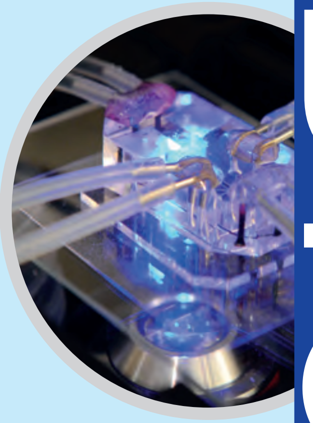
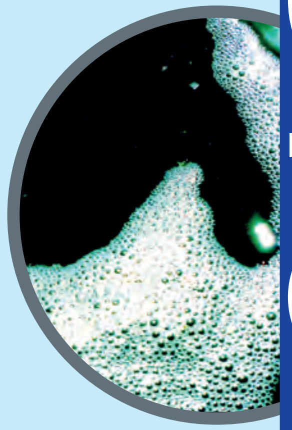


"The biggest innovations of the twenty-first century will be the intersection of biology and technology. A new era is beginning." So the Apple luminary Steve Jobs told his biographer, Walter Isaacson. *Bio Design*—featuring fabric grown from food waste, self-healing concrete, leaves that glow in the dark, and DNA that stores data—explores a future closer than we think.



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MYERS

BIO DESIGN

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WILLIAM MYERS

BIO DESIGN

nature
science
creativity

MoMA

BIO DESIGN

Nature • Science • Creativity

WILLIAM MYERS

Foreword by PAOLA ANTONELLI

with 467 illustrations, 436 color

THE MUSEUM OF MODERN ART, NEW YORK

To my teachers, especially Celeste Topazio, Lisa Farber, Michael Rosenfeld, and Alice Twemlow

William Myers lives in New York, where he teaches and writes about the history of architecture and design. He has written for *Domus*, *Metropolis*, *Architect's Newspaper*, *Next American City*, and the Pentagram design consultancy. William has also worked in a variety of roles for The Museum of Modern Art, the Solomon R. Guggenheim Museum, and the Smithsonian's Cooper-Hewitt, National Design Museum. He is a graduate of the Design Criticism MFA program at the School of Visual Arts in New York.

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Carnivorous Domestic Entertainment Robots.
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Blood Lamp. Image courtesy of Mike Thompson
Lung-on-a-Chip. Image courtesy of the Wyss Institute for Biologically Inspired Engineering at Harvard University
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Dune. Image courtesy of the architect
Carnivorous Domestic Entertainment Robots. Image courtesy of the designers
Future Venice. Image courtesy of Rachel Armstrong

The quotation on the back cover is taken from *Steve Jobs* by Walter Isaacson, published by Little, Brown in 2011.

Frontispiece:
Algaerium. Image Courtesy of Marin Sawa

VITAL DESIGN

Paola Antonelli

Design is not what it used to be. In schools and in studios, in corporations and in political institutions, designers are using their skills to tackle issues that were previously out of their bounds, from scientific visualization to interfaces, from sociological theories to possible applications and consequences of nanotechnology. They do so by teaming up for every case study with the right experts, who often seek designers' help in order to connect their theories with real people and the real world. In the late 1960s, Ettore Sottsass famously declared that design 'is a way of discussing society, politics, eroticism, food and even design. At the end, it is a way of building up a possible figurative utopia or metaphor about life.'[1] Design is indeed about life and, at a time of accelerated technological evolution and dramatic political, environmental, demographic, and economical concerns, designers' presence guarantees that human beings are always kept at the center of the discussion.

Designers' fascination with science is today reciprocated by a generation of scientists who are eager to get their brains dirty with reality. As explored first in the 2008 exhibition 'Design and the Elastic Mind' at the Museum of Modern Art, New York (full disclosure: yours truly was the curator), these novel collaborations are often joyous contaminations in which scientists feel, even if just for a moment, liberated from the rigor of peer review and free to attempt intuitive leaps. Indeed, physicists, mathematicians, computer scientists, engineers, chemists, and bioethicists have leaped at the opportunity, their contribution encouraged and celebrated in a few centers of 'irradiation,' such as London's Royal College of Art Design Interactions program or Le Laboratoire, an idea incubator in Paris. The results (based on current research) have the lyrical and demonstrative power of art and the realistic possibilities of design.

It is, however, the experiments with biologists that have garnered the strongest momentum, and a new form of organic design is rapidly evolving—the biodesign that William Myers explores in detail in this volume. Biodesign harnesses living materials, whether they are cultured tissues or plants, and embodies the dream of organic design: watching objects grow and, after the first impulse, letting nature, the best among all engineers and architects, run its course. It goes without saying that when the materials of design are not plastics, wood, ceramics, or glass, but rather living beings or living tissues, the implications of every project reach far beyond the form/function equation and any idea of comfort, modernity, or progress. Design transcends its traditional boundaries and aims straight at the core of the moral sphere, toying with our most deep-seated beliefs. In designers' ability to build scenarios and prototypes of behavior lies a power that they should protect and cherish, and that will become even more important in the future.

William Myers has collected an impressive variety and number of case studies that involve organisms at all scales, from plants and animals to bacteria and cells, to be used as architectural, graphic, or interior elements. Architects working on wet buildings that adapt to changing environmental conditions and levels of occupancy, almost as if they were living organisms; designers concocting new diagnostic and therapeutic tools that rely on animals and plants; engineers devising new, self-healing construction materials. If our relationship with nature is broken, this book makes us hope that perhaps we will be able to fix it from within.

1
As reported in Peter Dormer, 'What is a designer?', *Design Since 1945* (London: Thames & Hudson, 1993) p.10.

THE HYBRID FRONTIER

William Myers

This book presents an emerging and often radical approach to design that draws on biological tenets and even incorporates the use of living materials into structures, objects, and tools. Each chapter introduces a different theme, from designing for ecological integration to the use of speculative design and art as a teaching tool. Taken together, several of the projects profiled here reflect a pervasive shift in societal priorities, toward sustainable approaches to building and manufacturing. This unifying purpose is driving increased collaboration between designers and biologists—an essential ingredient in many of the projects—and offers thrilling new possibilities for design, art, and architecture. This volume brings together the most recent and representative examples of biodesign: a rapidly emerging approach observable in this collection of works from around the world.

Biodesign goes further than other biology-inspired approaches to design and fabrication. Unlike biomimicry, cradle to cradle, and the popular but frustratingly vague 'green design,' biodesign refers specifically to the incorporation of living organisms as essential components, enhancing the function of the finished work. It goes beyond mimicry to integration, dissolving boundaries and synthesizing new hybrid

typologies. The label is also used to highlight experiments that replace industrial or mechanical systems with biological processes. The final chapter ventures beyond functional or speculative design into the realm of fine art, presenting a range of recent work that incorporates living matter.

The structures, prototypes, and concepts chronicled here, including proposals that employ new technologies and impose principles observed only in nature, prompt several questions. What are the implications and likely outcomes of these speculative projects? Does the sum of these experiments, including an embrace of natural systems and collaboration with the life sciences, amount to a paradigm shift in design practice? If so, how does it compare with other field-changing shifts in the trajectory of technological developments, from industrialization to the invention of computers?

As answers to these questions unfold over time, the space for cross-disciplinary collaboration and creativity prompted by scientific research will only expand, propelled by global imperatives such as the urgency to develop and implement cleaner technologies and the rise of do-it-yourself 'homebrew' biology. This convergence of fields, as well as of the expert with the amateur, is ultimately necessary to support the ongoing effort to alleviate the negative impacts of the legacies of the Industrial Revolution. And it will lead to the reconception of the primary design principles of value generation, growth, and sustainability. This book sets out to accelerate this effort by highlighting achievements in, and new approaches to, design with biology, encouraging collaborations and providing historical context for this growing field in design.

BEYOND BIOMIMICRY

A NEW URGENCY

'It will be soft and hairy.' [1]

Salvador Dalí on the future of architecture, in response to Le Corbusier

Designers face an unprecedented urgency to alter their methods and reprioritize their goals to address the accelerating degradation of the environment. This new pressure—intellectual, ethical, and regulatory—demands recognition of the fragility of nature and our responsibility to preserve it for future generations. Under such shifting and intensifying constraints, designers are beginning to go beyond emulation to harness processes observed in the living world, where systems achieve perfect economies of energy and materials. Within this pursuit, working to achieve enhanced ecological performance through integration with natural systems, designers are turning to biologists for their expertise and guidance. This contrasts markedly with the design approach that characterized the 20th century: the mechanization of functions in order to overpower, isolate, and control forces of nature, usually by utilizing advances in chemistry and physics. The examples explored here illustrate how this new approach—designing with biology—lends itself to collaborations with life scientists and foreshadows what kind of consilience, or cooperation across fields, we can expect in the future.

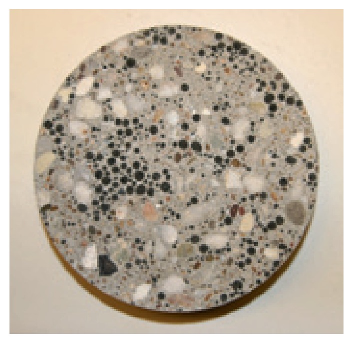
The integration of life into design is not a magic bullet to solve these pressing issues. Nor will it be free from harmful missteps, deliberate misuses, or controversy. Dystopian visions of the future awash in biodesign gone awry are credible possibilities, and they are included in this book. Beyond growing structures with trees or integrating objects with algae bioreactors, biodesign includes the use of synthetic biology and thereby invites the danger of disrupting natural ecosystems. These technologies will be wielded by people—the same biased and frail creatures who designed the world into a desperate mess in the first place. But the potential benefits, and the need to reform current practices toward an approach more in tune with biological systems, far outweigh these risks. Ultimately, design's embrace of nature—even coupled with the inevitable hubris that we can redesign and outdo it—is long overdue and the most promising way forward.

The focus of cross-disciplinary collaborations and their outcomes will, as always, depend on societal priorities and an array of market signals. Today there is a notable absence of the kind of regulation or system of incentives and disincentives that might lead to the eventual design and creation of environmentally remedial or zero-carbon objects and structures. The use of taxes and subsidies to spark such changes, for example, is still in its infancy. While Germany and Norway have made early and effective steps with policies that prioritize ecologically effective design, most of the industrialized world lags behind, especially the United States, where even the legitimacy of the federal agency to protect the environment is vulgarly challenged in political discourse.

Yet the costs of carbon emissions and climate change mount, and they will need to be addressed if a modern way of life, as we've come to know it, is to endure. Examples of biodesign profiled here anticipate this change: an accounting for, and eventual minimization of, what economists call negative externalities to the environment—the degradation of the air, soil, water, and life that does not figure into the end cost of manufacturing and building today. Only under new and sensibly designed constraints, such as a carbon tax on manufacturing, or incentives, such as a subsidy for structures that promote biodiversity, would projects such as 'Fab Tree Hab' (page 58) or 'BioConcrete' (page 80) become scalable.

ABOVE 1

In contrast with traditional architecture that is in combat with the environment, **Fab Tree Hab** is a housing concept that embraces and enhances the surrounding ecosystem. Living trees are integrated into the structures.



ABOVE 2

Researchers at Delft University of Technology have developed **BioConcrete**, which is embedded with limestone-making microorganisms that allow the material to repair itself.

ABOVE 3

A modular system of algae-filled tubes absorbs solar energy for electricity generation and shades interior spaces in **Process Zero**, a proposed retrofit for a General Services Administration building in Los Angeles (page 52).

