systems so that they are part of the skin or structure of the building rather than separate elements; this can square the current economics of solar energy
- Develop a plan for running the scheme on current solar income with numbers that add up. Work through the implications, which will almost certainly compel you to re-explore every opportunity for radical increases in resource efficiency

Using all resources: human, social and cultural value and information management

- Think about using human capabilities of inhabitants and owners to continue improving the design in use
- Different aspects of human and social value will be appropriate to different contexts, but thinking of them in a defined way makes them

easier to consider as components of an ecosystem
- Human values are at an individual level (equity, skills, knowledge, ability to travel, safety, health, happiness)
- Social values are collective concerns (participation, cohesion, regulation, development, cultural heritage, crime – e.g. the crime that accompanies drug addiction)
- The cultural setting is an often overlooked resource. Vernacular architecture and low-tech local traditions may offer solutions to diverse problems, working in tandem often with higher technologies. Use development anthropologists, NGOs for guidance and support
- Managing information, especially materials information, is a crucial design activity which enacts a circular economy principle in a practical way and empowers building owners and future users and designers

Integrating principles

- This is easiest when you have mastery of the goals of a project and sufficient scientific support

Overcoming obstacles

- Resist the temptation to return to conventional approaches: ‘Adversity is not the end of a story but, where there is courage and vision, the beginning of a new one, a greater one than before’ (Ben Okri[233])
- If the ideal solution is prevented by the brief, then you will need to apply a lever higher up in the chain of influence (refer to Donella Meadows’ essay ‘Leverage Points’[234])

Biomimicry for cost effectiveness

- Encourage whole-life value assessment, prevent short-termism. The cost of a building is a small percentage of its lifetime operating costs. Provide defined return-on-investment timelines to encourage solid decisions. Optimising value is not the same as cost-cutting
- Look at widening the comfort envelope of controlled temperature and humidity in order to design out expensive M&E equipment
- If the scheme uses heavy engineering to resolve problems, are there more benign solutions? Can you reduce structural performance requirements?
- Use more of what already exists (structures, on-site materials, etc.)
- Can you phase the scheme and just build the essential parts first?

Resources

- Guide to open-source biomimicry: http://www.asknature.org/
- Guide to working in a circular economy: http://www.ellenmacarthurfoundation.org/
- Use BioTRIZ to develop as-yet unknown solutions[235]
- Refer to David MacKay's *Sustainable Energy – Without the Hot Air*[236]
- Refer to Futerra's *The Rules of the Game*[237]
- Use Brian Eno's 'Oblique Strategies'[238] cards when you get stuck

Research organisations

- Wyss Institute for Biologically Inspired Engineering at Harvard
- Biodesign Institute at Arizona State University

- Center for Biologically Inspired Design at Georgia Tech
- Center for Biologically Inspired Materials & Material Systems at Duke University
- Mediated Matter Group at MIT Media Lab
- Swedish Center for Biomimetic Fiber Engineering
- BIOKON – The Biomimetics Association

Courses in biomimicry

- Biomimicry 3.8 runs a ‘Biologists at the Design Table’ programme of involvement and webinars, and an online foundation course: http://biomimicry.net/educating/online-courses/
- Schumacher College: https://www.schumachercollege.org.uk

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I would also like to thank the countless scientists who continue to reveal biological secrets and those who work in environmentally related fields, such as climate science, with the highest integrity and do so in spite of the media assault on their findings. It often seems that, 200 years after the age of the Enlightenment, we are entering the Endarkenment, in which unqualified sceptics are considered as reliable as scientists on matters of climatology, and monomathic economists create political policies with no regard for natural capital or long-term value. We will need polymaths and inspired collaboration more than ever during the decades ahead.

MICHAEL PAWLYN

Further reading

Abbott, Derek, ‘Keeping the energy debate clean: How do we supply the world’s energy needs?’, *Proceedings of the IEEE*, Vol. 98, No. 1, January 2010, pp. 42–66

Adrover, Esther Rivas, *Deployable Structures*, London, Laurence King Publishing Ltd, 2015, ISBN: 978-1-78067-483-4

Ashby, Michael F., *Materials and the Environment: Eco-Informed Material Choice*, Oxford, Butterworth-Heinemann, 2009, ISBN: 978-1-85617-608-8

Azad, M. A. K., Ellerbrok, D., Barthlott, W. and Koch, K., ‘Fog collecting biomimetic surfaces: Influence of microstructure and wettability’, *Bioinspiration and Biomimetics*, Vol. 10, No. 1, January 2015, doi: 10.1088/1748-3190/10/1/016004

Bar-Cohen, Yoseph, ‘Biomimetics: Using nature to inspire human innovation’, *Bioinspiration and Biomimetics*, Vol. 1, No. 1, 2006, pp. 1–12, doi: 10.1088/1748-3182/1/1/P01

Bar-Cohen, Yoseph, ‘Focus issue on biomimetics using electroactive polymers as artificial muscles, *Bioinspiration and Biomimetics*, Vol. 2, No. 2, 2007, pp. 1–3, doi: 10.1088/1748-3182/2/2/E01

Beukers, A. and Hinte, E. v., *Lightness: The Inevitable Renaissance of Minimum Energy Structures*, Rotterdam, 010 Publishers, 1999, ISBN: 90-6450-334-6

Beuvelot, J., Bergeret, C., Mallet, R., Fernandez, V., Cousseau, J., Baslé, M. F. and Chappard, D., ‘In vitro calcification of chemically functionalized carbon nanotubes’, *Acta Biomaterialia*, Vol. 6, No. 10, 2010, pp. 4110–4117, doi: 10.1016/j.actbio.2010.05.011

Buehler, Markus, J., 'Tu(r)ning weakness to strength', *Nano Today*, Vol. 5, No. 5, 2010, pp. 379–383

Burgess, I., Aizenberg, J. and Loncar, M., *Creating Bio-inspired Hierarchical 3D-2D Photonic Stacks Via Planar Lithography on Self-Assembled Inverse Opals*, 2012, Ithaca, NY, Cornell University Library, doi: 10.1088/1748-3182/8/4/045004.arXiv: 1211.6811

Comanns, P., Effertz, C., Hischen, F., Staudt, K., Böhme, W. and Baumgartner, W., 'Moisture harvesting and water transport through specialized micro-structures on the integument of lizards', *Belstein Journal of Nanotechnology*, Vol. 2, 2011, pp. 204–214

Corni, I., Harvey, T. J., Wharton, J. A., Stokes, K. R., Walsh, F. C. and Wood, R. J. K., 'A review of experimental techniques to produce a nacre-like structure', *Bioinspiration and Biomimetics*, Vol. 7, 23 pp., 2012, doi: 10.1088/1748-3182/7/3/031001

Craig, S., Harrison, D., Cripps, A. and Knott, D., 'BioTRIZ suggests radiative cooling of buildings can be done passively by changing the structure of roof insulation to let longwave infrared pass', *Journal of Bionic Engineering*, Vol. 5, No. 1, 2008, pp. 55–66

De Focatis, D. S. A. and Guest, S. D., 'Deployable membranes designed from folding tree leaves', *Philosophical Transactions of The Royal Society London A*, Vol. 360, 2002, pp. 227–238 (retrieved from rsta.royalsocietypublishing.org on 21.01.11)

