BIOMIMICRY *in* ARCHITECTURE

SECOND EDITION

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Michael Pawlyn

RIBA Publishing

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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

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.

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

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.

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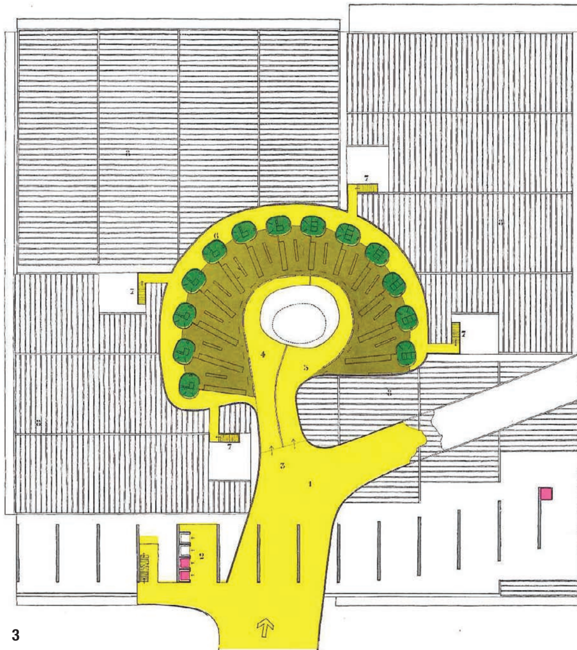
There are some other terms that are worth clarifying: 'biophilia', 'biomorphic', 'bio-utilisation' and 'synthetic biology'. 'Biophilia' was a term popularised by the biologist E. O. Wilson[13] and refers to a hypothesis that there is an instinctive bond between human beings and other living organisms. '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.

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



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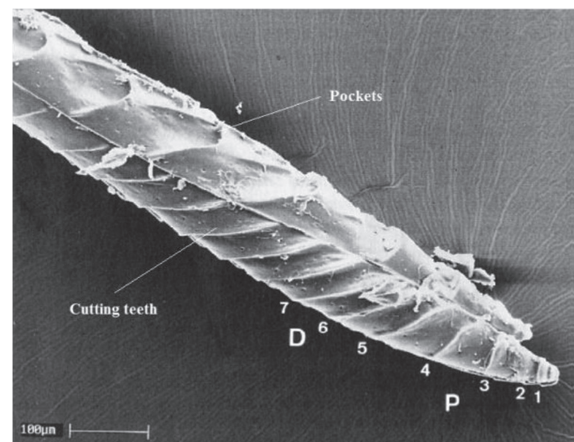
was used to great symbolic effect by Le Corbusier (fig. 3). But, in contrast, biomimicry is concerned with the way in which functions are delivered in biology. The distinction is important because we require a functional revolution of sorts, and I firmly believe that it will be biomimicry rather than biomorphism that will deliver the transformations described above.

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.