The imitation of nature in the design of objects and structures is an old phenomenon, recalling stylistic developments such as iron-enabled Art Nouveau in the 19th century through to the more recent titanium-clad fish shapes in the computer-aided designs of architect Frank Gehry. Yet this design approach is form driven and offers only a superficial likeness to the natural world for decorative, symbolic, or metaphorical effect. Design that sets out to deliberately achieve the qualities that actually generate these forms—adaptability, efficiency, and interdependence—is infinitely more complex, demanding the observational tools and experimental methods of the life sciences. The effort to master this complexity is well under way; it's been more than 30 years since scientists first altered a bacterium's DNA so that it could serve as a tiny factory producing an inexpensive and reliable source of human insulin.[2] At the beginning of the 21st century, the DNA-modifying techniques to reproduce such a feat and reconfigure the activity of a cell have become widely accessible. We have even reached the milestone of synthesizing an entirely artificial DNA molecule that has successfully replicated and formed new cells.[3] The affordability of the basic tools of biotechnology has put them within reach of engineers and designers who may now consider basic life forms as potential fabrication and form-giving mechanisms. Indeed, that is precisely the intention of architects such as David Benjamin, who is teaching and practicing how to wield life as a design tool and insists that 'This is the century of biology.'[4]

In the 19th century the combination of standardization of measurements, the Bessemer steel-making process, and the steam engine converged to enable the Industrial Revolution, answering the call of democratic, capitalistic nation-states seeking market growth. Facilitating this development was the increasing quality and plummeting price of steel, which rapidly fell from $170 per ton in 1867 to $14 per ton before the end of the century.[5] Similarly, and following what has become known as Moore's Law, the computing power of microchips has roughly doubled every two years since the 1990s. This phenomenon, amplified by the rise of the Internet and the worldwide adoption of standards like HTML, has supported a Digital Revolution.[6] Computer technology exponentially spread and intensified the practices and effects of the Industrial Revolution, and they addressed the demands of a rapidly globalizing economy. These demands include pressure to compete in foreign markets, to coordinate increasingly complex supply chains, and to achieve continual economic expansion through productivity gains. In fulfilling these needs, digital technology lubricates the gears of civilization as we know it, supporting economic growth and maintaining relatively low unemployment and stable governments across most of the developed world.

In the first decade of the 21st century and beyond, the forces that prompted industrialization and digitization persist, but a new, more urgent, and arguably longer-term need has arisen that calls for a new revolution—the requirement for ecologically sound practices in design that guide scarce resource management, particularly in manufacturing and building. Abundant evidence makes plain that the pace of world economic development in its current form, relying on the rapid consumption of natural resources (including fossil fuels), cannot be maintained.[7] The scale and scope of human activity and projected changes in climate, economic demand, urbanization, and access to resources over the next several decades will necessitate new standards of energy efficiency, waste elimination, and biodiversity protection.

Models that meet such rigorous demands have been found only in nature, the emulation of which is now moving beyond stylistic choice to survival necessity. Driven by research in the life sciences, the mechanisms of natural systems—from swamps to unicellular yeasts—are quickly being decoded, analyzed, and understood. The architectural program of many of these systems is DNA, the sequencing and synthesis of which are quickly becoming financially viable, following what has become known as the Carlson Curve: the costs of sequencing and synthesizing base pairs of DNA have fallen dramatically over the last 10 years, just as steel and computing power became inexpensive commodities in previous centuries.[8] The possibilities arising from this new accessibility of the basic ingredient of living systems will surely multiply, particularly given the pace of capital investment and the proliferation of entrepreneurial ventures poised to exploit its potential. Although these technologies are still new and require much more research before they can easily be applied to complex organisms, the pace of investment and growth is significant: more than 2 percent of United States GDP is now attributable to products that rely on genetic modification.[9] As the expertise to manipulate and wield the machinery of life spreads, it will impact numerous fields and lead to several collaborations; biodesign, as I have defined it, is an opportunity that designers will not miss and that is already attracting tinkerers of all stripes.

As it often does, art illuminated the path forward. Bioart of the last decade, including works by Eduardo Kac, such as the living, glowing 'GFP Bunny' in 2000 and the numerous projects that have emerged from SymbioticA, foreshadowed the now burgeoning do-it-yourself biology (DIY bio) movement. Facilitated by the availability of inexpensive equipment and emboldened by like-minded enthusiasts through instant communication over the web, amateur biologists are now creating transgenic organisms and even inventing novel equipment on their own. These new creators, some of them with design experience, also follow in the footsteps of tech entrepreneurs working out of garages in California in the 1970s and 1980s, and they bring an ethos of independence that is unlinked from the agendas or conventions of universities and corporations.

ABOVE 4

Art Nouveau attempted to mimic natural forms displaced by industrialization. The movement emerged in France but then spread swiftly around the world. The Hôtel Tassel in Brussels is a masterwork of Victor Horta, and it was completed in 1894 for the scientist Émile Tassel.

PHYSICAL SCIENCE TO LIFE SCIENCE: A HISTORY OF NATURE IN DESIGN

'The Stone Age did not end because humans ran out of stones. It ended because it was time for a re-think about how we live.'[10]

Architect William McDonough

The desire to follow nature, to adhere to its underlying forms in the pursuit of harmony, can be traced back to antiquity, to the writings of Vitruvius, as well as to Goethe's work on morphology and the Romantic notion that certain truths were observable in nature and unknowable to reason. The close examination and formal mimicry of nature by designers reached a height in the late 19th century, in the Art Nouveau style in France and in its iterations across Europe, coinciding with the work of naturalists and pioneers of biology, like Ernst Haeckel, who meticulously described, named, and illustrated thousands of new species. Shortly thereafter in *On Growth and Form* (1917), D'Arcy Thompson described numerous links among biological form, physics, and mechanics, and highlighted how optimization was frequently achieved in nature. This also coincided with the First World War, and the rapid rise of mechanized industry as a dominant feature of economic, aesthetic, and political life in Europe and the United States.

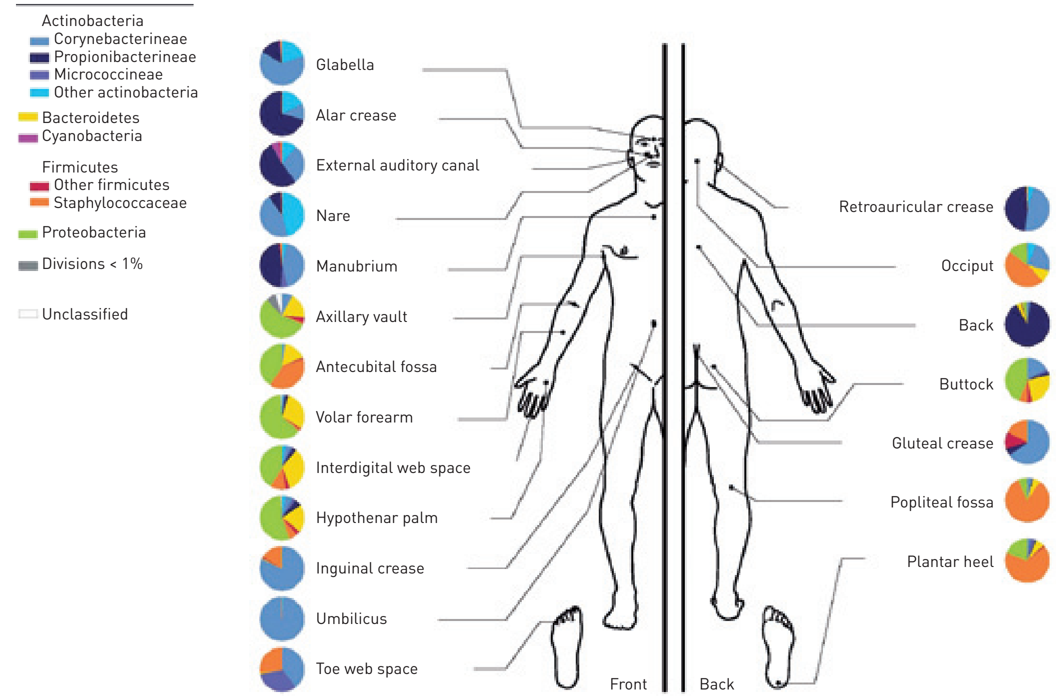
Interest in nature as a model or tool for design remained a consistent, if minor, current in architecture of the early 20th century. This was particularly so in the work of figures such as Frank Lloyd Wright, Alvar Aalto, and even Mies van der Rohe, for their focus on integration of indoor and outdoor spaces, use of natural materials, expression of structure, and consideration of architecture as a component of a larger whole—at least its immediate built surroundings. The idea of emulating nature on a larger scale emerged decades later in post-war Japan, articulated by the built and theoretical megastructures of the Metabolist movement that embraced impermanence, citing the fluctuations of nature as a logical guiding principle for buildings and cities, which themselves undergo massive transformations that can be considered in terms of cycles, including destruction and rebirth.

The more familiar contemporary understanding of the built environment and industrial manufacturing as systems affecting their natural surroundings matured in the wake of the environmental movement and the energy crisis of the 1960s and 1970s, as expressed through the works of Richard Buckminster Fuller, Rachel Carson, and Victor Papanek.[11] Perhaps the best representation of the ideas they espoused is the concept of industrial ecology, explained first and with cogent precision in 1989 by Robert Frosch and Nicholas Gallopoulos, two scientists working for General Electric.[12] Their thesis can be summarized: industrial processes can be designed to resemble ecosystems wherein every waste product becomes a raw material for another process. This idea was explored further, with a naturalist view, by Janine Benyus in her seminal book *Biomimicry: Innovation Inspired by Nature* (1997), and her continuing work through the Biomimicry Guild and Institute. Following similar principles, in *Cradle to Cradle: Remaking the Way We Make Things* (2002), architect William McDonough and chemist Michael Braungart retold the history of Western architecture and industrial design to highlight their inherently destructive relationship with the people and environments from which they had risen. These authors also demonstrated the sort of cross-disciplinary partnership necessary to connect scientific research and rigor to industrial and building technologies for improved ecological performance. In a sense, they symbolized a return to the type of consilience that characterized the sciences and applied arts from the Renaissance, when leading artists and architects were also scientists, until about the 18th century, when the effects of the Scientific Revolution took hold and led to dramatically specialized fields of study.

Today, this rift between fields is narrowing by necessity. We recognize that designers do not simply create things like teapots and office towers but instead act as initiators of systems of resource collecting, labor application, manufacturing, marketing, distribution, consumption, and disposal. These activities, all oversimplified by the tendency to consider the object as an end in itself, present a uniquely complex set of problems and support the assertion that from an ecological standpoint, there are no such things as things: there are only *systems*. This realization mirrors new research in biomedicine that suggests the human body hosts approximately ten foreign cells for every one of its own making. We

ABOVE 5

SymbioticA is a pioneering research laboratory at the University of Western Australia that enables artists and researchers to engage in wet biology practices. It hosts residents, workshops, and symposia to support the exploration as well as the critical evaluation of scientific developments.

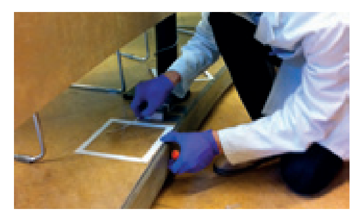


RIGHT 6

The Human Microbiome Project is a five-year research program undertaken by the US National Institutes of Health to identify and characterize the trillions of microorganisms that thrive both on and within the human body. Current estimates suggest that microbial cells outnumber the human variety by a factor of at least ten to one.

ABOVE 7

Illustrations of shells from a variety of gastropod mollusks, reproduced from Ernst Haeckel's influential *Kunstformen der Natur* ('Artforms of Nature'), which was published in 1904.



ABOVE 8

BioBE Center researchers at the University of Oregon at Eugene are working to map the microbiome (microorganism population) of the built environment, collecting samples from a variety of spaces and analyzing how these different groups impact human health.

depend on all this microscopic life—trillions of cells—for essential functions, like digestion and resistance to infection, making us all ecosystems in miniature.

