BEYOND BIOMIMICRY

A NEW URGENCY

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

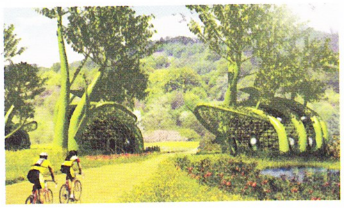
Salvador Dalí on the future of architecture, in response to Le Corbusier

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.

[illegible] 3

[illegible] system of algae-filled tubes [illegible] energy for electricity generation [illegible] spaces in **Process Zero**, [illegible] retrofit for a General Services [illegible] 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

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.

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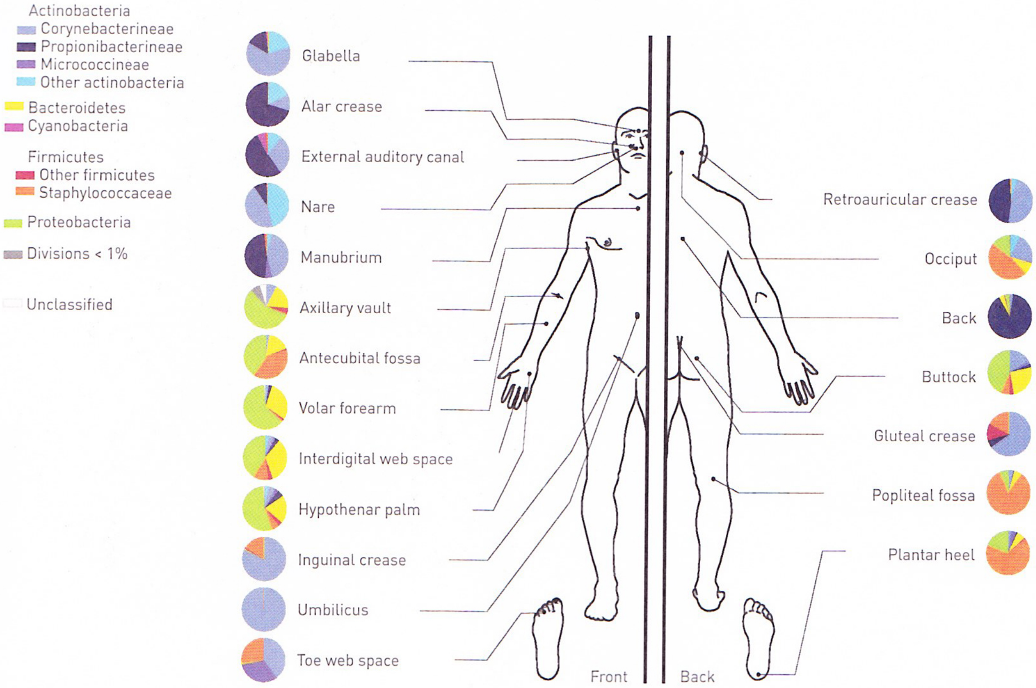
[illegible] Project is a five-year [illegible] undertaken by the US National [illegible] identify and characterize [illegible] microorganisms that thrive both [illegible] the human body. Current estimates [illegible] microbial cells outnumber the [illegible] by a factor of at least ten to one.



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[illegible] from a variety of gastropod [illegible] reproduced from Ernst Haeckel's [illegible] der Natur [Artforms [illegible] which was published in 1904.

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[illegible] researchers at the University [illegible] are working to map the [illegible] [microorganism population] of [illegible] environment, collecting samples [illegible] of spaces and analyzing how [illegible] groups impact human health.

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 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*

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

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.

[illegible] 11, 12, 13, 14, 15, 16

[illegible] ecological performance [illegible] the development of self-repairing [illegible] microorganisms naturally [illegible] as they form, extending the [illegible] material. The production [illegible] binding agent of concrete, [illegible] rapidly and is responsible for [illegible] percent of anthropogenic carbon [illegible] Any improvement in its [illegible] should represent a significant [illegible] construction's carbon footprint.