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



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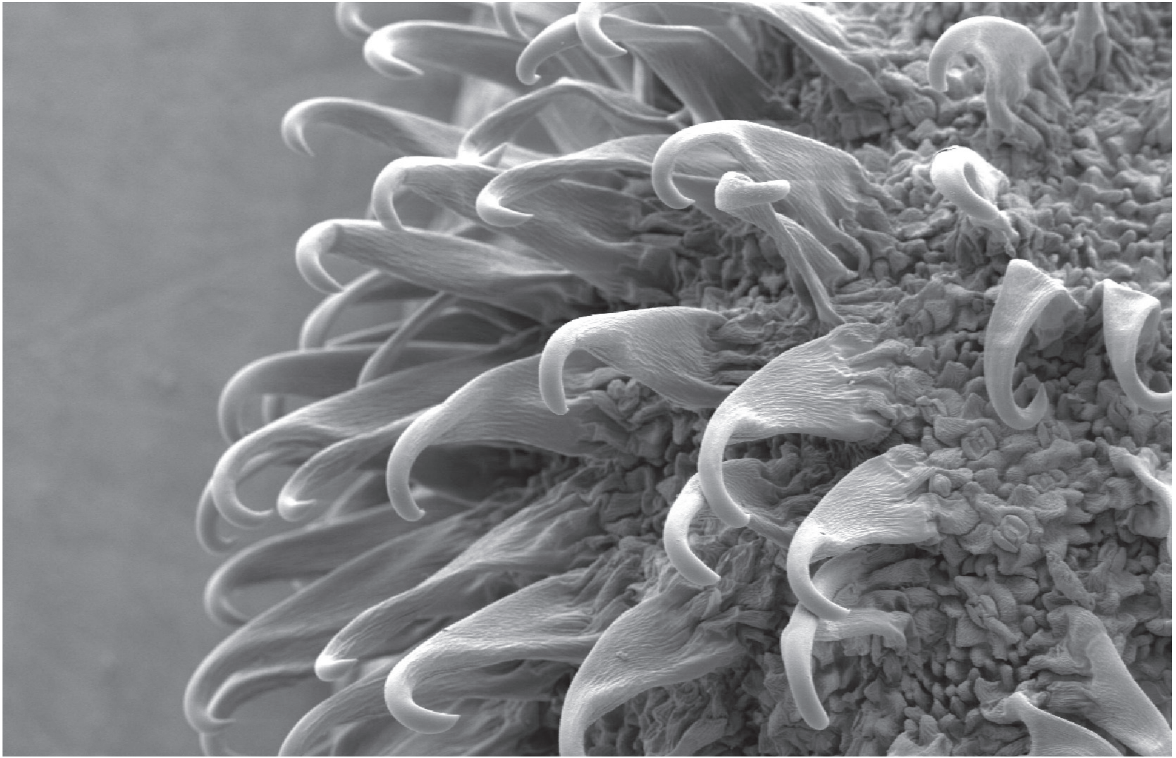

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is a reciprocating drill, made of two shafts that are semi-circular in cross-section, each with a barb at the pointed lower end (fig. 4). The two halves can slide back and forth relative to each other so that, when a barb on one side latches into a 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.

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

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

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

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

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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.

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

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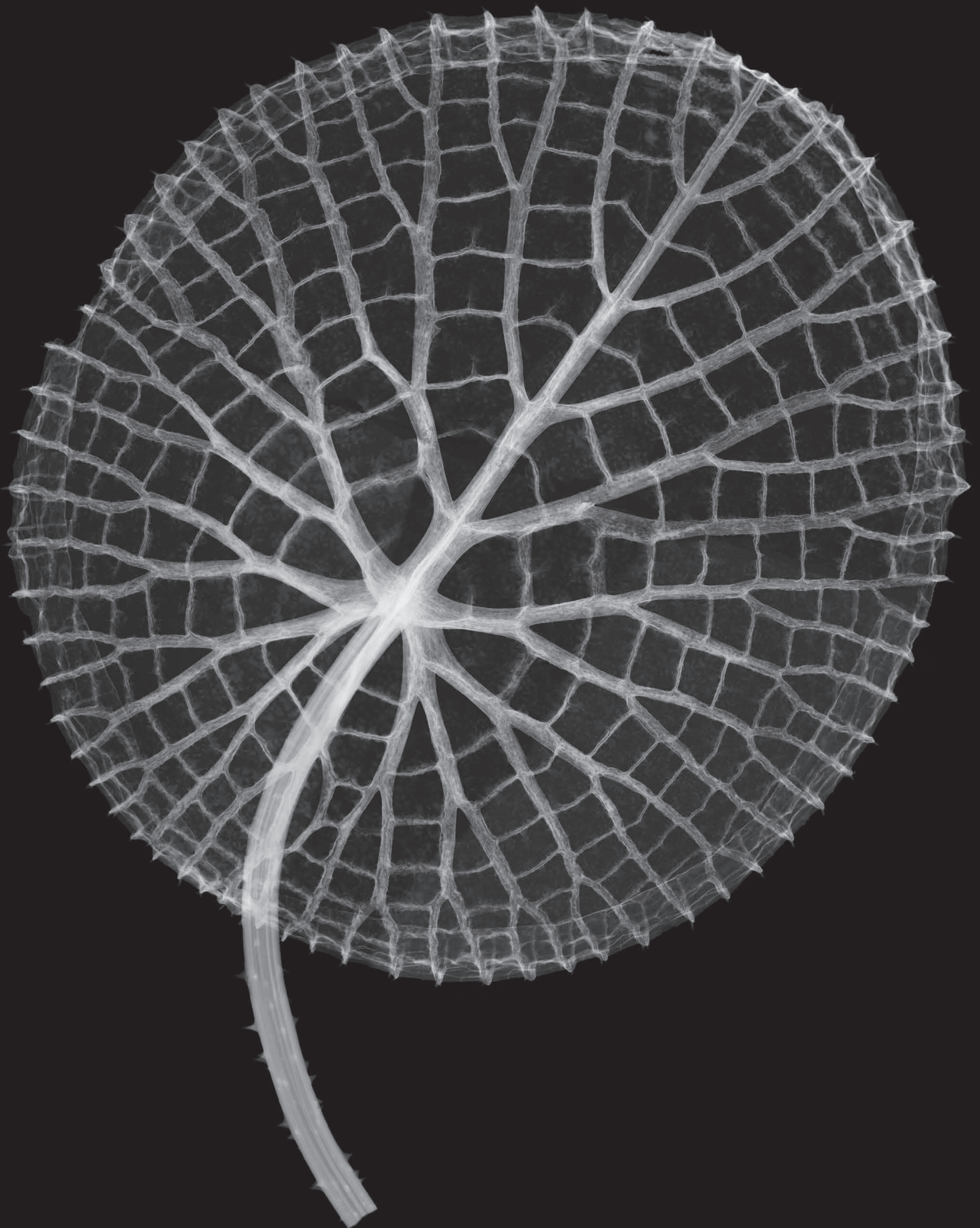
paradigm based on optimising positives and delivering regenerative solutions.