The built environment is no different: as research by the BioBE Center (page 248) suggests, a better understanding of microbial life in indoor spaces—a vast and undiscovered realm we interface with all the time—may inform a probiotic design approach that reduces reliance on mechanical ventilation. These realizations arise in part from new access to the nanoscale, the ability to manipulate matter on the cellular and molecular levels. Just as standardization and manufacturing tolerances to the millimeter scale were crucial to the move from craft to the Industrial Revolution, as well as to the practices and goals of the Bauhaus school, the ability to change the inner functioning of a cell exponentially increases designers' reach, and is enabling a move from the industrial to the biotechnological. This in turn is becoming the medium of choice for a new Bauhaus school to emerge, perhaps in the form of the One Lab School for Urban Ecology (page 247).

This new access in scale also offers new vocabulary to the language of form, and may satisfy a larger need to bring the living world closer to our everyday lives. Perhaps in the recent past the mere mimicry of forms displaced by industrialization and globalization was sufficient as a symbol, but that time has past. In *Complexity and Contradiction in Architecture* (1966), which laid the intellectual foundation for postmodernism in architecture, Robert Venturi argued that the labored rectilinear style of the modernists was in fact a dishonest representation of functionalism and that both greater visual harmony and expression of function was achieved through formal conflict: shapes, lines, and textures that disrupt one another. Echoing that critique, one can see nature-inspired design and its iterations, often posturing under the banner of biomimicry as a labored style for its own sake that does not represent biodesign, for its intention strays from the priority of delivering enhanced ecological performance.

It is primarily by cooperation, communication, and debate that effective approaches to biodesign will be developed and implemented, and a legible formal language will emerge. As progress is made, however, and as designers and scientists work together more frequently, it's essential to recognize the challenges along with the opportunities. As shown in a recent study at the University of Cambridge, which examined such collaborations, obstacles often arise, such as disagreement about how to share intellectual property rights, a lack of shared vocabulary, and conflicting working styles and standards.[13] These and other issues will be at the forefront as society acknowledges that the consumption of irreplaceable resources and the loss of biodiversity driven by economic activity cannot be sustained. Consequently, systems of nature and the biologists who work to understand them will be integral to new systems for designing and creating. Only this type of consilience might help to bring the material existence of artificial environments and objects into a sustainable harmony with nature, a state upon which everything ultimately depends.

LEFT 9

To the present day the Pantheon remains the largest unreinforced dome in the world. Its stable structure was made possible by concrete that was poured in sections and supported by a wood scaffold until it dried, combined with clever engineering to reduce the weight of the rock substrate with increasing height.

THE EVOLVING GOALS AND DESIGN OF CONCRETE: A TRAJECTORY TOWARDS BIODESIGN

'Our objective is to use bio-based materials and processes for civil engineering to reduce environmental pressure.' [14]

Henk Jonkers, Researcher and Instructor, Bio-based Geo- and Civil Engineering Program, Technology University of Delft

LEFT 10

An early example of iron-reinforced concrete, the Lighthouse of Port Said was completed in 1869, just a week prior to the opening of the Suez Canal. The building was an important asset in facilitating global trade and had come under British imperial control by 1882.

BEYOND BIOMIMICRY

RIGHT 11, 12, 13, 14, 15, 16

The emerging priority of ecological performance is expressed in the development of self-repairing concrete. Embedded microorganisms naturally seal cracks as soon as they form, extending the life of this ubiquitous material. The production of cement, the binding agent of concrete, is increasing rapidly and is responsible for more than 6 percent of anthropogenic carbon dioxide emissions. Any improvement in its performance should represent a significant reduction in construction's carbon footprint.

Concrete's 2,400-year history offers an insightful example of the shift over time to biodesign, from some of civilization's earliest structures to new methods of using bacteria as an ecological means of reinforcement. Concrete has served designers and engineers as the spine of infrastructure and the foundational material of structures since antiquity. First widely used in the 4th century BC, it was integral to the Roman Architectural Revolution, which spanned several hundred years and generated structures—including domes, arches, and aqueducts—that still stand today.[15] Soon after the fall of Rome, the formula for concrete, calling for particular proportions of calcium oxide, pulverized rock, clay, ash, and water, was lost for thirteen centuries. It is useful to pause for a moment to ponder how builders for so long looked at ancient monuments that bested their own engineering ability. This age without concrete ended with its rediscovery in 1756 in England, the precise time and place of the dawn of the Industrial Revolution.

Approximately a century later, reinforced concrete was developed in France by François Coigent and was deployed to create several structural typologies that are common today.[16] The utility and historical significance of the material is well illustrated by many of his projects, from the sea wall in Saint-Jean-de-Luz, to the lighthouse in Port Saïd, Egypt, and the Aqueduc de La Vanne in Paris. All of these projects met infrastructure needs arising from the forces brought to bear by widespread industrialization and the rise of global capitalism in the form of colonialism: constructing ports to facilitate the movement of freight to support commerce, and infrastructure to facilitate rapid growth in urban populations. Similarly, the first structure in Britain to feature a reinforced concrete frame was a factory: a flourmill built in Swansea in 1897.[17]

With the benefit of centuries of hindsight, it is possible to see concrete's evolution—from its discovery, loss, and rediscovery to its current widespread use in reinforced form—as closely intertwined with the evolving needs and priorities of the societies that used it. In the centuries during which its formula was unknown, much building occurred, but the forces driving it apparently did not create a strong enough imperative for the material's rediscovery to occur. The needs of an empire—roads, bridges, ports, barracks, and aqueducts—demanded such a material from the Roman builders who, through experimentation and discovery, found a way to deliver it. With the dissolution of the empire, the need for a material like concrete was likewise diminished, although many builders, mocked by the splendid monuments in their midst, would be in want of its formula.[18] Similarly, one can see the needs of the industrial age to maximize land use—by means of factories, bridges, ports, and ever-taller buildings—as driving the deliberate search for a leap in material technology, one that was answered by iron and, eventually, steel-reinforced concrete

Today, a new and powerful need is emerging to reduce the environmental impact of human activities, including building: use fewer materials and less energy, and consider the entire design life cycle, from conception through manufacture to disposal. Understood as part of the continuum of developments in material technology, this need introduces a new dimension to how performance is evaluated: the degree of sustainability. Design in the 21st century is expected to perform in new ways that take into account its impact on worldwide energy and material cycles. The effects of the rapid development of the global economy and the rising prosperity of hundreds of millions of people—particularly in India and China—are exacerbating scarcities of natural resources and demanding that systems of design, manufacture, and consumption evolve. The poor example set by the United States and Western Europe, in terms of environmental degradation and waste of material resources throughout the 19th and 20th centuries, simply cannot be followed by all the world's citizens, now numbering more than seven billion—the environment cannot endure it.[19]

The urgency of this demand for material sustainability and ecological preservation grows even as the world recovers from an economic downturn. At current rates of production and consumption, carbon emissions would lead to an uninhabitable climate for much of the planet within 300 years.[20] Developing strategies to respond to this bleak outlook results in exercises such as considering how to build in a desert with precious few resources, as shown by the architect Magnus Larsson in his proposal 'Dune' (page 62), which would harness bacteria to build walls that halt the spread of the Sahara. Ultimately, the constraints of extreme environments force designers to examine and replicate life: the only resource-management system that is known to function within conditions as harsh as those of a desert.

It is with such a view that a new type of concrete is being developed at Delft University of Technology in the Netherlands. There, Henk Jonkers has adopted the use of bacteria to create a living, self-healing concrete that might outlast, and be cheaper to maintain than, the conventional variety (page 80).[21] The bacteria offer a means of reinforcement, infusing the material and lying dormant for years or decades until a crack appears, weakening the concrete, whether in a road or structural support. By admitting oxygen and moisture, the crack prompts these bacteria to secrete limestone, effectively sealing it naturally. If perfected and widely adopted, such biointegrated material technology could have an enormous impact: a full 5 percent of human-generated carbon emissions result from the manufacture of concrete, so even a marginal increase in the material's service life would amount to a breakthrough. It is precisely this type of research, led by a biologist focused on making civil engineering more ecologically sound through integration with a living process, that heralds a new approach to designing with biology.

For much of history, performance and quality were measured by the degree to which a designed material, object, or structure addressed a set of needs only once it was completed and handed off to the user. This primacy and narrow definition of function is no longer valid. In the 21st century it is being replaced by a new, more sophisticated understanding of factors, such as the impact of carbon emissions, product life cycle, and resource scarcity. In addition, new dimensions of function have become increasingly important, such as an object's ability to restore a sense of human connectivity, enable new forms of interaction, or make critical observations about the future trajectory of technologies and behaviors. As a result, as this examination of concrete illustrates, the performance of a design has come to be judged by a much larger set of criteria.

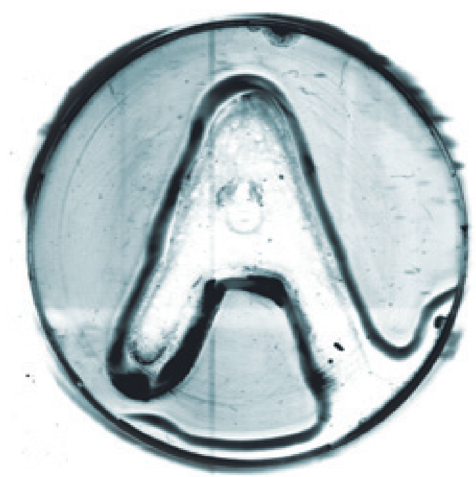
THE PROMISES AND PERILS OF PARADIGM SHIFT

'If we were incapable of handling nature as we found it without causing lasting damage, why would we handle its manipulation any better?' [22]

Angeli Sachs, Curator, Museum of Design, Zurich

The demand to design differently—to bring production and construction into a more integrated relationship with natural processes—is growing and will accelerate collaborations between designers and biologists. This phenomenon is being encouraged by educators like Maria Aiolova, organizer of the One Lab; Alberto T. Estévez, who heads the program in genetic-biodigital architecture at the International University of Catalonia; and David Benjamin, who introduces architecture students at Columbia University to the emerging field of synthetic biology. Simultaneously, regulatory action to combat climate change by enforcing ecological performance standards and preserving what remains of natural resources gains ground, albeit slowly. Promising advances in synthetic biology and the availability of tools for genetic engineering also multiply the possible benefits of harnessing nature, much like HTML standards helped lay the groundwork for the web.

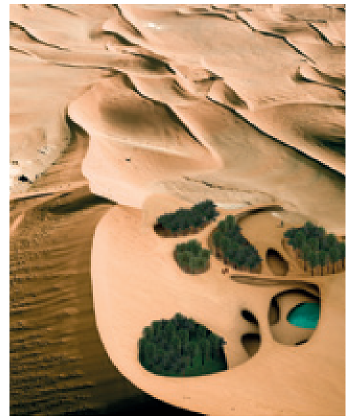
Beyond stylistic consideration or symbolic meaning, biodesign pioneers collaborate with the greatest urgency and potential for positive impact, propelled by societal forces and new research. A major difference between a proposal like Le Corbusier's *The Radiant City* (1935) and Magnus Larsson's 'Dune' (2008) is that the latter is a response to a new conception of necessity. Lewis Mumford, criticizing Le Corbusier, wrote: '[his] skyscrapers had no reason for existence apart from the fact that they had become technological possibilities.'[23] In contrast, Larsson's proposal both addresses and harnesses elements of nature in a struggle more consequential than those that Le Corbusier pondered, his declarations of 'architecture or revolution' notwithstanding.[24] The 20th century did



not demand as dramatic a transformation as that which the 21st century appears to require. Building with bacteria and other organisms is simultaneously becoming a technological possibility and a *necessity*.

