THE NERI OXMAN MATERIAL ECOLOGY CATALOGUE

MoMA

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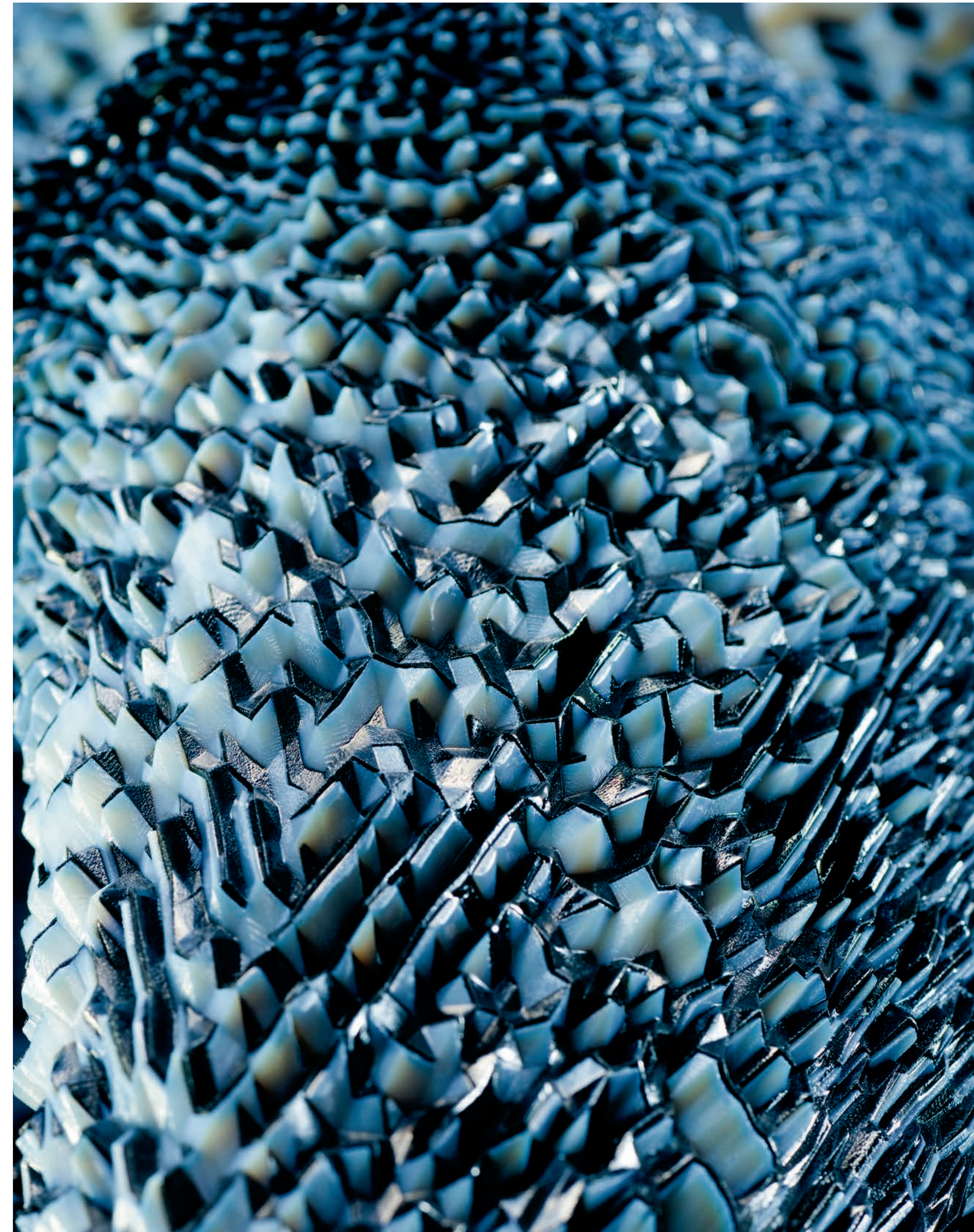
PAOLA ANTONELLI
WITH ANNA BURCKHARDT

THE MUSEUM OF MODERN ART, NEW YORK

Silk Pavilion I



Imaginary Beings: Doppelgänger

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and Anna Burckhardt, Curatorial Assistant,
Department of Architecture and Design