Dindyal, Shiva, 'The sperm count has been decreasing steadily for many years in Western industrialised countries: Is there an endocrine basis for this decrease?', *The Internet Journal of Urology*, Vol. 2, No. 1, 2004, ISSN: 1528-8390 (retrieved on 24.01.11)

Gallagher, C. L. (ed.), *Bioinspiration: An Economic Progress Report*, Fermanian Business and Economic Institute at Point Loma Nazarene University, commissioned by San Diego Zoo, 2013

Gallagher, C. L. (ed.), *Can 3D Printing Unlock Bioinspiration's Full Potential?*, Fermanian Business and Economic Institute at Point Loma Nazarene University, August 2014

Gruber, Petra, 'The signs of life in architecture', *Bioinspiration and Biomimetics*, Vol. 3, No. 2, 2008, doi: 10.1088/1748-3182/3/2/023001

Gruber, Petra and Jeronimidis, George, 'Has biomimetics arrived in architecture?', *Bioinspiration and Biomimetics*, Vol. 7, No. 1, 2012, doi: 10.1088/1748-3182/7/1/010201

Hassan, Tarek and Ye, Jilin (eds), *Proceedings of the 1st International Conference on Industrialised, Integrated, Intelligent Construction (I3CON)* Loughborough University, 14–16 May 2008

Hawken, P., Lovins, A. and Lovins, L. H., *Natural Capitalism*, New York, BackBay Books/Little, Brown and Company, 1999, ISBN: 978-0-316-35300-7

Hensel, M., Menges, A. and Weinstock, M., *Emergent Technologies and Design: Towards a Biological Paradigm for Architecture*, London and New York, Routledge, 2010, ISBN: 10 0-415-49344-7

Jones, David Lloyd, *Architecture and the Environment: Bioclimatic Building Design*, London, Lawrence King Publishing Ltd, 1998, ISBN: 1-85669-103-9

Kaplinsky, Joe, 'Biomimicry versus Humanism', *Manmade Modular Megastructures*, Architectural Design Special Issue, Vol. 76, No. 1, January/February, 2006, pp. 66–71, doi: 10.1002/ad.212

King, M. J. and Vincent, J. F. V. 'The mechanism of drilling by wood wasp ovipositors', *Biomimetics*, Vol. 3, No. 4, 1996, pp. 187–201

Knippers, Jan and Speck, Thomas, 'Design and construction principles in nature and architecture', *Bioinspiration and Biomimetics*, Vol. 7, No. 1, 2012, doi: 10.1088/1748-3182/7/1/015002

Kobayashi, H., Kresling, B. and Vincent, J. F. V., 'The geometry of unfolding tree leaves', *Proceedings of the Royal Society London*, B265, pp. 147–154

Lepora, Nathan F., Verschure, Paul and Prescott, Tony J., 'The state of the art in biomimetics', *Bioinspiration and Biomimetics*, Vol. 8, No. 1, 2013, doi: 10.1088/1748-3182/8/1/013001

McDonough, W. and Braungart, M., *Cradle to Cradle*: *Remaking the Way We Make Things*, New York, North Point Press, 2002, ISBN-13: 978-0-86547-587-8

Menges, Achim, 'Biomimetic design processes in architecture: Morphogenetic and evolutionary computational design', *Bioinspiration and Biomimetics*, Vol. 7, No. 1, 2012, 10 pp., doi: 10.1088/1748-3182/7/1/015003

Miserez, A., Weaver, J. C., Thurner, P. J., Aizenberg, J., Dauphin, Y., Fratzl, P., Morse, D. E. and Zok, F. W., 'Effects of laminate architecture on fracture resistance of sponge biosilica: Lessons from nature', *Advanced Functional Materials*, Vol. 18, No. 8, 2008, pp. 1241–1248, doi: 10.1002/adfm.200701135

Mogas-Soldevila, L., Duro-Royo, J. and Oxman, N., 'Water-based robotic fabrication: Large-scale additive manufacturing of functionally-graded hydrogel composites via multi-chamber extrusion', *3D Printing and Additive Manufacturing*, Vol. 1, No. 3, 2014, pp. 141–151

Nervi, P-L., *Considerations on the Architecture of Our Time*, transcript of the British Italian Society Leconfield Lecture by Pier Luigi Nervi, Pier Luigi Nervi archive folder held at the British Architectural Library, Portland Place, London

Nikolov, S., Fabritius, H. O., Petrov, M., Friák, M., Lymperakis, L., Sachs, C., Raabe, D. and Neugebauer, J., 'Robustness and optimal use of design principles of arthropod exoskeletons studied by ab initio-based multiscale simulations', *The Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 4, No. 2, 2011, pp. 129–145

Otto, F., Ansell, M., Baier, B., Barnes, M., Blum, R., Burkhardt, B., Cook, M., Croome, D., Dickson, M., Drüsedau, H., Greiner, S., Happold, E., Harnach, J., Harris, B., Haug, E., Hennicke, J., Howell, J., Lidell, I., Münsch, R., Racah, E., Williams, C., Schauer, E. and Schwenkel, D., Institute for Lightweight Structures, volumes IL1 to IL32 (dates from 1971), published by Institut für leichte Flächentragwerke, Universität Stuttgart, School of Architecture and Building Engineering, University of Bath, Universität Essen, Gesamthochschule, Fachbereich Bauwesen

Sachs, Jeffrey, *Common Wealth: Economics for a Crowded Planet*, London, Penguin Books Ltd, 2008, ISBN: 978-0-713-99919-8

Thompson, D'Arcy Wentworth, John Tyler Bonner (ed.), *On Growth and Form*, abridged edition, Cambridge, Cambridge University Press, 1961, ISBN: 0-521-09390-2

Trask, R. S., Williams, H. R. and Bond, I. P., 'Self-healing polymer composites: Mimicking nature to enhance performance', *Bioinspiration and Biomimetics*, Vol. 2, No. 1, 2007, pp. 1–9, doi: 10.1088/1748-3182/2/1/P01

Turner, J. Scott, *The Extended Organism: The Physiology of Animal-Built Structures*, Cambridge, MA and London, Harvard University Press, 2000, ISBN: 0-674-00151-6

Notes

[1] Buckminster Fuller, R., *Utopia or Oblivion*, new edition, Lars Muller Publishers, 2008.

[2] Amory Lovins' term, Schumacher College course 'Natural Capitalism', delivered by Janine Benyus and Amory Lovins, 23–26 September 2003.

[3] Buckminster Fuller, R., *Operating Manual for Spaceship Earth*, New York: Simon and Schuster, 1969.

[4] Jacob, F., 'Evolution and Tinkering', *Science*, Vol.196, 1977, p. 1162.

[5] Australian geneticist Jenny Graves asserts that 'the human eye is really stupidly designed – it's kind of inside out. We would do much better with squid eyes that are the right way round. So everywhere you look things really don't work very optimally, but evolution has made the best of it and polished it up a bit. But it never starts from scratch.' BBC, 2013. 'Jenny Graves'. Podcast. *The Life Scientific*, http://www.bbc.co.uk/programmes/b03bqw3z (accessed 06.04.16).

[6] Petra Gruber discusses this at greater length. See Gruber, P., *Biomimetics in Architecture: Architecture of Life and Buildings*, Springer, 2011 p. 109, ISBN-10: 3709103312.