An analysis of the history of technology and design rightly prompts skepticism about the embrace of new design that uses living matter, regardless of how extreme the conditions of climate change or other pressures might become. Evidence strongly suggests that designers could misuse the new powers they are obtaining with the help of biology. Designers and architects are still people bound to their cultural biases and personal frailties. Aspects of inherited, dysfunctional impulses, such as neo-colonialism, a rush to change for its own sake, myopic pursuit of profit, and media-savvy theatricality out of proportion with practical potential, will persist as design develops new intersections with the life sciences. Designers and artists are also responding to these looming dangers and have created numerous objects and narratives to articulate dark potential futures that we may unwittingly bring into being. Alexandra Daisy Ginsberg has envisioned such futures in critical projects like 'E.Chromi' (page 167) and 'The Synthetic Kingdom' (page 168), and—disturbingly—has found them frequently misinterpreted as literal, earnest proposals for new technologies. One goal of this book is to incite discussion and careful consideration of the potential unintended consequences of biodesign, something that is too often overlooked in the breathless optimism that characterizes discussion of this field today.

Should biodesign be the next design paradigm, as foreshadowed throughout this book, in which biological and biomimetic processes replace those that are mechanized and digitized today, we can expect a host of benefits and burdens. The spread of biodesign promises to be much like mechanization in the 20th century, as described by historians such as Sigfried Giedion in *Mechanization Takes Command* (1948): upending accepted practices, extinguishing traditions, attenuating natural beauties, and shaping an alien way of life. How we manage this change is yet to be observed, but Giedion struck a prescient, cautionary note when examining how mechanization had infiltrated agriculture and the raising of livestock: 'A new outlook must prevail if nature is to be mastered rather than degraded. The utmost caution is imperative. This calls for an attitude turning radically away from the idolatry of production.'[25] As vast, unsustainably managed agribusinesses attest, his vision was accurate. Fixation on economic growth through unfettered markets may be our undoing: disaster looms if new biological inventions simply accelerate the current cycles of environmentally destructive design and building in the relentless pursuit of short-term gains.



ABOVE 17

By harnessing bacteria to form rigid structures from a mixture of sand and nutrients, Magnus Larsson's project **Dune** proposes the formation of habitable oases in the desert that will also help to protect endangered arable soil.

LEFT 18

Resembling the first digitally created typeface, Digi-Grotesk S, **Symbiosis** utilizes bacterial cultures in petri dishes to shape letters, with variations created by elements in the growing environment (page 142).

ABOVE 19

A dark future may await a world awash in biological innovation. In the fictional narrative of **E.Chromi** (page 142), a Dutch terrorist organization (Orange Liberation Front) is compelled to threaten the world's biologically generated and patented colors with antibiotics.

ABOVE 20

According to **Synthetic Kingdom** (page 168), unintended yet horrifying possibilities could result from biological alterations set loose upon the environment, such as lungs within a smoker that are crystallized by carbon monoxide biosensors.

NOTES

1
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4
David Benjamin, 'Bio fever' *Domus*, published online on March 30, 2011 (http://www.domusweb.it/en/op-ed/bio-fever/).

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Andrew Carnegie, *The Empire of Business* (New York: Doubleday, Page & Co., 1902) (see especially 'Steel Manufacture in the United States in the Nineteenth Century' pp. 229–242).

6
As measured by the number of transistors fitting onto an integrated circuit.

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Corinne Le Quere, Michael R. Raupach, Josep G. Canadell, and Gregg Marland 'Trends in the sources and sinks of carbon dioxide' *Nature Geoscience*, November 17, 2009: 2(12) 831–836.

8
Rob Carlson, *Biology Is Technology: The Promise, Peril, and New Business of Engineering Life* (Cambridge: Harvard University Press, 2010) pp. 63–79.

9
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10
As quoted in 'Eco-designs on future cities' BBC News, June 14, 2005 (http://news.bbc.co.uk/1/hi/sci/tech/4682011.stm).

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R.A. Frosch and N.E Gallopoulos, 'Strategies for manufacturing' *Scientific American*, 1989: 261(3) 144–152.

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Alex Driver, Carlos Peralta, and James Moultrie, 'Exploring how industrial designers can contribute to scientific research' *International Journal of Design*, April 30, 2011: 5(1) 17–28.

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Interview with the author, January 18, 2010.

15
William MacDonald, *The Architecture of the Roman Empire*, Vol. 1 (New Haven: Yale University Press, 1982) pp. 18–22.

16
Sigfried Giedion, *Building in France, Building in Iron, Building in Ferroconcrete,* ed. Sokratis Georgiadis (Santa Monica: Getty Center, 1995) pp. 150–151.

17
Patricia Cusack, *Early Reinforced Concrete*, ed. Frank Newby (Surrey: Ashgate Publishing, 2001) p. 82.

18
Masterworks, such as those of Filippo Brunelleschi in the 14th and 15th centuries, were exceptional examples of engineering achievement that rivaled those of the Roman Empire, without the benefit of concrete.

19
Thomas Friedman, *Hot, Flat, and Crowded* (New York: Farrar, Straus and Giroux, 2008) pp. 53–76.

20
Anthony J. McMichael and Keith B. G. Dear, 'Climate change: Heat, health, and longer horizons' *Proceedings of the National Academy of Sciences*, May 25, 2010: 107(21) 9483–9484.

21
Henk Jonkers et al., 'Application of bacteria as self-healing agent for the development of sustainable concrete' *Ecological Engineering*, 2010: 36, 230–235.

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Angeli Sachs, 'Paradise lost? Contemporary strategies of nature design' *Nature Design* (Zurich: Museum für Gestaltung Zürich, 2007) p. 273.

23
Lewis Mumford, 'Yesterday's city of tomorrow' *The Lewis Mumford Reader* (New York: Pantheon, 1986) p. 212.

24
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BEYOND BIOMIMICRY

ROOT BRIDGES OF MEGHALAYA

Living constructions that last for centuries.

Rubber tree (Ficus elastica), betel nut palm (Areca catechu).

Numerous designers, Khasi tribespeople, within present-day India

IN PRODUCTION

The northeastern Indian state of Meghalaya includes some of the wettest places on the planet, with up to 1,200 cm (470 in.) of rain annually. In the Khasi and Jaintia hills, the water creates numerous swift-flowing rivers that are dangerous to cross and require bridges to afford basic mobility to the local people. In a predominately agrarian economy made up of tribes that have lived in the area for centuries, a natural and effective solution has been developed: bridges grown from the roots of rubber trees.

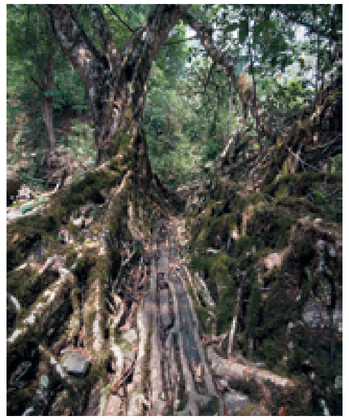
Without the need for specialized training and equipment that other types of bioengineering require, the **Root Bridges of Meghalaya** are coaxed from the natural, albeit slow, growth of *Ficus elastica*—a rubber tree within the banyan group of figs. These trees thrive on the slopes of hills and have strong rooting systems. The growth of their many secondary roots, which would normally fan out in all directions, can be guided using a betel nut trunk that has been sliced down the middle and then hollowed out into a half-cylinder. Placed across a river, these trunks ensure that the thin, tender roots grow straight and eventually reach the opposite bank, where locals encourage them to take hold in the soil. Given enough time and repeated with several trees in each part of the river, this process ensures that sturdy, ever-evolving living structures are created, the form of which adjusts over time and is never fully complete.

Some of these root bridges, which take approximately 15 years to become functional, are more than 30 m (100 ft) long. The stresses of use and weather can strengthen them over time, allowing them to last for hundreds of years. Although precise dating is difficult, it is widely accepted that many are in excess of 500 years old (the practice is thought to have begun in the 1500s). One example, partly named after the river that it spans, is known as the Umshiang Double-Decker Root Bridge and is a remarkable testament to the engineering possibilities of living structures.

Sadly, many of the region's rivers have in recent years been poisoned by the runoff from nearby illegal mines. If the disruption to local ecosystems continues unabated, these ingenious works of design that are engineered to live indefinitely will shrivel and die.

OPPOSITE 32

Over time, bridges are shaped from the roots of several trees. These natural structures are capable of lasting for hundreds of years.



ABOVE 33

The bridges are ever changing in form and they are strengthened by the addition of branch and grass clippings, which nourish the roots.

ABOVE 34

The Double-Decker Root Bridge: a dramatic two-storey structure that spans the Umshiang River.

LEFT 35

As with all living structures, the bridges rely on a healthy environment for their maintenance. Abundant clean air, water, and soil are essential.

FAB TREE HAB

Can we draw on ancient methods of construction to create homes that truly work with, rather than against, nature?

Computer numerical controlled produced scaffolds, a variety of native trees.

Mitchell Joachim (American) / Lara Greden (American) / Javier Arbona (American)—Massachusetts Institute of Technology, Cambridge, USA

CONCEPT

This concept suggests an alternative to the sterile, stand-alone homes that are at odds with their immediate environment. It offers a method for growing residential accommodation from native trees that remain living and integrated with the ecosystem. Here, a growing structure is grafted into shape with prefabricated computer numerical controlled reusable scaffolds. Depending on the weather conditions and location, it should take approximately seven years to grow.

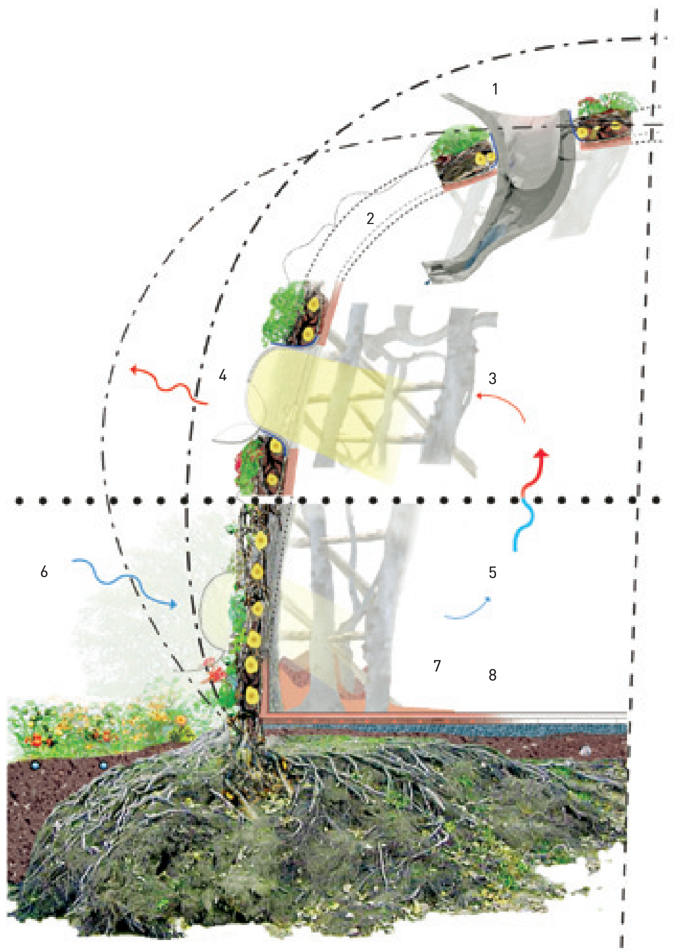
The creation of **Fab Tree Hab** relies heavily on 'pleaching', the ancient process of tree shaping in which tree branches are woven together so that as they continue to grow they form archways, lattices, or screens. The trunks of inosculating (self-grafting) trees, such as elm, oak, and dogwood, form the load-bearing elements, while the branches provide a continuous crisscross frame for the walls and roof. Interlaced throughout the exterior is a dense protective layer of vines, which is interspersed with soil pockets that support growing plants.

During the slow process of construction, the trees and plants are allowed to grow over a computer-designed removable plywood frame. Once the living elements are interconnected and stable, the wood is removed and can be reused. Research at the Massachusetts Institute of Technology, where the designers undertook their studies, has explored the potential of woody plants that grow quickly and develop an interwoven root system that is soft enough to 'train' over a scaffold but then hardens to be very durable. The inside walls would be made from conventional clay and plaster.