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Neri Oxman and The Mediated Matter Group.
Silk Pavilion I. 2013 (see page 98)
Image modified by Irma Boom

CONTENTS

Project texts by Neri Oxman (Materialecology and Imaginary Beings),
and by Neri Oxman and The Mediated Matter Group (all others)


Imaginary Beings: Arachne

Foreword

With the founding of the Department of Architecture and Design, in 1932, The Museum of Modern Art began its positioning of design as a means for building a better present and future. The department's influential programs and displays have highlighted new techniques, typologies, and technologies, and have explored how they might change all of our lives for the better. Early exhibitions such as *Modern Architecture: International Exhibition*, in 1932, and *Machine Art*, in 1934, introduced innovative architects and buildings from all over the world and presented the elegant precision of industrial objects by showcasing them reverentially on pedestals "like Greek sculptures," according to the press release for *Machine Art*. This was just one of the ways in which Philip Johnson, who organized both exhibitions (the former in collaboration with Henry-Russell Hitchcock), used the language of art to elevate the role of architecture and design in cultural discourse.

Neri Oxman's work honors Johnson's vision and turns it on its head. At first glance, her arresting artifacts could easily be confused for sculpture. Their aesthetic elegance, however, is only a function of the processes they embody: the advanced science and technology—including synthetic biology, digital computation, and additive manufacturing—through which she and her collaborators are designing new ways of building. They envision dynamic materials and techniques that produce objects that behave as if grown in response to their context and environment—customizable, intelligent, and specific. Her first appearance at MoMA was in 2008, in the exhibition *Design and the Elastic Mind*, Paola Antonelli's comprehensive foray into design's relationship with science. Over the past twelve years, her work has been an important part of MoMA's evolving vision of architecture and design's present and future roles—a vision that extends beyond buildings to include processes, materials, and strategies privileging an ecosystemic view. Now, with *Neri Oxman: Material Ecology*, our investigation into the relationship between design and science continues, in an exhibition that surveys a selection of Oxman's work since 2008, some of it now in MoMA's collection, as well as a new commission, the site-specific installation Silk Pavilion II.

The term Material Ecology, coined by Oxman around the same time as *Design and the Elastic Mind* was conceived, encapsulates one of our priorities in collecting and exhibiting design in the twenty-first century. Material Ecology is a pragmatic philosophy: a method of design and production that brings together humans, automated processes, and nature to transform architecture into a hybrid act of building and growing. The striking objects included in the exhibition and in this publication are not sculptures, but neither are they architectural fragments or design items—at least not in the way we are accustomed to think of architecture and design. They are demonstrations of the kinds of tools that should and will be available to architects and designers, perhaps sooner than we think; displayed with videos of the experiments that generated them, they paint an incisive picture of a possible future.

I thank Paola Antonelli, Senior Curator, and Anna Burckhardt, Curatorial Assistant, in the Department of Architecture and Design for organizing this extraordinary exhibition, which brings to MoMA the work of an architect and designer who is paving the way in her field, proposing a path forward in this era of anxiety and uncertainty, galvanizing her community, and stimulating cross-disciplinary collaborations in order to advance positive change. I would also like to thank the many colleagues who have collaborated with the curators to bring this complex exhibition to life.

I am also deeply grateful to Allianz, whose generosity has made this timely project possible, and to The International Council of The Museum of Modern Art and The Modern Women's Fund for their support.

Glenn D. Lowry
The David Rockefeller Director
The Museum of Modern Art, New York

Silk Pavilion II

THE NATURAL EVOLUTION OF ARCHITECTURE

PAOLA ANTONELLI

**EVERYTHING FLOWS, AND NOTHING STAYS THE SAME.
—HERACLITUS [1]**

One of the most distinctive characteristics of the human species is a fraught relationship with change. Inescapable, change touches each creature, community, and system uniquely; to each, it manifests at distinct speeds and scales and in different cycles. Most entities—glaciers, plankton, clouds, tigers, or dandelions, for instance—go with the flow, adapting and evolving over time to accommodate change and accept its aftermath, however unfortunate. Not humans. Except for the faithful or the wisest among us, most human beings either resist, pursue, seek to control, or amplify change. We take pride in our ability to interfere with and even manipulate the flow. In so doing, we create consequences—not only for us, but for all species. So much have we tinkered that we seem to have lost control of the mutation, which now ever accelerates, like a cancerous growth.