[7] For the origins of the term, see Bernadette Bensaude-Vincent, Hervé Arribart, Yves Bouligand and Clément Sanchez, 'Chemists and the school of nature', *New Journal of Chemistry*, Vol. 26, 2002, pp. 1–5.

[8] Julian Vincent, Olga Bogatyrev, Nikolaj Bogatyrev, Adrian Bowyer and Anja-Karina Pahl, 'Biomimetics: Its practice and theory', *Journal of the Royal Society*, Vol. 3, No. 9, 2006, doi: 10.1098/rsif.2006.0127

[9] Eggermont, M., 'Interview with Julian Vincent', *Zygote Quarterly*, Vol. 1, Spring 2012, p. 26.

[10] Schumacher College course, *op. cit.* Janine Benyus more recently refers to 'life's genius' rather than 'nature's genius': http://www.biomimicry.net/about/biomimicry/ (accessed 15.07.16).

[11] Myers, W., *Biodesign: Nature + Science + Creativity*, London, Thames & Hudson, 2012.

[12] These characteristics are derived from Hoeller, N. *et al.*, 'Developing a common ground for learning from nature', *Zygote Quarterly*, Vol. 7, 2013, pp. 137–143.

[13] Wilson, E.O., *Biophilia*, Cambridge, Harvard University Press, 1984.

[14] Liu F. *et al.*, 'Deformation-as-control for a biologically inspired steerable needle', *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pp. 848–853.

[15] Lang, N. *et al.*, 'A blood-resistant surgical glue for minimally invasive repair of vessels and heart defects', *Science Translational Medicine*, Vol. 6, No. 218, 2014, p. 218, doi: 10.1126/scitranslmed.3006557.

[16] Victoria Gill, 'Cool ice cream innovations', http://news.bbc.co.uk/1/hi/sci/tech/8141203.stm (accessed 14.04.16).

[17] Lepora, N. *et al.*, 'The state of the art in biomimetics', *Bioinspiration and Biomimetics*, Vol. 8, No. 1, 2013.

[18] This has been widely quoted and the first use is hard to establish. It is quoted in Quinn, D., *Beyond Civilization: Humanity's Next Great Adventure*, Harmony Books, 1999, p. 137.

[19] Vincent, J.F.V. 'Stealing ideas from nature', *RSA Journal*, Aug./Sept., 1997, pp. 36–43.

[20] Vincent, J. and Owers, P., 'Mechanical design of hedgehog spines and porcupine quills', *Journal of Zoology*, Vol. 210, No. 1, 1986, pp. 55–75.

[21] See Mattheck, C., *Design in Nature – Learning from Trees*, Berlin, Heidelberg, New York, Springer-Verlag, 1998.

[22] Similar results can be achieved with finite element analysis, of which SKO is a variant.

[23] Vogel, S., *Cats' Paws and Catapults: Mechanical Worlds of Nature and People*, New York, W. W. Norton & Company, 1998, pp. 431–432.

[24] 'Buttresses' is the usual term but it is a misnomer because they actually work in tension. Just as with a guy-rope, shifting the connection point further from the base of the upright gives greater resistance to overturning.

[25] I say this in a metaphorical sense. Nature, of course, has no conscious intention – it proceeds by evolution and epigenetics.

26 Source: Steve Corbett, Green Oak Carpentry, launch of the 2011 Wood Award, The Building Centre, 24.03.11.

27 Quoted in Hansell, M., *Animal Architecture,* Oxford, Oxford University Press, 2005, p. 145.

28 *Considerations on the Architecture of Our Time* – transcript of the British Italian Society Leconfield Lecture by Pier Luigi Nervi.

29 *Ibid.*

30 Thompson, D.W., *On Growth and Form,* Dover Publications, 1917, reprinted 1992.

31 Calcite is a form of calcium carbonate and can grow in various crystal formations.

32 Su, X. *et al.*, 'The structure of sea urchin spines, large biogenic single crystals of calcite', *Journal of Materials Science*, Vol. 35, No. 22, 2000, pp. 5545–5551 and Tsafnat, N. *et al.*, 'Micromechanics of sea urchin spines', *PLoS ONE*, Vol. 7, No. 9, 2012.

33 Achim Menges, quoted in Stinson, L., 'Peanut-shaped building designed and built by robots', *Wired*, Technology, July 2014, http://www.wired.co.uk/news/archive/2014-07/07/peanut-house/viewgallery/336507 (accessed 06.04.16).

34 Naleway, S. *et al.*, *Bioinspiration from the Distinctive Armored Carapace of the Boxfish*, Materials Science and Engineering Program, Department of Mechanical and Aerospace Engineering, University of California, 2013.

35 Collagen is a structural protein and a common connective tissue in animals.

36 Barnes, Robert D., *Invertebrate Zoology*, Philadelphia, Holt-Saunders International, 1982, p. 104, ISBN: 0-03-056747-5.

37 The structure is described in great detail in Weaver, J. *et al.*, 'Hierarchical assembly of the siliceous skeletal lattice of the hexactinellid sponge *Euplectella aspergillum*', *Journal of Structural Biology*, Vol. 158, No. 1, 2007, pp. 93–106.

38 *Ibid.*, p. 101. See also Deshpande, V. *et al.*, 'Foam topology bending versus stretching dominated architectures', *Acta Materialia*, Vol. 49, 2001, pp. 1035–1040. See also Aizenberg, J. *et al.*, 'Skeleton of *Euplectella* sp.: Structural hierarchy from the nanoscale to the macroscale', *Science*, Vol. 309, 2005, pp. 275–278.

39 Aizenberg *et al.*, 2005, *op. cit.*, propose that this may be to provide additional surface area for attachment of the top sieve plate.

[40] Personal communication with Foster + Partners' Communications Department.

[41] The helical ridges go in opposite directions, which also provides resistance to torsional failure.

[42] Lichtenegger, H., *et al.*, 'Variation of cellulose microfibril angles in softwoods and hardwoods: A possible strategy of mechanical optimization', *Journal of Structural Biology*, Vol. 128, 1999, pp. 257–269.

[43] Nikolov, S., *et al.*, 'Robustness and optimal use of design principles of arthropod exoskeletons studied by ab initio-based multiscale simulations', *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 4, No. 2, 2011, pp. 129–145.

[44] Hansell, M., *Built by Animals – The Natural History of Animal Architecture*, 2007, Oxford University Press, pp. 76–77.

[45] *Ibid.*, pp. 19–20.

[46] Otto, F., *et al.* Institute for Lightweight Structures volumes IL1 to IL32 (dates from 1971), published by Institut für leichte Flächentragwerke, Universität Stuttgart, School of Architecture and Building Engineering, University of Bath, Universität Essen, Gesamthochschule, Fachbereich Bauwesen.

[47] Quoted in Kimpian, J., 'Pneumatrix – The Architecture of Pnuematic Structures in the Digital World', unpublished PhD thesis dissertation, Royal College of Art, 2001. Original source given as (without page reference): Dessauce, M. (ed.), *The Inflatable Moment: Pneumatics and Protest in '68*, New York, Princeton Architectural Press, 1999.

[48] Vogel, 1998, *op. cit.*, p. 148.

[49] Kimpian, J., 'Pneumatrix – The Architecture of Pneumatic Structures in the Digital World', unpublished PhD thesis dissertation, Royal College of Art, 2001.

[50] *Ibid.*

[51] Adrover, E.R., *Deployable Structures*, London, Laurence King Publishing Ltd, 2015, p. 13.