Technical demonstration and innovation is still required for some components—principally the bioplastic windows that can adapt to growth of the house, and the management of nutrient flows across the walls to ensure that the interior remains dry and free from insects. The time required for it to be habitable is approximately 5 years—far longer than for a more 'traditional' construction, but its health and longevity should be far greater. Above all, the 'growth' of such a home should be achievable for a minimal price, requiring little labor or fabricated materials. The realization of these structures will begin as an experiment but thereafter it is envisioned that the concept of renewal will take on a new architectural form—one of interdependency between nature and people.

OPPOSITE 77

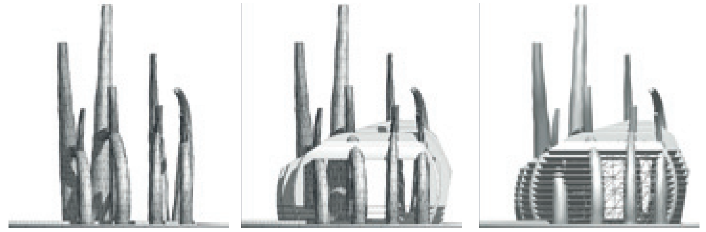
By directing their growth, trees and woody plants can be integrated into built structures. This slow construction method creates living architecture integrated with—and enhancing—the environment.



1. Rainwater harvested
2. Thermal fill (clay- and straw-based)
3. Vine surface lattice
4. Bioplastic windows
5. Buoyancy driven ventilation
6. Cool air intake
7. Packed-earth and tile flooring
8. Solar-heated water pipes under floor

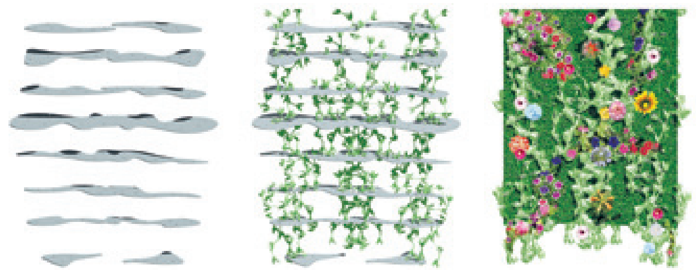
ABOVE 78

Energy and nutrient flows are connected with the natural cycles of the surrounding ecosystem, thereby harnessing both cool air and rainwater.



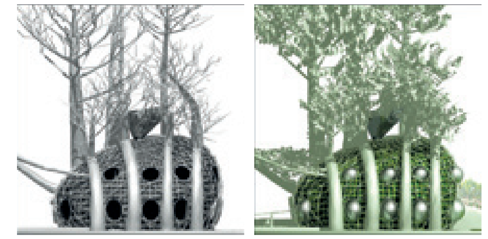
ABOVE / BELOW / OPPOSITE 79

After the structure is grafted into shape a variety of plants fill in the gaps in the façade, encouraged by the use of perforated scaffolding through which stems and leaves can intertwine.



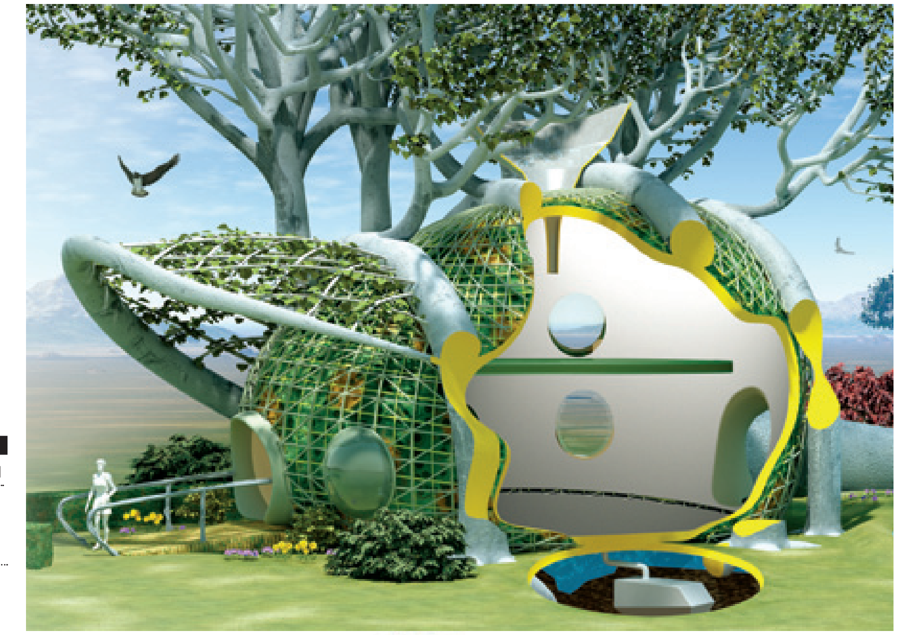
BELOW 80

A living structure is slowly grafted into shape with the help of prefabricated and reusable scaffolding. Organic processes and time together become the essential construction materials. Depending on the climate, it takes about 5 years of guided tree growth before the house is functional.



RIGHT 81

The interdependency between architecture and the environment that underpins this home is an incentive to preserve clean air, water, and soil.



DUNE

Could microorganisms help to build the equivalent of the Great Wall of China across the Sahara to prevent the spread of the desert?

Sand, bacteria (Sporosarcina pasteurii), water, urea, calcium chloride.

Magnus Larsson (Swedish)—Architectural Association, London, UK / Magnus Larsson Studio, London, UK

CONCEPT

This architect envisions building structures out of sand in the Sahara and forming a 6,000 km (3728 mile) barrier to protect against the spread of the desert. This speculative, audacious plan would harness the ability of a particular bacterium to perform construction by naturally converting dunes into sandstone (based on work by Jason De Jong's team at the Soil Interactions Laboratory, University of California, Davis). During the process, the stone would be shaped to collect moisture, protect trees, and shelter thousands of people at relatively little cost.

The urgency of the problem that this project attempts to address cannot be overstated. A United Nations study (Adeel et al., 2007) concludes that 'Desertification has emerged as an environmental crisis of global proportions, currently affecting an estimated 100 to 200 million people, and threatening the lives and livelihoods of a much larger number.' The displacement of communities that is often generated by the spread of the desert regularly aggravates political instability in several of the affected countries, such as Sudan, Chad, and Nigeria.

Dune was inspired by the ongoing project in the same area to plant trees and vegetation across a dozen countries in the region, the goal of which is to protect the Sahel Belt—a stretch of dry savanna just south of the desert. Funds for this Great Green Wall are still being raised, but there has been progress in Senegal, where some 500 km (311 miles) of trees have been planted.

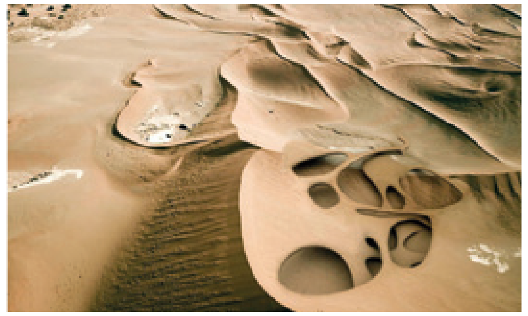
Bacteria, water, urea, and calcium chloride would be injected into the sandscape and would—via a process called microbial-induced calcite precipitation—produce calcite, a natural cement, that would cause the sand to solidify within 24 hours. By choosing where to apply the microorganism, the architect would have a degree of control over the process, but the final form would be heavily influenced by the environment. While the principal aim would be to produce a barrier against sand moved by the wind, the structure's formation would be augmented by wind action. Thus the design elegantly harnesses the energy embodied in the problem to propose its solution.

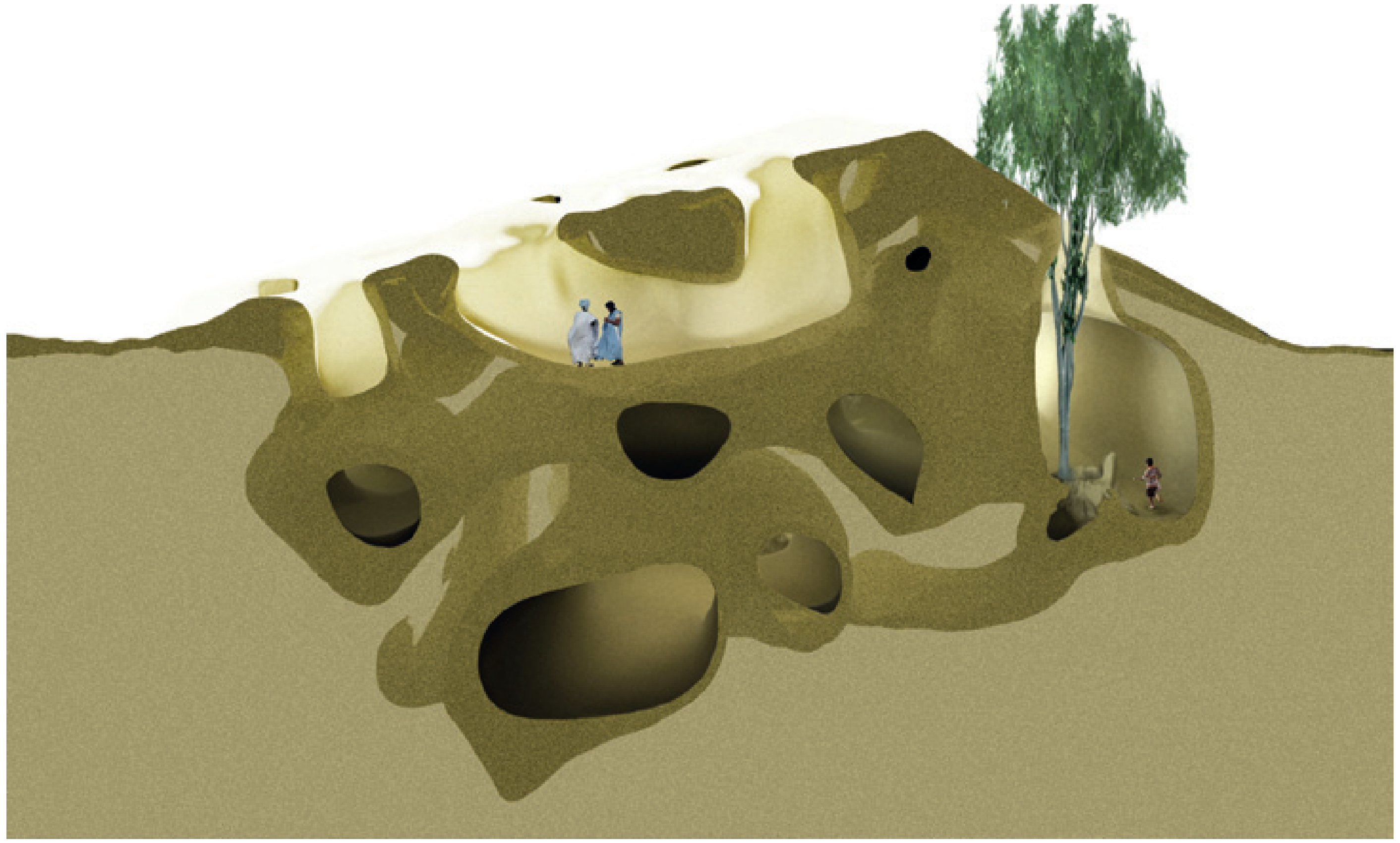
ABOVE 82

Sand solidified by bacteria and shaped by the wind eventually allows water to accumulate and forms a barrier against the spread of the desert.

RIGHT 83, 84

The wind and sand that result in expansion of the desert, threatening settlements and arable land, are exploited in biological construction.