Indeed, humans themselves are like cancerous cells, so self-absorbed and single-minded about their survival and predominance that they have invaded and destroyed much of what's around them. Neri Oxman, by contrast, seems in no rush. Her practice is a powerful anticipation of a better possible future, and it is projected toward that future without apparent anxiety, patiently weaving connections between disciplines and between species, slowing down the pace of making by marrying the latest technologies with the most ancient and deliberate of tempos—those of silkworms, bees, and microbes. She engages change using change's own momentum.

I met Oxman in 2006. We were introduced by the architect Enrique Norten, who thought she would be a great fit for an exhibition I was preparing at the time. *Design and the Elastic Mind* addressed the unexplored affinities between design and science and their ability to communicate with each other without relying on technology—a well-meaning but sometimes misleading interpreter. Indeed, technology was played down in the exhibition as an instrument with which scientists and designers could realize their joint visions and ventures. On display were mighty examples of scientists' and designers' unbridled collaboration, organized according to scale—albeit a new set of dimensions that took the digital universe into account, one based not only on physical size but also on complexity.

Norten was right: Oxman and her work were the embodiment of the exhibition's thesis. An architect by training, Oxman started medical school before following the family tradition (both parents are architects), attending Tel Aviv's Technion and London's Architectural Association. Her belief in science did not wane, however; she learned its language and dialects in order to be able to engage scientists in productive conversations and collaborations. She also immersed herself in technology, understanding its syntactic power to enact those collaborations. She chose the Massachusetts Institute of Technology (MIT) for her doctoral studies, but even at that forge of so many twentieth- and twenty-first-century revolutions—the wind tunnel, radar, the PET scan, and e-mail among them—Oxman tried her best to avoid being gratuitously seduced by technology, trying instead to look at it as a means she could prod and shape to her ends.

fig. 1 Installation view of *Design and the Elastic Mind*, The Museum of Modern Art, New York, February 24–May 12, 2008

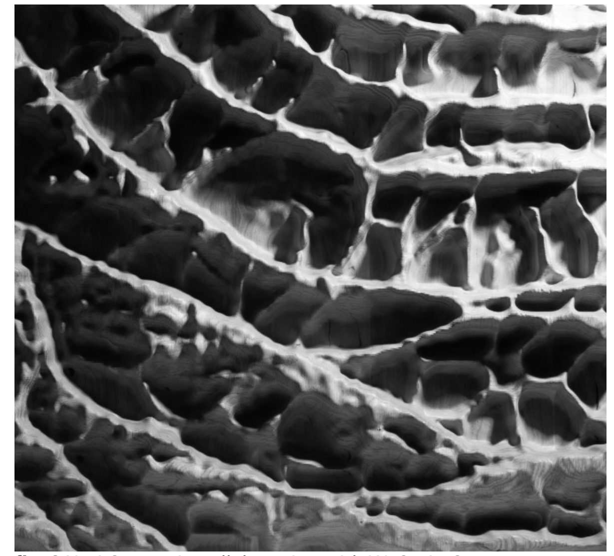


fig. 2 Neri Oxman in collaboration with W. Craig Carter. Subterrain. 2007. Wood composite, 20 × 20 × 2 ¼ in. (50.8 × 50.8 × 5.7 cm). The Museum of Modern Art, New York. Gift of The Contemporary Arts Council of The Museum of Modern Art

Micrograph image of scorpion-claw tissue. The image was analyzed and reconstructed in three dimensions using a CNC mill and wood composite.

At the time of *Design and the Elastic Mind*, Oxman was also ambitiously contemplating working across scales. She framed the issue clearly a decade later in her tenure statement: "To date, designers invariably encountered a dimensional mismatch between the 'environment space' and the 'object space.' In principle, this mismatch entailed a loss of information when a higher dimensional environment is projected or mapped onto a lower dimensional object."[2] Her overarching goal in response was to detect and decipher nature's myriad structural and essential design lessons and render them digitally for future application *at all scales*, for the benefit of architects and designers. To steer the relationship with science and modulate fluctuations in scale, she mastered the most expedient ingredient of all contemporary technologies: computation. To me, intent on finding new and innovative ways to conceive organic design, Oxman's approach seemed most timely and effective, visionary yet pragmatic, augmented by the extra gear that only digital technologies and morphologies could offer. She called it Material Ecology: "An emerging field in design denoting informed relations between products, buildings, systems, and their environment. Defined as the study and design of products and processes integrating environmentally aware computational form-generation and digital fabrication, the field operates at the intersection of biology, material science and engineering, and computer science, with emphasis on environmentally informed digital design and fabrication."[3]