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 Said, 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.

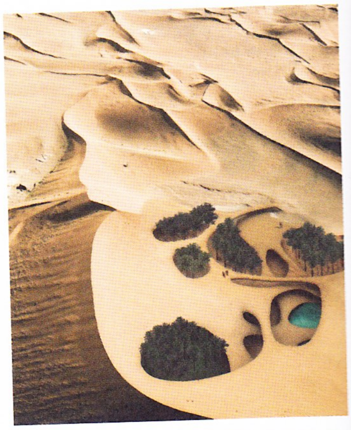
It is with such a view that a new type of concrete is being developed at Delft University of Technology in the Netherlands. There, Henk Jonkers has adopted the use of bacteria to create a living, self-healing concrete that might outlast, and be cheaper to maintain than, the conventional variety (page 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*

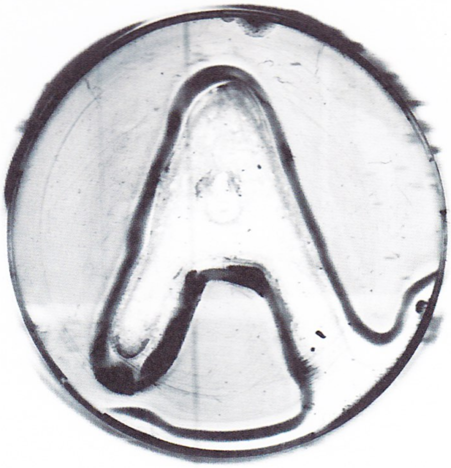
The demand to design differently—to bring production and construction into a more integrated relationship with natural processes—is growing and will accelerate collaborations between designers and biologists. This phenomenon is being encouraged by educators like Maria Aiolova, organizer of the One Lab; 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.



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.

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*.



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).

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

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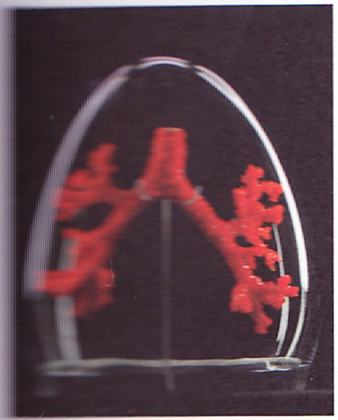
[illegible] world awash in [illegible]. In the fictional narrative [illegible] a Dutch terrorist [illegible] Liberation Front) is [illegible] the world's biologically [illegible] colors with antibiotics.



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[illegible] Synthetic Kingdom (page [illegible] terrifying possibilities [illegible] biological alterations [illegible] the environment, such as [illegible] that are crystallized [illegible] biosensors.

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.

NOTES

1
Salvador Dalí, *The Unspeakable Confessions of Salvador Dalí* (New York: HarperCollins, 1981) p. 230.

2
Using recombinant DNA to alter *Escherichia coli* bacteria to create human insulin, the first synthetic insulin was produced and distributed by Genetech in 1978.

3
J. Craig Venter et al., 'Creation of a bacterial cell controlled by a chemically synthesized genome' *Science*, July 2, 2010: 329 (5987), 52–56.

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

5
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.

7
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.

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

9
This measure includes pharmaceuticals, industrial applications and genetically modified crops; ibid pp. 150–178.

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).

11
See R. Buckminster Fuller and Kiyoshi Kuromiya, *Critical Path* 2nd edn (New York: St. Martin's Griffin, 1982); Rachel Carson, *Silent Spring* (Boston: Houghton Mifflin,1962); Victor Papanek, *Design for the Real World: Human Ecology and Social Change* (New York: Pantheon Books,1971).

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

13
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.

14
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
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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.

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

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The more complete quote is 'Architecture or revolution. Revolution can be avoided.' Le Corbusier, *The Radiant City* (New York: Orion Press, 1933, republished 1964) p. 289.

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Sigfried Giedion, *Mechanization Takes Command* (New York: Oxford University Press, 1948) p. 256.