ABOVE 85

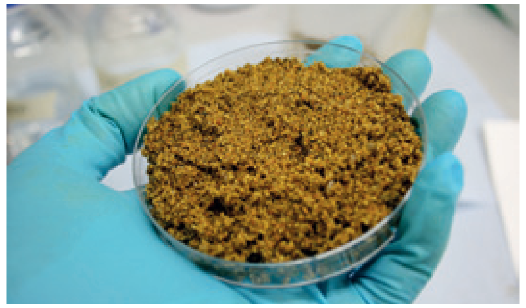
A dune cross-section with rigid chambers where precious moisture and soil might be preserved.

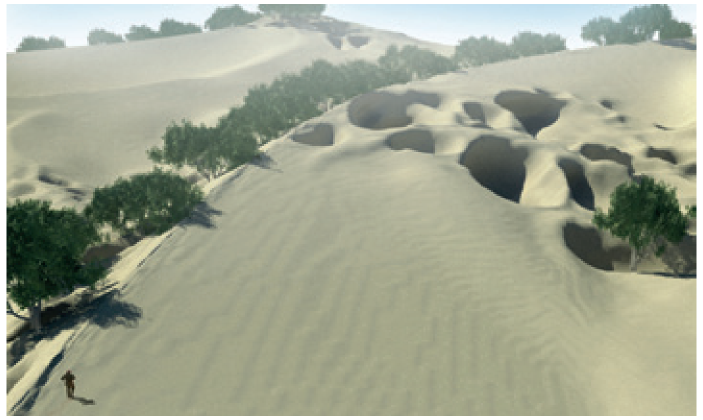
ABOVE 86

The shape of the structure here is shown in a tafoni pattern—characteristic of rock that has been eroded by wind or moisture for many years.

ABOVE 87

Resisting the spread of the desert becomes ever more difficult and yet important as the climate warms. The vast savanna of the Sahel Belt is one of many areas that are currently under threat.





ABOVE 88, 89

Microbially induced cementation is a natural process that can be observed in swamps and lakes. It is not harmful to humans and will cease once available nutrients have been depleted.

ABOVE 90

The architect's proposal stemmed from an examination of extreme environments, such as desert, ocean, and tundra, where traditional approaches to building are simply unfeasible.

BIOBRICK

Can the humble brick be turned from an environmental menace into the building block of a more sustainable future?

Sand aggregate, bacteria (Sporosarcina pasteurii).

Ginger Krieg Dosier (American)—American University of Sharjah, United Arab Emirates / Vergelabs

PROTOTYPE

The brick is a ubiquitous and effective construction component that has endured for thousands of years, relatively unchanged. Its inherent simplicity—it demands few skills, materials, or technologies, is durable, and is sized to fit the human hand—can be much admired. But while its form and function have been mastered, its standard method of production requires reform: intense heat energy, usually applied in kilns that burn coal, with a requirement for large quantities of agricultural soil, leaves a significant ecological footprint.

In contrast, the **BioBrick** utilizes a natural process found in common bacteria to fuse sand particles and thereby create a rigid shape with strength and durability comparable to those of conventional bricks. Here, the architect combines the microorganisms with sand and a solution of calcium chloride and urea to initiate microbial-induced calcite precipitation (MICP), whereby the bacteria glue the grains of the sand together to form stone.

As with all life processes, this one is sensitive to environmental conditions and doesn't yet align with the demanding pace of industry. Factors such as temperature, density of nutrients, and pH levels must all be maintained within particular ranges for it to work, and it can take a full week to form a single brick, instead of the usual two days.

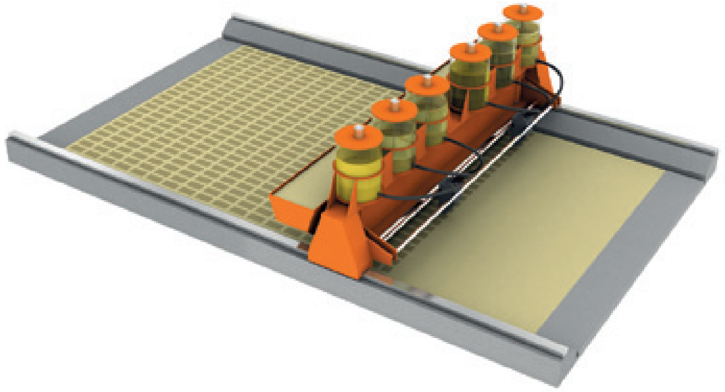
Another challenge of biologically grown bricks is their toxic by-product: ammonia. Production on a large scale would require supplementary processes to contend with this potentially dangerous gas. While this represents a considerable obstacle, alternatives to traditional brick making are sorely needed. The sheer scale of world production is daunting: more than 1.23 trillion bricks are made every year, many in developing countries and at great ecological expense—they produce more pollution than the world's airplanes during the same period. So alternatives must be explored as resource depletion accelerates. In nature, MICP has been slowly creating rock formations on earth for billions of years and has only recently captured the interest of scientists and engineers who are motivated to harness it for human ends.

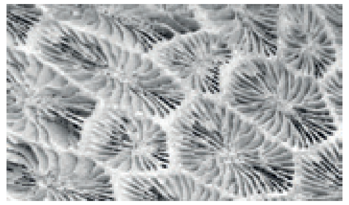
ABOVE 109

A comparison of a microbially formed BioBrick (left) and a standard concrete brick (right).

BELOW 110

A prototype of a full-scale 3D printer that precisely deposits bacteria, urea, and calcium ions onto a bed of sand in successive layers.



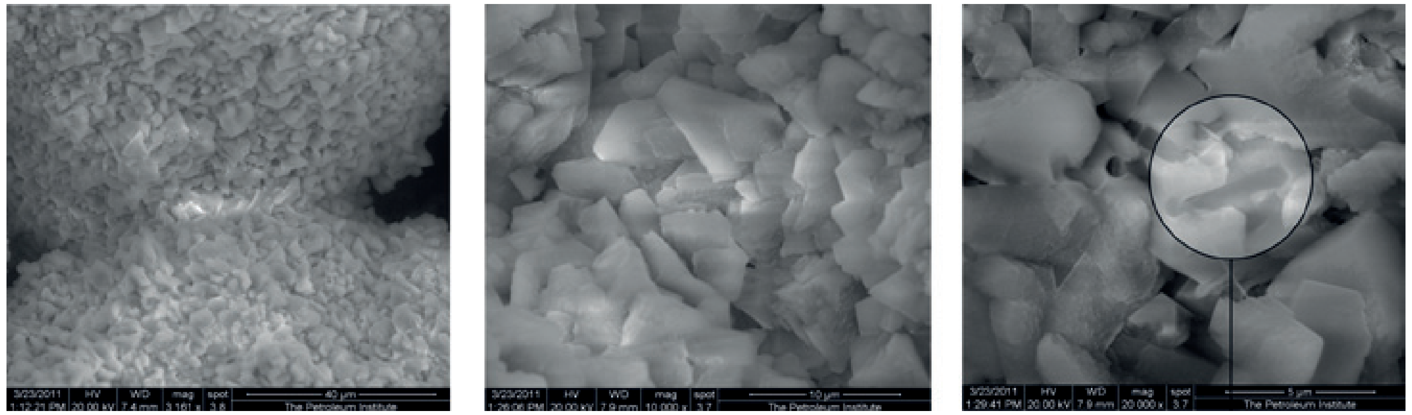


ABOVE 111

A scanning electron microscope image of bacterially cemented aggregate. With increasing magnification, the rhombohedral geometry of the calcite is revealed. Bacterial 'fossils' appear within the cement as rod-shaped voids.

ABOVE / RIGHT 112, 113

Some 75 percent of brick production worldwide takes place in India, China, and Pakistan, where energy-intensive, traditional methods dominate. In contrast, the reactions involved in forming the BioBrick can occur at room temperature.



ABOVE 114, 115, 115

Sections of *Leptastrea transversa* coral, taken from a vernacular fort wall in Sharjah in the United Arab Emirates, revealing patterns of natural calcium carbonate formation.

ABOVE 152

A design concept for a series of biological devices for the home, aimed at creating an ecosystem capable of filtering, processing, and recycling sewage, effluent, garbage, and wastewater.

RIGHT 153

Larder is a dining table with terracotta boxes at its heart for storing food at different temperatures.

MICROBIAL HOME

With bio-digestion at its center, can the home become more self-sufficient and less wasteful of natural resources?

Mixed media, including wood, ceramics, methane digester, various bacteria.

Jack Mama (British), Clive van Heerdan (British, born South Africa)—Philips Design, Eindhoven, the Netherlands

PROTOTYPES

Microbial Home is a concept that comprises several integrated appliances that heat, refrigerate, and generate food, as well as digest waste products. The units are designed to work in a cyclical way that resembles an ecosystem, the aim being to maximize the use of the mass and embodied energy that normally moves through our domestic spaces. The designers adopt a view of the home as a biological machine for filtering, processing, and recycling what we conventionally view as waste.

The **Methane Bio-digester** is central to the idea. Embedded in a kitchen island that includes a chopping surface, a waste grinder, and a gas cooking range, it generates methane from the work of bacteria digesting organic matter in the waste-disposal unit. The gas powers the range, as well as lights and water-heating components in other parts of the system.

The **Larder** is a combined dining-room table and food storage unit. Terracotta boxes set into the table's center are warmed by the hot water pipes from the bio-digester and are of varying thicknesses and volumes to provide a range of temperatures.

The **Paternoster** is a device for 'up-cycling' plastics (provided they are free from toxic chemicals). They are ground into small pieces that can be digested naturally by fungi, which can, in turn, be harvested and eaten. The mushrooms grow in a removable wheel-shaped holder for easy access.

The **Bio-light** is an array of glass cells that can be hung or wall mounted and are connected via silicon tubes to a food reservoir at the base. Illumination is provided either by bioluminescent bacteria—maintained by methane from the bio-digester—or by chemically charged liquid florescent proteins. Both methods produce light at low temperatures, as opposed to incandescence, which involves significant heat waste.

The **Urban Beehive** is designed to allow domestic beekeeping. It can be installed in an exterior wall, with the outside portion fitted with an opening that allows the bees to enter and exit. On the inside, contained in a glass vessel, is a chamber that can be viewed, similar to an ant farm, from inside the home. The insects find a preexisting honeycomb structure on which they can begin to build their wax cells, while the interior glass permits the entry of orange light, which they need to see. The device includes a system for pacifying the occupants with smoke in order to facilitate harvesting of the honey from the inside.

The concept of the **Filtering Squatting Toilet** recognizes waste as a necessary component of a domestic ecosystem and highlights the essential shift from utility-dependent sanitation to regenerative, localized solutions. An array of charcoal, sand, and ceramic filters diverts solids to the bio-digester and generates graywater for other uses. It aims to show the energy value of human waste and raise awareness about wasting water—the flush mechanism is based on the one liter flush toilet technique developed by the Sulabh Foundation in India.

RIGHT 154

Containing charcoal, sand, and ceramic filters, the **Filtering Squatting Toilet** draws out nutrients that can be used to cultivate plants, thereby highlighting the value of what we consider waste.

RIGHT 155

Mounted on a window and open to the outside, the **Urban Beehive** offers an updated version of the ant farm concept. Viewers from indoors can watch bees construct and maintain their hive.

ABOVE / BELOW 156, 157, 158

The **Larder** uses energy from the **Bio-digester** to alter the temperature of its food-storage boxes.