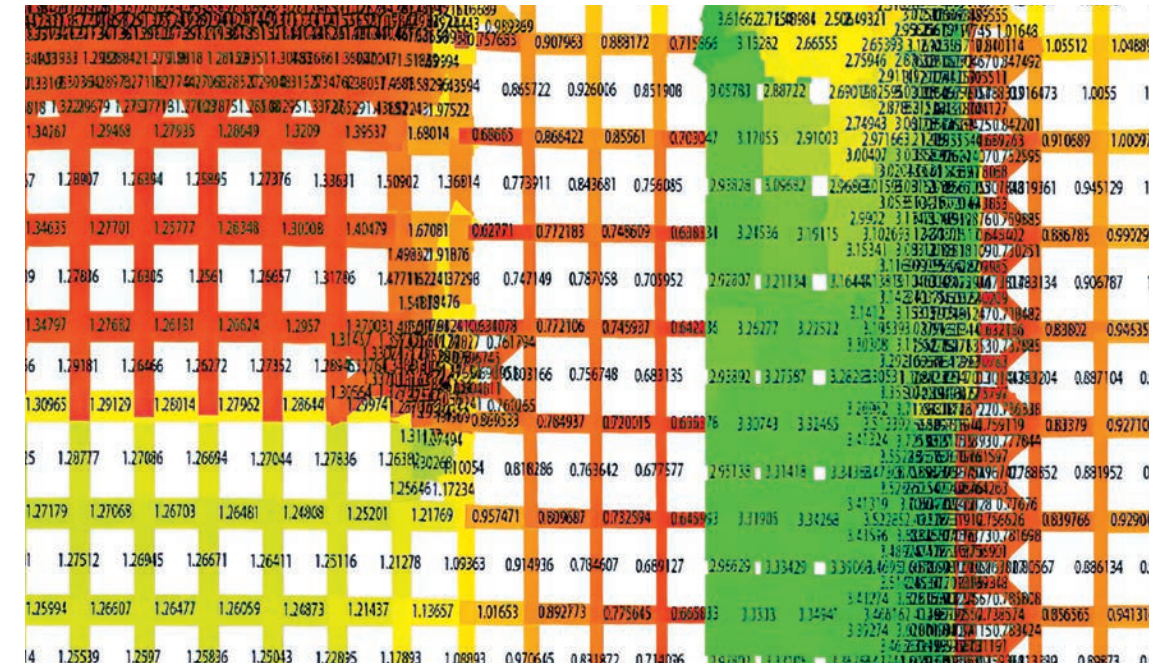


fig. 3 Subterrain. Diagram detail.