[52] Vincent, J., *Deployable Structures in Nature*, Centre for Biomimetics, University of Reading, UK but accessed from University of Bath, Biomimetics and Natural Technologies website, http://www.bath.ac.uk/mech-eng/biomimetics/DeployableStructs.pdf (accessed 21.01.11).

[53] The deployable structure designed by Guest and Pellegrino is described in Guest, S. *et al.*, 'Inextensional wrapping of flat membranes', *First International Conference on Structural Morphology*, Montpellier, R. Motro and T. Wester (eds), 7–11 September 1992, pp. 203–215.

[54] Manufacturers of ETFE claim that it can be made in a closed-loop cycle that does not release perfluorinated compounds (which are environmentally persistent) to the environment and that it is 100 per cent recyclable.

[55] Gennaro Senatore (University College London) in collaboration with Expedition Engineering developed the novel methodology and control system to design adaptive building structures. A large-scale prototype of an adaptive truss structure was built at the UCL structures laboratory to test/validate the methods. See G. Senatore, P. Duffour, S. Hanna, F. Labbe and P. Winslow, Large Scale Adaptive Structures for Whole Life Energy Savings, *International Associa tion for Shell and Spatial Structures (IASS)*, Vol. 52, No. 4 December n. 170, 2011; G. Senatore, P. Duffour, P. Winslow, C. Wise, "Infinite stiffness structures via active control" in *Proceedings of the International Association for Shell and Spa tial Structures (IASS) Symposium* 2015, Amsterdam. See Expedition website and links: http://expedition.uk.com/projects/adaptive-truss/ (accessed 14.04.16).

[56] Timber gridshells, for instance, often have problematic junctions with glazed walls underneath. Conceivably, this could be solved more elegantly with an ETFE clerestory that deliberately allowed a higher degree of roof deflection than would normally be tolerated by conventional movement joints.

[57] Some commentators argue that we should strive to release humans from all forms of physical labour, but that seems to be based on a negative starting point – that all forms of labour represent drudgery.

[58] Benyus, J., *Biomimicry: Innovation Inspired by Nature*, New York, Harper Collins, 1998, p. 97.

[59] Mueller, T., 'Biomimetics', *National Geographic*, April 2008, http://ngm.nationalgeographic.com/2008/04/biomimetics/tom-mueller-text/1 (accessed 06.04.16).

[60] Interestingly, recent experiments that involved spraying spiders with graphene flakes have resulted in the strongest fibre ever measured. If you're into strong materials, then you should also look at limpet teeth, which may be stronger than spider silk (http://www.bbc.co.uk/news/science-environment-31500883 (accessed 06.04.16)) and the mantis shrimp, which can accelerate its high-strength dactyl club at 102,000 m/s^2 – see Weaver *et al.*, 'The stomatopod dactyl club: A formidable damage-tolerant biological hammer', *Science,* Vol. 336, 2012, pp. 1275–1280.

[61] Vincent, J., 'Biomimetics: A review', *Proc. IMechE Part H: J. Engineering in Medicine*, Vol. 223, 2008, pp. 919–939.

62 Some recent articles described the iron-reinforced shell of the scaly-foot snail, which has been studied by the defence industry, but the shell contains iron sulphides, which are minerals rather than metals: http://www.cbc.ca/news/technology/snail-s-iron-armour-eyed-by-military-1.941044 (accessed 06.04.16).

63 Allen, Robert (ed.), *Bulletproof Feathers: How Science Uses Nature's Secrets to Design Cutting-Edge Technology*, Chicago and London, University of Chicago Press and Ivy Press Limited, 2010. Refer to the chapter by Vincent, J., pp. 134–171. The last pair (about elements) on the list is from Benyus, J., Schumacher College course, *op. cit.*

64 Beukers, A. and van Hinte, E., *Lightness: The Inevitable Renaissance of Minimum Energy Structures,* Rotterdam, 010 Publishers, 1999.

65 A more detailed description of hierarchical structures can be found in McKeag, T., 'Little things multiply up: Hierarchical structures', *Zygote Quarterly*, Vol. 9, 2014, pp. 10–27.

66 Gordon, J., *The New Science of Strong Materials*, London, Penguin Books, second edition, 1976, p. 118.

67 The three main articles are: Barthelat, F., *et al.*, 'Nacre from mollusk shells: A model for high-performance structural materials', *Bioinspiration and Biomimetics*, Vol. 5, 2010, pp. 1–8; Porter, M., *et al.*, 'It's tough to be strong: Advances in bioinspired structural ceramic-based materials', *American Ceramics Society Bulletin*, Vol. 93, No. 5, 2014, pp. 18–24; Barthelat, F. *et al.*, 'A laser-engraved glass duplicating the structure, mechanics and performance of natural nacre', *Bioinspiration and Biomimetics*, Vol.10, No. 2, 2015.

68 Aizenberg *et al.*, 2005.

69 Numerous other advantages of 3D printing are described in Gallagher, C. L. (ed.), *Can 3D Printing Unlock Bioinspiration's Full Potential?*, Fermanian Business and Economic Institute at Point Loma Nazarene University, August 2014, p. 10.

70 Shelley, T., 'Rapid manufacturing set to go mainstream', *Eureka Magazine*, 14.11.2007.

71 Mogas-Soldevila, L., *et al.*, 'Water-based robotic fabrication: Large-scale additive manufacturing of functionally-graded hydrogel composites via multi-chamber extrusion', *3D Printing and Additive Manufacturing*, Vol. 1, No. 3, 2014, pp. 141–151.

72 Wegner, T. H. and Jones, P. E., 'Advancing cellulose-based nanotechnology', *Cellulose*, Vol. 13, 2006, pp. 115–118.

[73] Quoted in Farrell, B., ‘The View from the Year 2000’, *LIFE magazine*, 26 February 1971.

[74] Thermodynamically, of course, there will be some energy involved but it presumably comes from nutrients supplied to the bacteria – likely to be many orders of magnitude less than kiln-firing.

[75] Biorock is trademarked and patented by Thomas Goreau and Wolf Hilbertz.

[76] The steel frames acquire a coating of mineral within days of being submerged and then form an ideal substrate for attaching coral species.

[77] The accretion rate is also partly determined by the surface area of the steel and the ionic composition of the seawater.

[78] Tibbits, S., TED talk, https://www.ted.com/talks/skylar_tibbits_the_emergence_of_4d_printing?language=en (accessed 06.04.16).

[79] Reichert S. et al., ‘Meteorosensitive architecture: Biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness’, *Computer-Aided Design*, 2014.

[80] Gruber, 2011, *op. cit.*, p. 131.

[81] Dry, Dr. C., 2011, *Development of a Self-Repairing Durable Concrete*, Natural Process Design Inc., http://www.naturalprocessdesign.com/Tech_Concrete.htm (accessed 06.04.16).

[82] Jonkers, H., *Bioconcrete*, Technical University of Delft, http://www.tudelft.nl/en/current/latest-news/article/detail/zelfherstellend-biobeton-tu-delft-genomineerdvoor-european-inventor-award/ (accessed 15.04.16).

[83] This effect is described in greater detail in McKeag, T., ‘Return of the Swamp Thing’, *Zygote Quarterly*, Fall 2012, pp. 12–14.

[84] *Ibid.*, pp. 15–27.