ABOVE 159

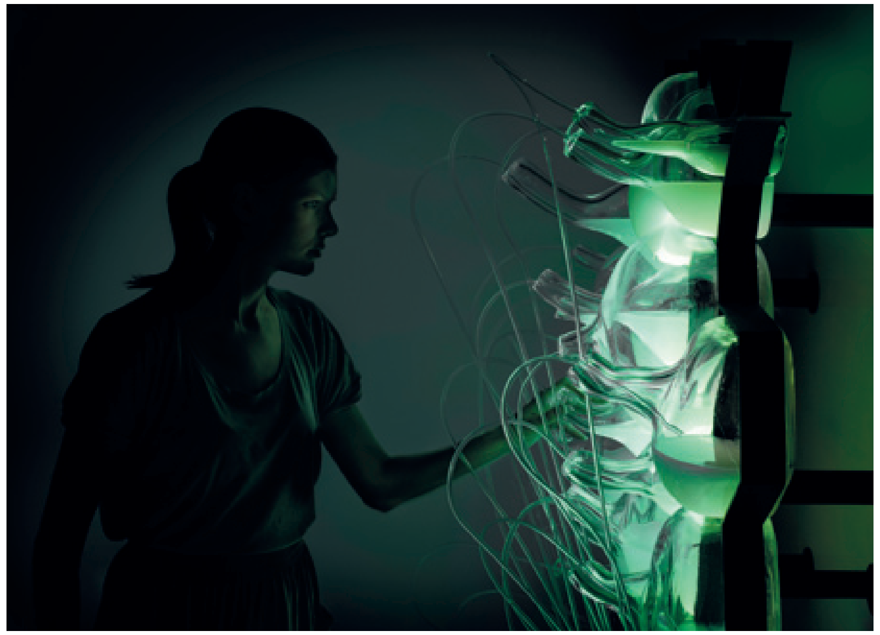
The **Bio-digester** is a kitchen waste-disposal system. It houses bacteria that consume unwanted organic matter and produce methane to power the cooking range and water heater.

ABOVE 160

Named after the old passenger lift system that moved people in a looping conveyor, this hand-powered appliance—the **Paternoster**—breaks down certain plastics so that they can be digested by fungi that, in turn, can be harvested and eaten.

RIGHT 161

Detail of the internal grinding mechanism of the **Paternoster**. Plastics must be free from toxic inks and finishes to safely grow mushrooms.



ABOVE / LEFT 162, 163

The **Bio-light** comprises glass chambers filled with either bioluminescent bacteria and nutrients or the enzymes and proteins needed to sustain illumination, which works at lower temperatures than those required for incandescent lighting.

SYMBIOSIS

Living letters that grow, change color, and eventually die.
Could this herald a future of living, dynamic graphic design?

Bacteria (Escherichia coli), paper, growth media, petri dishes.

Jelte van Abbema (Dutch)—Lab van Abbema, Eindhoven, the Netherlands / Department of Microbiology, University of Wageningen, the Netherlands

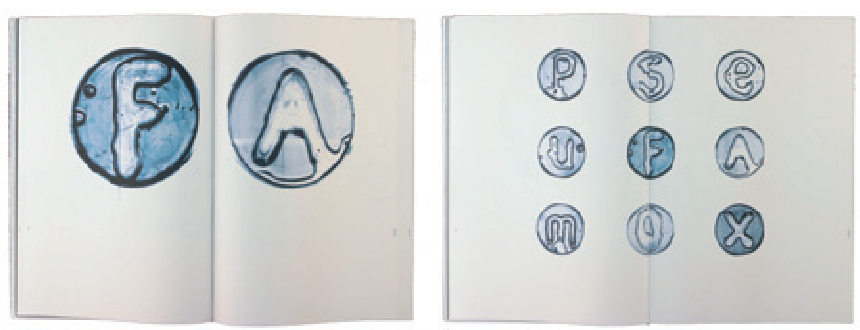
PROTOTYPE

This experimental project responds to the vast resource consumption and pollution generated by printed media. Going beyond the adoption of alternatives such as soy ink or natural pigments to alleviate the impact of media waste, **Symbiosis** takes a radical approach, utilizing bacteria to grow letters in petri dishes. In these experiments, the cultures —living on growth media configured with nutrients to guide their development—multiplied, changing form and color over time, before ultimately dying.

In the larger, poster box format, he appropriated a piece of public space that usually features an advertisement and transformed it into a giant petri dish, the temperature and moisture levels of which could be adjusted to achieve an optimal outcome.

To control growth so that it would generate legible type, he experimented with techniques adopted from the history of print—from screen-printing to moveable type using authentic wood-cut lettering—and this resulted in familiar character shapes and proportions. In essence he created what might be called the first living typeface, which constantly shifts in response to changes in the environment.

The designer studied in the Department of Microbiology at the University of Wageningen to learn how to go about this work safely and effectively.

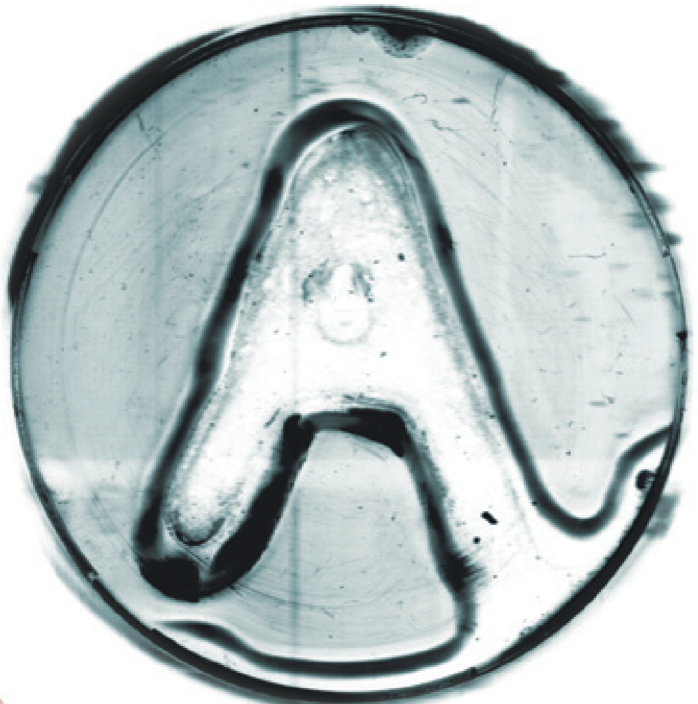


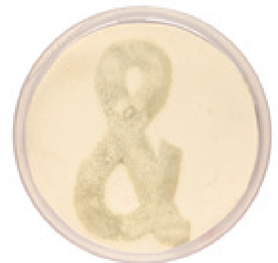
ABOVE 239

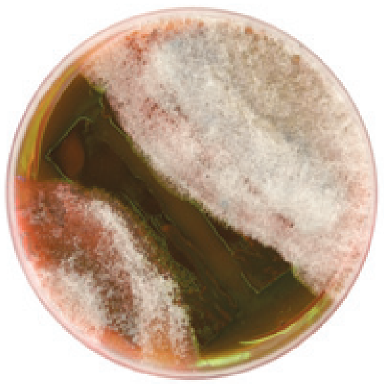
Images of bacteria spread and coaxed into growing in the form of familiar letters within petri dishes.

OPPOSITE 240

A poster box repurposed as a growth medium for biologically rendered letters. The characters develop in form and color, eventually dying and decomposing as the nutrients are depleted.

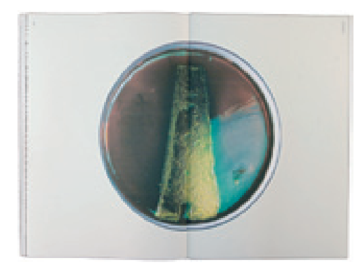


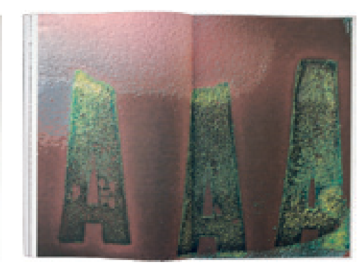


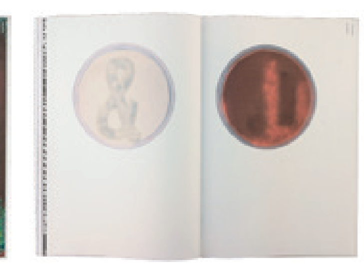


ABOVE 241, 242, 243, 244

Letters and symbols grown in the lab studio.

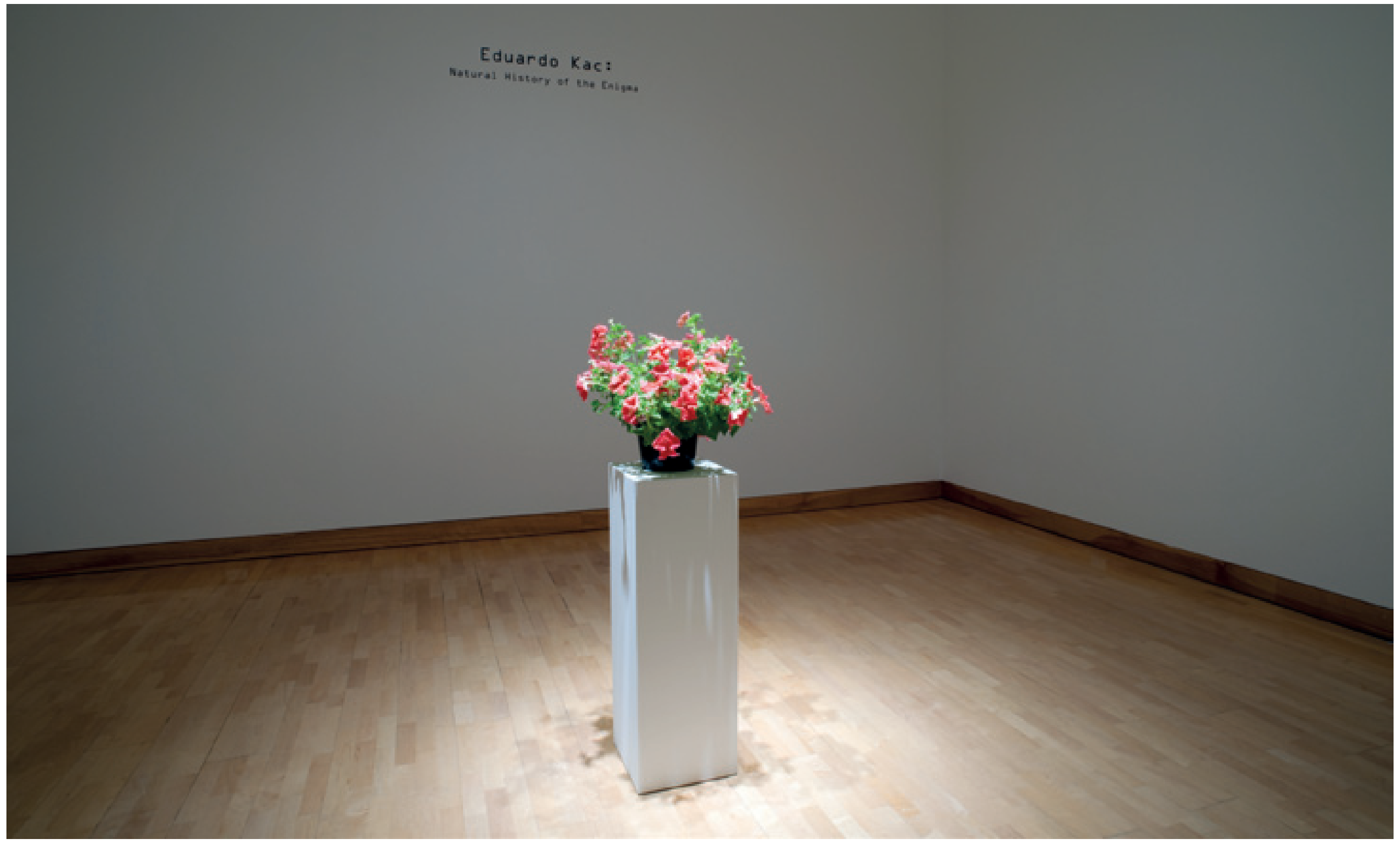






ABOVE 245, 246, 247, 248

The artist combined traditional printing, movable type, and screen-printing techniques in his exploration of using biology to generate form.