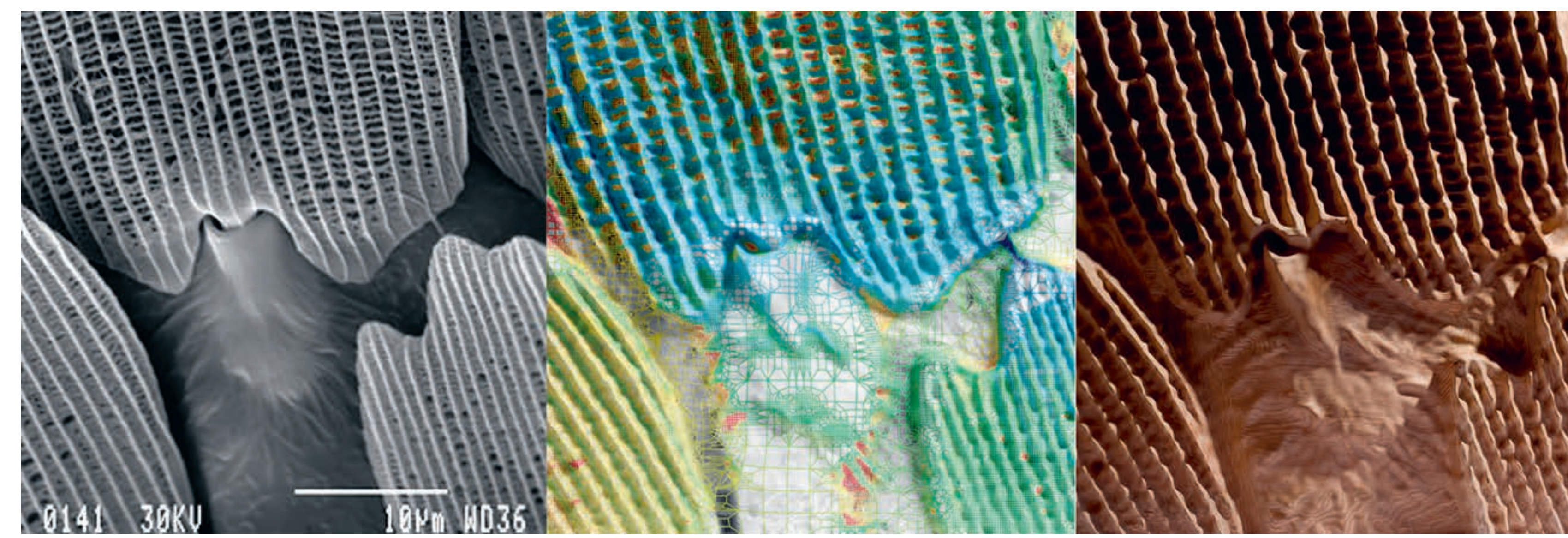
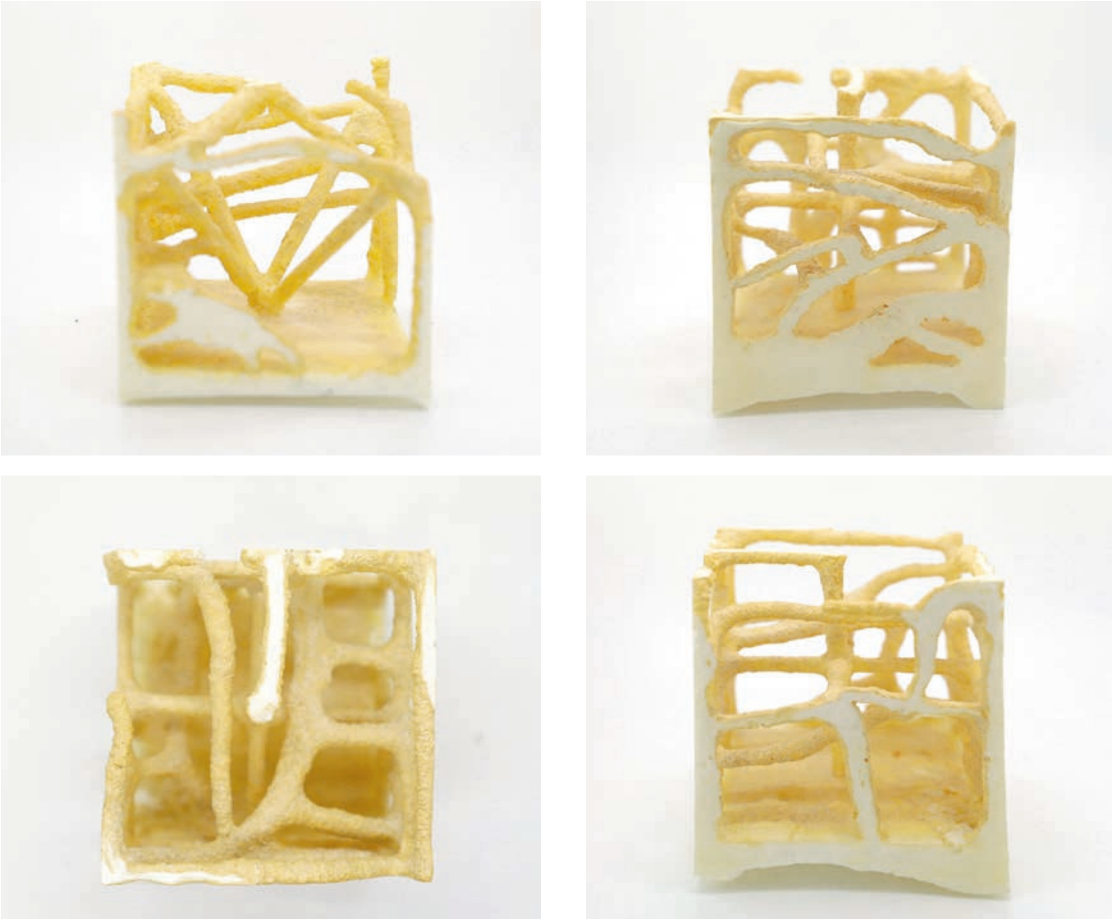