[85] Cradle to Cradle® and C2C are registered trademarks of MBDC, LLC.

[86] McDonough, W. and Braungart, M., *Cradle to Cradle: Remaking the Way We Make Things*, New York, North Point Press, 2002.

[87] Three European studies show consistent trends of ca. 50 per cent decline in sperm counts since 1938. These are summarised in Dindyal, S., ‘The sperm count has been decreasing steadily for many years in Western industrialised countries: Is there an endocrine basis for this decrease?’, *The Internet Journal of Urology*, Vol. 2, No. 1, 2004.

[88] There is some semantic disagreement about terminology here. Some people refer to technologies as 'carbon negative' (because they remove carbon from the air) while others refer to them as 'carbon positive' because they add carbon to a sequestered sink. Recent developments, such as Unilever announcing their intention to go 'carbon positive', suggest that the consensus will move towards the 'positive'. Anyone in the communications industry who wants action on climate change is likely to favour the positive version.

[89] Globally, about 15 billion tonnes of concrete are poured every year, of which roughly 80 per cent is aggregates. By atomic weight, the carbon dioxide that becomes part of the calcium carbonate represents 44 per cent of the weight. This suggests that, with full deployment of carbon-negative aggregates, concrete construction could sequester 5 billion tonnes of carbon dioxide per annum.

[90] 'Drawdown technologies' seems to be the common terminology, although Tim Flannery refers to them as 'Third-way technologies'. He describes some strong candidate technologies in *Atmosphere of Hope: Solutions to the Climate Crisis*, Penguin Books Ltd, Kindle edition. 2015.

[91] Readers interested in the role materials play in our lives would do well to read Miodownik, M., *Stuff Matters: The Strange Stories of the Marvellous Materials that Shape Our Man-Made World*, Penguin Books Ltd, 2013.

[92] *Plastiki & the Material of the Future,* http://plastikithemovie.com/ (accessed 06.04.16).

[93] Hansell, M., 2005, *op. cit.*, p. 75.

[94] Thixotropy is defined in the *Chambers Dictionary* as 'the property of showing a temporary reduction in viscosity when shaken or stirred'.

[95] Williams, R., 'Big Delta: The 3D printer that prints clay houses', *Daily Telegraph*, 22 September 2015, http://www.telegraph.co.uk/technology/news/11882936/Big-Delta-the-3D-printer-that-prints-clay-houses.html (accessed 06.04.16).

[96] A more detailed description of the characteristics of bioplastics can be found in McKeag, T., 'Case study: Oh, so plastic', *Zygote Quarterly 14*, Vol. 3, 2015, p. 16.

[97] McKeag, T., 'Case study: Sticky wicket: A search for an optimal adhesive for surgery, *Zygote Quarterly 14*, Vol. 3, 2015, p. 19.

[98] The ICD/ITKE Research Pavilion was a joint project of students and research associates of the ICD (Achim Menges) and ITKE (Jan Knippers) at the University of Stuttgart. Their work has been widely published and perhaps the best summary can be found in 'Material synthesis: Fusing the

physical and the computational', guest edited by Achim Menges, *Architectural Design*, Vol. 85, No. 5, 2015.

99 If we attempt to quantify the energy savings achievable, we could compare the embodied energy of, say, aluminium with wood and then assume that additive manufacturing with cellulose could create structural elements with, as an educated guess, one-sixth of the embodied energy of a solid timber section. The diagrams earlier in the chapter explaining shape and hierarchy showed that it is relatively straightforward to reduce the weight of an element to 14 per cent or even 5 per cent of its original mass. A factor-6 saving for AM with cellulose relative to solid timber feels relatively conservative. Using embodied energy figures (from Prof. Geoff Hammond, Craig Jones, Sustainable Energy Research Team, Department of Mechanical Engineering, Bath University 'Inventory of Carbon and Energy (ICE). Version 1.6a') of 157.1 MJ/kg for aluminium and 9.4 MJ/kg for timber and the assumed efficiencies achieved through AM, this would suggest an embodied energy reduction from 157.1 down to 1.57 MJ/kg (a factor-100 increase in resource efficiency).

100 Allen, Robert (ed.), 2010, *op. cit.* Refer to the chapter by Vincent, J., pp. 134–171.

101 Stamets, P., '6 Ways Mushrooms Can Save The World', TED Talk, 2008.

102 von Liebig, J., *Die Grundsatze der Agricultur-Chemie*, Braunschweig, 1855. The historical debate about London's sewers is described at some length by Carolyn Steel in *Hungry City*, Chatto & Windus, 2008, pp. 249–281, and by Herbert Girardet in *Cities, People, Planet: Liveable Cities for a Sustainable World*, Chichester, John Wiley & Sons, 2004, p. 77.

103 Lovins, Amory, course at Schumacher College, *op. cit.* Also in Benyus, Janine, *Biomimicry, op. cit.*

104 To clarify this summary: flows of energy are, as dictated by laws of thermodynamics, always linear. Flows of other resources, such as carbon, nitrogen, water, etc. are mostly closed loop in ecosystems, although there are some limited exceptions to this. Arguably, fossil fuels are an example of waste and it could be seen as ironic that we are currently getting ourselves into difficulties as a direct result of using waste from ancient ecosystems. Similarly, the carbon cycle involves some flows between atmosphere, hydrosphere and lithosphere that are linear in the short-term but closed loop over a geological timescale. 'Feedback-rich' is an observation from Ken Webster at the Ellen MacArthur Foundation, which is intended to convey the idea that flows of resources in ecosystems effectively involve information flows as well, in the sense that they influence the numbers of predators and prey in a dynamic relationship.

105 Some biological organisms have evolved to use toxins, but only for a specific purpose and all the toxins break down after use to harmless constituents

106 'Panarchy' is a term used by systems theorists as an antithesis to hierarchy.

107 Interview between the author and Professor Marc Weissburg, 23.12.15.

108 Benyus, Janine, course at Schumacher College, *op. cit.* Also in Benyus, J., 1998, *op. cit.*

109 Susannah Hagan describes this approach with great persuasiveness in Hagan, Susannah, *Ecological Urbanism: The Nature of the City*, Taylor & Francis, Kindle edition, 2014, pp. 4–5.

110 Zero Emissions Research and Initiatives (ZERI), *Brewing a Future*, http://www.sdearthtimes.com/et0101/et0101s7.html (retrieved 19.09.10, accessed 06.04.16).

111 Tragically, the Green Business Network was subjected to swingeing government cuts in 2015 and the ABLE Project is no longer operating. Given the extensive benefits delivered by the project, this is surely a classic example of short-term, narrow-focus economics that delivers long-term loss.

112 This idea too has antecedents in the work of John Todd, Nancy Jack Todd and William McLarney at the New Alchemy Institute, which experimented with projects called 'The Ark', see https://en.wikipedia.org/wiki/New_Alchemy_Institute.

113 The idea of vertical farms, which have been given extensive coverage in recent years, suffers from exactly these kinds of functional challenges. Agriculture is almost totally dependent on light and to substitute natural light with artificial light is both a financial and a practical challenge.

114 Steel, C., 2008, *op.cit.*

115 Desai, P., *One Planet Communities: A Real-Life Guide to Sustainable Living*, Chichester, UK, John Wiley & Sons Limited, 2010, p. 103.