ABOVE 326

The genetically modified 'Edunia' plant exhibited at the Weisman Art Museum, Minneapolis.

RIGHT 327

The artist watering his own genetic offspring.

ABOVE 328

The flower of the 'Edunia' plant with the artist's DNA expressed in the red veins of the petals.

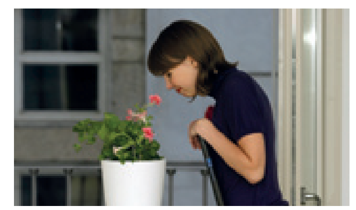
NATURAL HISTORY OF THE ENIGMA

Gene manipulation offers an entirely new and expansive medium to artists.

Petunia DNA, artist's DNA, soil, water.

Eduardo Kac (American, born Brazil)—Studio Eduardo Kac, Chicago, USA

COMPLETED



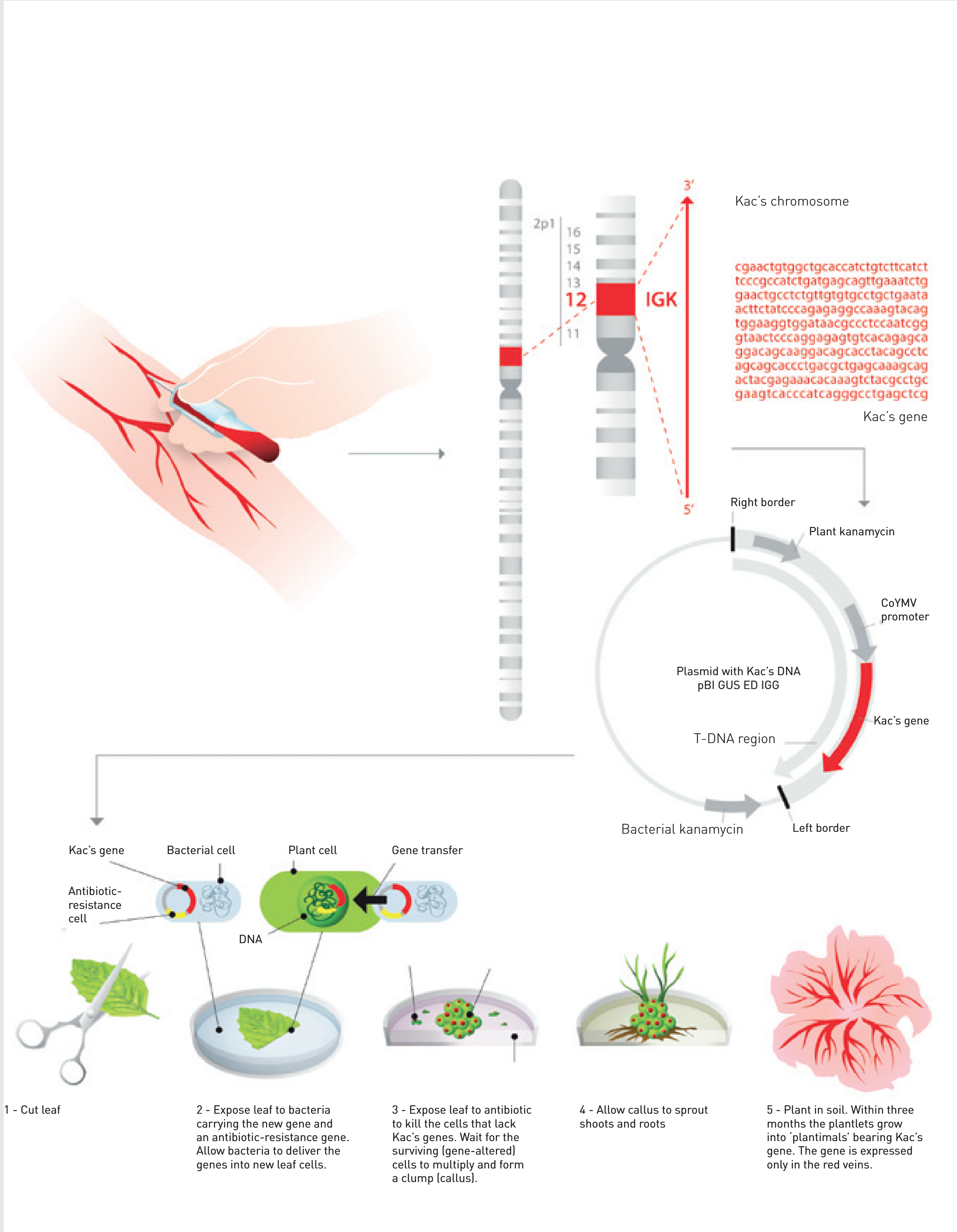
ABOVE 329, 330

From the top: the transgenic plant exhibited at the Factoría art gallery, Santiago de Compostela and the Weisman Art Museum, Minneapolis.

Transgenic art is a nascent discipline in which portions of genetic code are added to and expressed by a host organism. **Natural History of the Enigma** involves a range of items that include a new life form—a genetically engineered flower that is a hybrid of the artist and a petunia. The result, 'Edunia', was developed through the application of molecular biology and so is not found in nature. The alien, human gene that the plant contains was isolated and sequenced from a sample of blood. It produces an immunoglobulin, a protein that functions as an antibody and is used by the immune system to identify and neutralize foreign antigens (antibody generators that trigger an immune response). The gene produces a protein that makes the veins of the flower's petals red, creating a living image of human blood within a flower. The creation of this novel organism, which entailed using a virus promoter to insert the gene precisely, was overseen by Professor Olszewski in the Department of Plant Biology at the University of Minnesota.

In anticipation that Edunia would be distributed and planted outside of galleries and museums, the artist created limited edition seed packs. Embedded magnets keep them closed while visitors are invited to open and examine them like books. The project includes several watercolors, photographs, and lithographs. All of the blooms featured are genetically identical clones, yet they look quite different, supporting the view that all life, no matter how similar genetically, is fundamentally unique.

This work suggests a broad scope of artistic opportunities offered by newly accessible techniques for synthesizing and working with genes. A couple of decades ago such endeavours would have required thousands of dollars in funding, but today only about one-tenth of the financial outlay is necessary.



ABOVE 332

Edunia Seed Pack Studies I–VI on display in the Factoría art gallery, Santiago de Compostela.

OPPOSITE 331

Diagram showing how the artist's DNA becomes part of the plant and is expressed in its flowers.

ABOVE 333

Handmade paper objects with 'Edunia' seeds and magnets formed part of the installations.

CO-EXISTENCE

The symbiotic relationship between humans and the trillions of microorganisms we host inspires a thought-provoking portrait.

Perspex, lighting, 9000 petri dishes, photographs of various bacteria.

Julia Lohmann (German); commissioned by the Wellcome Trust

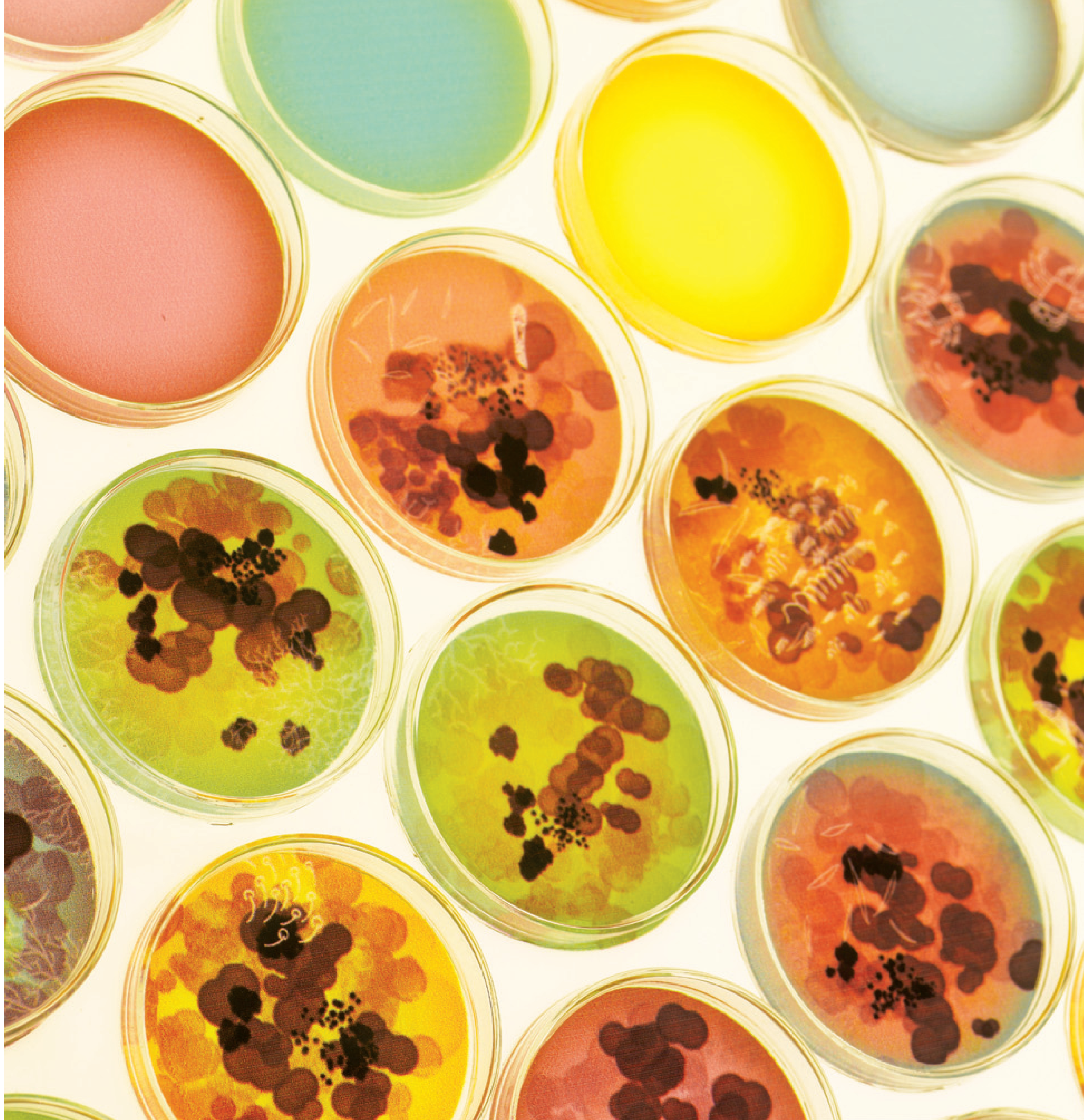
COMPLETED

This project was inspired by the universe of unseen organisms that inhabit our bodies. The artist, with the help of microbiologist Michael Wilson, produced a pair of dramatic pixelated images of two reclining nude women. Each 'pixel' was represented by a petri dish containing a photograph of a culture of bacteria—all species that are commonly found in or on the human body. The positioning of each dish within the artwork corresponded to the part of the body in which its inhabitants are usually found. The choice of the female form reflects centuries of art history, as well as the fact that women generally support a greater variety of microorganisms than men.

Underlying **Co-existence** is the recent widespread realization that the human body is essentially a hybrid of human and bacterial cells. We are made up of trillions of cells, of which around 10 percent are human and the rest are of other origin—mostly bacteria that inhabit the gut. We host all this company for our own benefit: critical functions such as digestion and maintaining the immune system rely on symbiotic relationships with other organisms. In other words, we are complex ecosystems in miniature—a blend of human and non-human life working together.

OPPOSITE 369

Petri dishes containing bacteria and other tiny microorganisms that reside on and within our body. These microscopic guests, many of which have adapted to live with us symbiotically, outnumber our own cells by at least ten to one.



ABOVE 371

Some nine thousand petri dishes, each housing samples of microorganisms from the human body, were dyed and used to represent individual pixels in an image of a reclining nude figure.

LEFT 370

The placement of each dish relates to the origin of those microorganisms on on or in the body.

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