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]

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

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



CHAPTER ONE

How can we build more efficient structures?

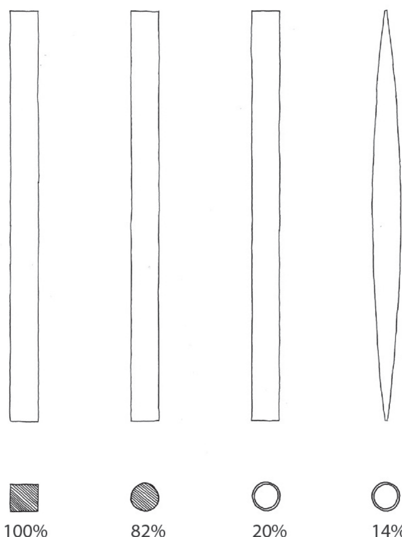
In nature, materials are expensive and shape is cheap.
PROFESSOR JULIAN VINCENT[19]

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.

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



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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

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*)

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.

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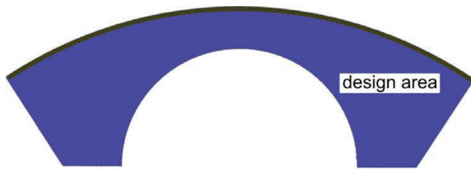
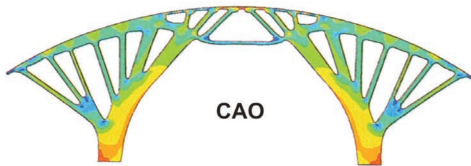
Trees: solid forms

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





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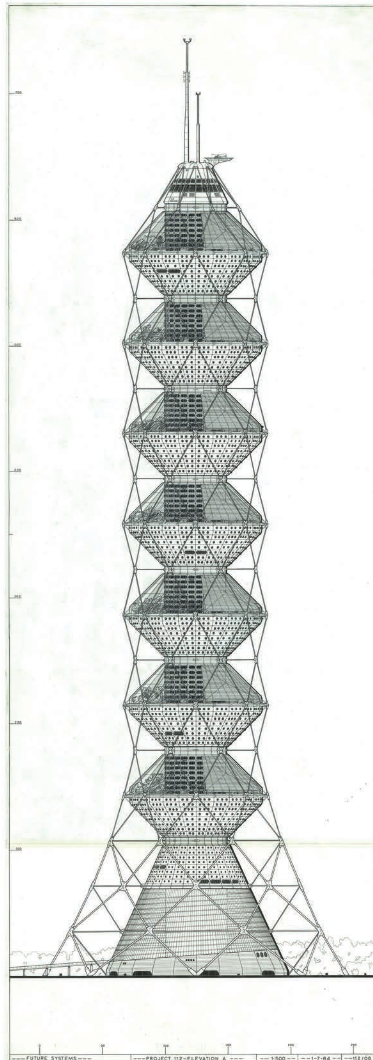
could do the same with buildings and achieve huge increases in material efficiency while producing more elegant and structurally legible forms.

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).



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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

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

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

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