116 UK Sustainable Development Commission, *Healthy Futures: Food and Sustainable Development,* 2004. http://www.sd-commission.org.uk/publications.php?id=71 (accessed 23.08.16)

117 Donella Meadows was one of the most eloquent writers about systems thinking and her work is essential reading: Meadows, D., *Thinking in Systems: A Primer*, Chelsea Green Publishing. Kindle edition, 2008, pp. 3–4.

118 Rodin, J., *The Resilience Dividend: Managing Disruption, Avoiding Disaster, and Growing Stronger in an Unpredictable World*, London, Profile Books, Kindle edition, 2014, Kindle Locations 125–127.

119 *Ibid.*, Kindle Locations 182–183.

[120] Layton, A., Bras, B. and Weissburg, M., 'Industrial ecosystems and food webs: An expansion and update of existing data for eco-industrial parks and understanding the ecological food webs they wish to mimic', *Journal of Ecology*, Yale University, 2015, doi: 10.1111/jiec.12283.

[121] *Ibid.*, p. 5.

[122] I must credit this excellent line to my editorial consultant Alison McDougall-Weil.

[123] This aspect is described in considerably more detail in Ball, J. D. and Melton, P., 'Circular economy at scale: Six international case studies', *Environmental Building News*, Vol. 24, No. 10, 2015, pp. 1–7.

[124] Hagan, S., 2014, *op. cit.*, p. 13.

[125] This is the basis of much of the new enterprises collectively referred to as 'the sharing economy'.

[126] Schmidt-Nielsen, K. *et al.*, 'Desaturation of exhaled air in camels', *Proceedings of the Royal Society of London, Series B, Biological Sciences*, Vol. 211, No. 1184, (11 March 1981), pp. 305–319.

[127] Fuel cells produce approximately 0.5 l/kWh, of which probably 60 per cent could be captured. Expressed in terms of drinking water per kWh of electricity, the average US household uses 0.17 l/kWh, so that requirement could easily be provided by a fuel cell.

[128] Parker, A. R. and Lawrence, C. R., 'Water capture by a desert beetle', *Nature*, Vol. 414, 2001, pp. 33–34. A lot of papers have been written about the fog-basking beetle and scientific understanding has moved on considerably, so it is worth checking more recent papers, such as Malik, F. T. *et al.*, 'Nature's moisture harvesters: A comparative review', *Bioinspiration and Biomimetics*, Vol. 9, No. 3, 2014.

[129] Wang, Y., 'A facile strategy for the fabrication of a bioinspired hydrophilic–superhydrophobic patterned surface for highly efficient fog-harvesting', *Journal of Materials Chemistry A*, 2015, 3,18963.

[130] See http://www.fogquest.org/ (accessed 06.04.16) and Aleszu Bajak, 'Fog catchers pull water from air in Chile's dry fields', *New Scientist*, 25 June 2014.

[131] Lev-Yadun, S. *et al.*, '*Rheum palaestinum* (desert rhubarb), a self-irrigating desert plant', *Naturwissenschaften*, 2008, doi: 10.1007/s00114-008-0472-y.

[132] Ju, J., 'A multi-structural and multi-functional integrated fog collection system in cactus', *Nature Communications*, Vol. 3, No. 1247, 2012, doi: 10.1038/ncomms2253.

133 Interview between the author and Professor Colin Caro.

134 Harman, J., *The Shark's Paintbrush: Biomimicry and How Nature is Inspiring Innovation*, Nicholas Brealey Publishing, 2013.

135 Vogel, S., *Life in Moving Fluids: The Physical Biology of Flow*, Chichester, UK, Princeton University Press, 1994, pp. 317–321.

136 Lee, J. *et al*., 'Murray's law and the bifurcation angle in the arterial micro-circulation system and their application to the design of microfluidics', *Microfluidics and Nanofluidics*, Vol. 8, No. 1, 2010, pp. 85–95.

137 Schumacher College course, *op. cit.*

138 The team's analysis extended to the characteristics of the biome in terms of water collection, filtration and storage, solar gain and reflectance, carbon sequestration, evapotranspiration, nutrient cycling, biodiversity, soil building and temperature amongst many other biological processes, and they applied biomimicry to every aspect of the design process. The water story is focused on here because it transforms a problem of over-abundance ingeniously.

139 Thomas, D., 'The mineral depletion of foods available to us as a nation (1940–2002): A review of the 6th edition of McCance and Widdowson', *Nutrition and Health*, Vol. 19, 2007, pp. 21–55, doi: 0260–1060/07.

140 Kompetenz Zentrum Wasser Berlin website, *Sanitation Concepts for Separate Treatment*, http://www.kompetenzwasser.de/SCST.22.0.html (accessed 14.04.2016).

141 Thermophiles live at temperatures above 100 0C in submarine volcanic vents.

142 Hansell, M., 2005, *op. cit.*, p. 4.

143 Nicholls, H., 'Peak performer', *New Scientist,* Vol. 220, No. 2939, pp. 46–47.

144 I have used the common terminology but they should be called 'weather-adaptive'. 'Climate' refers to how the atmosphere behaves over a long period of time, whereas 'weather' is what happens over a short period.

145 When I say 'loosely', I do not mean this in a critical way – only to explain why I have not gone into more detail to clarify the source of inspiration and how the function is delivered in nature.

146 Flectofin was a joint project between ITKE (Prof. Jan Knippers, University of Stuttgart), the Plant Biomechanics Group (Prof. Thomas Speck, University of Freiburg) and the Institute for Textile

Technologies (ITV, Prof. Markus Millwich, Denkendorf). ITKE was the initiator and coordinator of this research project, funded by the German Ministry of Research.

147 Lienhard, J. *et al.*, ‘Flectofin: A hingeless flapping mechanism inspired by nature’, *Bioinspiration and Biomimetics*, Vol. 6, No. 4, 2011, doi: 10.1088/1748-3182/6/4/045001.

148 The Thematic Pavilion uses a slightly different compliant mechanism which was inspired by previous research on the Flectofin. The kinematic facade was designed by soma, Vienna and engineered by Knippers Helbig Advanced Engineering, Stuttgart.

149 This was primarily the work of Julian Vincent and his colleagues Drs Olga and Nikolay Bogatyrev at the University of Bath. For further information, see chapters written by Vincent in Robert Allen (ed.), *op cit.,* 2010.

150 Disappointingly, this scheme did not win the competition. If the idea were to be pursued, it would be worth exploring the potential of electro-osmosis (a naturally occurring form of osmosis induced by an electric field) together with bio-utilisation of plants as evaporating surfaces.

151 Webb, R., ‘Offices that breathe naturally’, *New Scientist*, No. 1929, 11.06.94 and J. P. E. C. Darlington, ‘The structure of mature mounds of the termite *Macrotermes michaelseni* in Kenya’, *Insect Science and Its Applications*, Vol. 6, 1986, pp. 149–156.

152 Soar, R. and Turner, S., ‘Beyond biomimicry: What termites can tell us about realizing the living building’, *First International Conference on Industrialized, Intelligent Construction (I3CON)*, Loughborough University, 14–16 May 2008.

153 Convective heat transfer is defined by Wikipedia as ‘the transfer of heat from one place to another by the movement of fluids’, see https://en.wikipedia.org/wiki/Convective_heat_transfer. Fluids include not just the colloquial meaning of liquids, but also gases.