fig. 4 Subterrain. Micrograph image of a butterfly wing (left); analysis of material behavior according to stress, strain, heat flow, stored energy, and deformation from applied loads and temperature differences (middle); reconstructed tissue (right).

Design and the Elastic Mind featured four works from Oxman's Materialecology project—Subterrain, Raycounting, Monocoque, and Cartesian Wax (all 2007; **fig. 1**). Each explored natural and biological phenomena and the potential to use computation to reconstruct them at larger scales, demonstrating how this new technology could inform the future of designing and making objects.[4] In Subterrain (**figs. 2–4**), three tissues (a leaf section, a butterfly wing, and a scorpion claw) were analyzed at the microscale and reconstructed in macroscale using a digitally controlled, very fine mill to create three-dimensional wood prototypes. Raycounting (page 52) generates accurate three-dimensional replicas of objects by measuring the intensity and orientation of light rays—a tool that could hypothetically mimic natural behaviors and apply them to facade treatments, for instance. In three prototypes built using the Monocoque technique (page 64), "veins" on the skin, rather than an internal structure, carry the loads. In Cartesian Wax (page 58), the object's surface is thickened where it is structurally required to support itself, and its transparency also modulates according to light conditions and heat flux. Together, the experiments shown in *Design and the Elastic Mind* highlighted Oxman's early preoccupation with architecture and design's ability to be fluid, to adapt to changing environmental conditions, to contextual, functional, and infrastructural configurations, as well as to levels of occupancy. Computation, digital fabrication, material science, and biology enabled her aspirations. Further, Oxman's research was then already focused on the centrality of individual experience and the ability of architecture and design to respond to local and personal conditions. Oxman's disciplinary breadth, depth, and curiosity made me recognize in her a kindred spirit thirteen years ago. She has since willed dreams into experiments, and experiments into prototypes.



figs. 5–8 Neri Oxman and The Mediated Matter Group. Swarm Fabrication Studies. 2017. Polyurethane foam, 6 × 6 × 6 in. (15 × 15 × 15 cm)

Structures formed by a swarm of ants directed with UV lighting.

The Mediated Matter Group, the Media Lab, and the Nevalogue

In 2010, not long after *Design and the Elastic Mind*, Oxman established The Mediated Matter Group (MMG) at the MIT Media Lab. MMG has been the center of her collaborative practice ever since. The Media Lab, founded in 1985 by Nicholas Negroponte and Jerome Wiesner, is organized in several interdisciplinary—or, as its former director Joi Ito would say, *antidisciplinary*—research groups that bring together advanced technology and engineering with science, art, and design. The groups' names—Tangible Media, Sculpting Evolution, Fluid Interfaces, for example—combine the familiar and the cutting edge, suggesting their future-facing and yet still human-scale research strands.[5] The MMG team currently comprises two computer scientists focusing on computational design and artificial intelligence (Christoph Bader and Jean Disset), a multimedia designer (João Costa), a product designer (Felix Kraemer), three architects (Nic Lee, Joseph H. Kennedy Jr., and Ramon Weber), a biologist (Sunanda Sharma), a biomedical engineer (Rachel Soo Hoo Smith), a mechanical engineer (Michael Stern), an artist (Ren Ri), a marine scientist (James C. Weaver, as a research affiliate), and a weaver (Susan Williams). The studio includes a biosafety level 2 wet lab (allowing work with moderately hazardous pathogens)—a first in a design studio—and the group has worked with tools, species, and materials as diverse as silkworms, incandescent glass, ants, bitmap printers, bacteria, robotic arms, and bees (**figs. 5–10**), to name just a few. Broadly stated, as Oxman has described it, the team of researchers is focused on "inventing and developing new design tools, techniques, and technologies that have the potential to redefine the way we make things."[6] Oxman also often refers to a Venn diagram (**fig. 11**) that shows the intersection of four research areas—computation, additive manufacturing, materials engineering, and synthetic biology. "Computation allows us to design complex forms with simple code," she has explained. "Additive manufacturing lets us produce parts by adding material rather than carving it out. Materials engineering lets us design the behavior of materials in high resolution. Synthetic biology enabled us to design new biological functionality by editing DNA."[7] The results are complex, articulated, fine-tunable demo objects made with one process and often a single material.