154 Loonen, R. *et al.*, ‘Climate adaptive building shells: State-of-the-art and future challenges’, *Renewable and Sustainable Energy Reviews*, Vol. 25, 2013, p. 488.

155 This is the approach advocated by Biomimicry 3.8 – aiming to design buildings and cities to match all the ecological performance standards of the ecosystem that would have existed in that location prior to the Anthropocene. This would mean, for instance, matching the level of carbon sequestration, the level of biodiversity supported, the way the water is cycled, etc.

156 Yamanashi, T. *et al.*, ‘BIO SKIN urban cooling façade’, *Architectural Design*, Vol. 81, No. 6, 2011, pp. 100–108.

157 Soar and Turner, 2008, *op. cit.*

158 Corbusier, L., *Towards A New Architecture*, Courier Corporation, 1931.

159 Boyce, P. R., 'Review: The impact of light in buildings on human health', *Indoor and Built Environment*, Vol. 19, No. 1, 2010, pp. 8–20.

160 Aizenberg, J. *et al.*, 'Designing efficient microlens arrays: Lessons from Nature', *Journal of Materials Chemistry*, Vol. 14, 2004, pp. 2066–2072.

161 Holt A. *et al.*, 'Photosymbiotic giant clams are transformers of solar flux', *Journal of the Royal Society, Interface*, Vol. 11, No. 101, 2014, 20140678.

162 Land, M., 'Biological optics: Deep reflections', *Current Biology*, Vol. 19, No. 2, 2008, pp. 78–80, doi: 10.1016/j.cub.2008.11.034. See also: Partridge, J. *et al.*, 'Reflecting optics in the diverticular eye of a deep-sea barreleye fish (*Rhynchohyalus natalensis*)', *Proceedings of the Royal Society B: Biological Sciences*, Vol. 281, No. 1782, 2014, 9 pp.

163 Sundar, V. C. *et al.*, 'Fibre-optical features of a glass sponge', *Nature*, Vol. 424, 21 August 2003, pp. 899–890.

164 In some cultures glass sponges are given as wedding presents, which seems to represent curious symbolism given the nature of the shrimps' existence.

165 Weiss, P., 'Channeling light in the deep sea', *Science News*, Vol. 164, No. 12, 20 September 2003, p. 190.

166 Hoeller, N. *et al.*, 2013, *op cit.* See also Bay, A. *et al.*, 'Improved light extraction in the bioluminescent lantern of a *Photuris* firefly (Lampyridae)', *Optics Express*, Vol. 21, No. 1, 2013, pp. 764–780.

167 Deheyn, D. *et al.*, 'Bioluminescent signals spatially amplified by wavelength-specific diffusion through the shell of a marine snail', *Proceedings of the Royal Society of London B*, Vol. 278, No. 1715, 2011, pp. 1–10.

168 Somewhat predictably, a lot of the related funding and research has been directed towards military rather than civilian applications.

169 Woolley-Barker, T., 'Learning from the master shape-shifter: Cephalopod technologies', *Zygote Quarterly*, No. 4, Winter 2012, pp. 12–27, http://zqjournal.org/?p=158 (accessed 04.04.16).

170 McKeag, T., ‘Requiem for a butterfly: Mirasol’s market meltdown’, *Zygote Quarterly*, No. 5, Spring 2013, pp. 12–29.

171 Burgess, I. *et al.*, *Creating Bio-Inspired Hierarchical 3D-2D Photonic Stacks via planar Lithography on Self-Assembled Inverse Opals*, Cornell University Library, 2012, doi: 10.1088/1748-3182/8/4/045004, arXiv:1211.6811.

172 See https://www.seas.harvard.edu/news/2013/01/bioinspired-fibers-change-color-when-stretched (accessed 07.04.16); also Kolle, M. *et al.*, ‘Bio-inspired band-gap tunable elastic optical multilayer fibers’, *Advanced Materials*, Vol. 25, No. 15, 2013, pp. 2239–2245, doi: 10.1002/adma.201203529.

173 Park, D. *et al.*, ‘Dynamic daylight control system implementing thin cast arrays of polydimethylsiloxane-based millimeter-scale transparent louvers’, *Building and Environment*, Vol. 82, 2014, pp. 87–96.

174 The micro-fluidic aspects are described in Hatton, B., *et al.*, ‘An artificial vasculature for adaptive thermal control of windows’, *Solar Energy Materials and Solar Cells*, Vol. 117, October 2013, pp. 429–436.

175 See ‘Lifelike cooling for sunbaked windows: Adaptable microfluidic circulatory system could cut air-conditioning costs’, 30 July 2013, Harvard Press Release. For DDCS details, Park, D. *et al.*, 2014, *op. cit.* On adaptive microfluidics, see Hatton, B. *et al.*, 2013, *op. cit.*

176 Scheer, H., *The Solar Economy*, London, Earthscan, 2002.

177 There are a very limited number of exceptions to this, such as thermophiles.

178 Iceland sources 100 per cent of its electricity and a large amount of its heat from renewables. Several other countries, such as Norway, Albania and Costa Rica, are effectively run on 100 per cent renewable electricity. This leaves energy for heat and transportation, which remain substantially fossil-fuel based.

179 The earth continuously receives about 174,000 terawatts (TW) of energy from the sun, of which 30 per cent is reflected back into space, 19 per cent is absorbed by clouds and 89,000 TW reaches the surface. Our average annual energy consumption between 2008 and 2010 was very close to 15 TW. The earth therefore receives 11,600 times as much energy and, at the surface, we receive 5,933 times as much as we consume. Sources: IEA Key World Energy Statistics 2010.

180 One of the most thorough and impartial assessments of energy options is MacKay, D., *Sustainable Energy – Without the Hot Air*, Cambridge, UIT, 2008.

181 Abbott, D., ‘Keeping the energy debate clean: How do we supply the world’s energy needs?’, *Proceedings of the IEEE*, Vol. 98, No. 1, January 2010, pp. 42–66.

182 Geothermal energy is not renewable, but the size of the resource compared to the most optimistic rate at which we could extract the energy results gives an operating period of hundreds of millions of years.

183 Amory Lovins refers to these as ‘things that go pump in the night’, Schumacher College course, *op. cit.*

184 ‘Offshore wind power and wave energy devices create artificial reefs’, *ScienceDaily*, 19.01.10.

185 Nauclér, T. and Enkvist, P. A., *Pathways to a Low Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve*, 2009, McKinsey & Company http://www.mckinsey.com/client_service/sustainability/latest_thinking/greenhouse_gas_abatement_cost_curves (accessed 07.04.16).

186 MacKay, 2008, *op. cit.*

187 Fish, F. *et al.*, ‘The humpback whale’s flipper: Application of bio-inspired tubercle technology’, *Integrative and Comparative Biology*, Vol. 51, 15.05.2011, pp. 203–213 http://icb.oxfordjournals.org/content/early/2011/05/14/icb.icr016.full.pdf+html (accessed 07.04.16).

188 Vogel, S., 1998, *op. cit.*, pp. 96–100.

189 Sandia National Laboratories, ‘A mighty wind’, http://www.sandia.gov/news/publications/labnews/articles/2016/22-01/wind_blades.html (accessed 07.04.16).

190 Whittlesey, R. *et al.*, ‘Fish schooling as a basis for vertical axis wind turbine farm design’, *Bioinspiration and Biomimetics*, Vol. 5, No. 3, 2010. See also Dabiri, J., ‘Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays’, *Journal of Renewable Sustainable Energy*, Vol. 3, 2011, 043104 http://dx.doi.org/10.1063/1.3608170 (accessed 07.04.16).

191 They actually claim a factor-10 increase is possible.

192 Noone, C. *et al.*, ‘Heliostat field optimization: A new computationally efficient model and biomimetic layout’, *Solar Energy*, Vol. 86, No. 2, 2012, pp. 792–803.

193 Greiner, C., *et al.*, ‘Bio-inspired scale-like surface textures and their tribological properties’, *Bioinspiration and Biomimetics*, Vol. 10, 2015, 044001, doi: 10.1088/1748-3190/10/4/044001.

194 Amongst the most promising is the work of Daniel Nocera at MIT, Prof. Dr. Arved Hübler at the University of Technology Chemnitz, Germany and Jiaxing Huang at Northwestern University, US.

195 http://www.extremetech.com/extreme/188667-a-fully-transparent-solar-cell-that-could-make-every-window-and-screen-a-power-source (accessed 07.04.16).

196 This anecdote was relayed to me by Professor Patrick Hodgkinson.

197 Herbert Girardet describes this in *Cities, People, Planet: Liveable Cities for a Sustainable World*, Chichester, England, John Wiley & Sons Ltd, 2004, pp. 45–46.

198 The Pilot Plant is described in McKeag, T., ‘The Sahara Forest Project: Seeing the forest for the trees’, *Zygote Quarterly*, Vol. 4, Issue 11, 2014, pp. 10–35.

199 The challenges of this approach are also described in McKeag, T., 2014, *op. cit.*

200 It would have been even better if floral and microbial biodiversity had also been monitored, but budgets were limited.

201 Considerable debate persists about what the peak will be. The consensus is between 9 and 10 billion. Scientific breakthroughs that fundamentally change life expectancy could change this number substantially.

202 This book is essential reading for all architects, as one of the best books about urban design in recent decades. Hagan, S., *Ecological Urbanism: The Nature of the City*, Taylor and Francis. Kindle edition, 2014, pp. 19–20.

203 Hagan, S., 2014, *op. cit.*, p. 31.

204 Benyus, J., 1998, *op. cit.*, pp. 253–254.

205 It is not possible to do justice to the depth of thought and design input that the Arup team invested here. For more insight, see Peter Head’s ‘Brunel Lecture 2008: Entering the Ecological Age’, http://publications.arup.com/publications/e/entering_the_ecological_age_the_engineers_role and read Chapter 7 of Benyus, J., 1998, *op. cit.*

206 Ecological footprinting was developed by Mathis Wackernagel – see the introduction of Peter Head, 2008, *op. cit.*

207 Head, P., *op. cit.*, p. 18.

208 Webster, K., *The Circular Economy: A Wealth of Flows*, Ellen MacArthur Foundation Publishing, 2015.

209 *Ibid.*

210 Zipcar's annual Millennial Survey of 1,015 adults reports that millennials are the only age category to rate their mobile devices (phone and laptop) above their car, in terms of the greatest negative impact of losing that technology on their daily routine. http://www.citylab.com/commute/2013/02/millennials-say-theyd-give-their-cars-their-computers-or-cell-phones/4841/ (accessed 07.04.16). MIT City Lab looked into the use of mobile phone data to understand the new noncentralised city: http://web.mit.edu/schlmark/www/SMART_Seminar.pdf (accessed 07.04.16).

211 Sceptics might wonder what it did to journey times but, counter-intuitively, journey times in the centre of Seoul actually improved – a great example that demonstrates Braess' paradox.

212 Quoted from press release provided in private communication between the author and the architects.

213 Wiscombe, T., 'Beyond assemblies: System convergence and multi-materiality', *Bioinspiration and Biomimicry*, Vol. 7, No. 1, 2012, pp. 1–7, doi: 10.1088/1748-3182/7/1/015001.

214 *Ibid.*, p. 2.

215 *Ibid.*, p. 4.

216 *Ibid.*, p. 4.

217 Anderson, R., *Confessions of a Radical Industrialist*, London, Random House Business Books, 2009, p. 9.

218 Interface Sustainability Report 1997, http://www.interfaceglobal.com/app_themes/interface/pdfs/interface_sustainability_report_1997.pdf (accessed 14.01.16).

219 Hawken P., Lovins, A. and Lovins, L. H., *Natural Capitalism*, New York, BackBay Books/Little, Brown and Company, 1999, p. 133.

220 At the time of writing the initiative had collected 66,860 kg of discarded fishing nets, http://net-works.com/ (accessed 07.04.16).

221 Anderson, R., 2009, *op. cit.*, p. 4.

222 Quoted in Farrell, B., ‘The View from the Year 2000’, *LIFE magazine*, 26 February 1971.

223 Schumacher course *op. cit.*

224 Marshall, A., ‘Biomimicry’, *Encyclopaedia of Corporate Social Responsibility*, Berlin, Heidelberg, Springer 2013, p. 174.

225 Kostelanetz, R., *Conversing with Cage,* London, Routledge, 2003.

226 Bernet, A and Smith, C., blog post, ‘Nature and business: developing a sustainable society together’, 7 July 2015. http://biomimicry.org/nature-business/#.VrC8dzaLQo8 (accessed 07.04.16).

227 UK Government’s chief scientist John Beddington: Ian Sample, ‘World faces “perfect storm” of problems by 2030, chief scientist to warn’, *Guardian*, 18.03.09.

228 A good example of this would be certain Gulf states that have responded to water scarcity by making water effectively free. This may alleviate farmers’ concerns but it completely undermines the potential for innovative technologies that save water. A braver approach would be to tax water and allocate all the tax revenue to subsidising water-saving technologies.

229 This observation comes from Satish Kumar. Kumar once asked the head of the London School of Economics if the school had a department of ecology. He followed that up by asking ‘How can you manage your home without knowledge of it?’ Source: personal conversation between the author and Satish Kumar.

230 Rosling, H., ‘Hans Rosling on global population growth’, TED talk, filmed June 2010, posted July 2010, http://www.ted.com/talks/hans_rosling_on_global_population_growth.html (accessed 07.04.16).

231 Speck, T. and Speck, O., ‘Process sequences in biomimetic research’, *WIT Transactions on Ecology and the Environment*, Vol. 114, 2008.

232 I am choosing my words carefully here and I stress that I advocate compromising as little as **necessary** rather than as little as possible. The former is what is required to deliver innovative solutions; the latter is the province of the *prima donna.*

233 Okri, B., *A Time for New Dreams: Poetic Essays,* London, Rider, 2011.

234 Meadows, D., *Leverage Points: Places to Intervene in a System*, The Sustainability Institute, 1999, http://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/ (accessed 14.04.16). This has become influential, and Nesta has developed it into a 12-point guide.

[235] BioTRIZ, www.biotriz.com/ (accessed 07.04.16).

[236] MacKay's book is available gratis online, on his website, http://www.withouthotair.com/ (accessed 07.04.16).

[237] Futerra, *The Rules of the Game: Principles of Climate Change Communications*, report, February 2005, http://www.stuffit.org/carbon/pdf-research/behaviourchange/ccc-rulesofthegame.pdf (accessed 14.04.16).

[238] Oblique Strategies, http://www.oblicard.com/ (accessed 07.04.16).

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