One principle emerges from MMG's motley array of techniques: the process and the materials are the object—of research, of investment, of passion—or, put simply, the end shapes the means. Oxman draws on Gottfried Semper's ideas on this subject: "That matter is secondary to shape constitutes the fallacy of design after craft. By nature, and in its rite, the material practice of craft is informed by matter, its method of fabrication, and by the environment."[8] The ends, one could add, are shaped by culture, one that Oxman has designed for herself and for MMG to be attuned to the systems of nature, a great architect and builder that can be engaged as a powerful partner. Engaging nature, however, requires all hands on deck, a new creative culture that foregrounds symbiotic collaboration among disciplines and practices. If a Venn diagram, with its eureka moment of encounter and superimposition, sufficed to describe the tools necessary to define a new way to design and make, it is inadequate when the goal is to distill a new interdisciplinary approach to applied creativity—one that might also entail unmaking. That purpose is better served by the complexity of the Krebs metabolic cycle (pages 16–17, **figs. 12–14**).

Oxman's polymathic background made her an ideal fit for the Media Lab, a unique academic sandbox mixing art, design, technology, engineering, science, and entrepreneurship. Ito and the distinguished alumnus John Maeda espoused a theory, based on a book favored by MIT students and professors, Rich Gold's *The Plenitude: Creativity, Innovation, and Making Stuff*, that they called the Creative Compass.[9] The compass, rendered in four quadrants, includes art and design in addition to engineering and science. Ito argued that the Media Lab needed more teachers and students who could integrate all four quadrants. Maeda, while the president of Rhode Island School of Design, from 2007 to 2013, lobbied the United States government to add art to the traditional STEM (science, technology, engineering, and math) curriculum, making it STEAM.[10] Such interdisciplinary integration was uncommon at the time in U.S. academic circles, which were steadfast in mimicking the division between sides of the brain and espoused a contrived hierarchization of the disciplines (science on top of engineering, art on top of design). Their integration was instead natural to architects, like Oxman, who were steeped in European education, more theoretical and open to contamination.

fig. 9 Neri Oxman and The Mediated Matter Group. Beehive Studies. 2018. Natural beeswax, 3D-printed resin, stainless steel, polycarbonate, and prepared DC motor, 15 ½ × 19 ½ × 11 ¾ in. (40 × 50 × 30 cm)

Remains of beehive generated by the interaction of honeybees and a rotation mechanism.

fig. 10 Neri Oxman and The Mediated Matter Group. Studies for Synthetic Apiary. 2015. Polypropylene, honey, *Apis mellifera*, and wax, 2 ¼ in. (6 cm) diam. × ½ in. (1.5 cm)

A small sample from the first hive, which was installed on the roof of the MIT Media Lab.

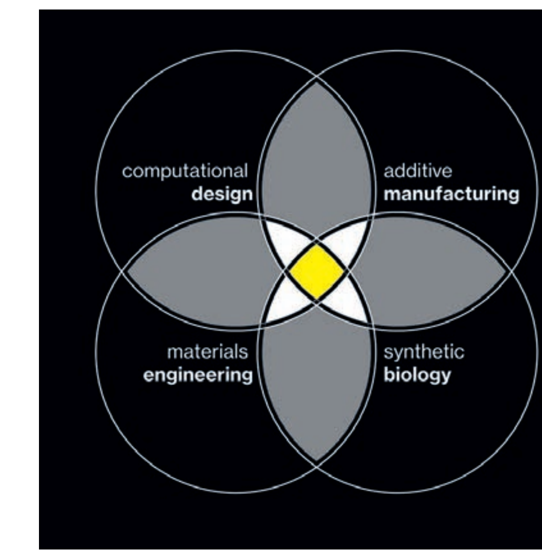


fig. 11 Neri Oxman. Material Ecology Venn diagram. 2015

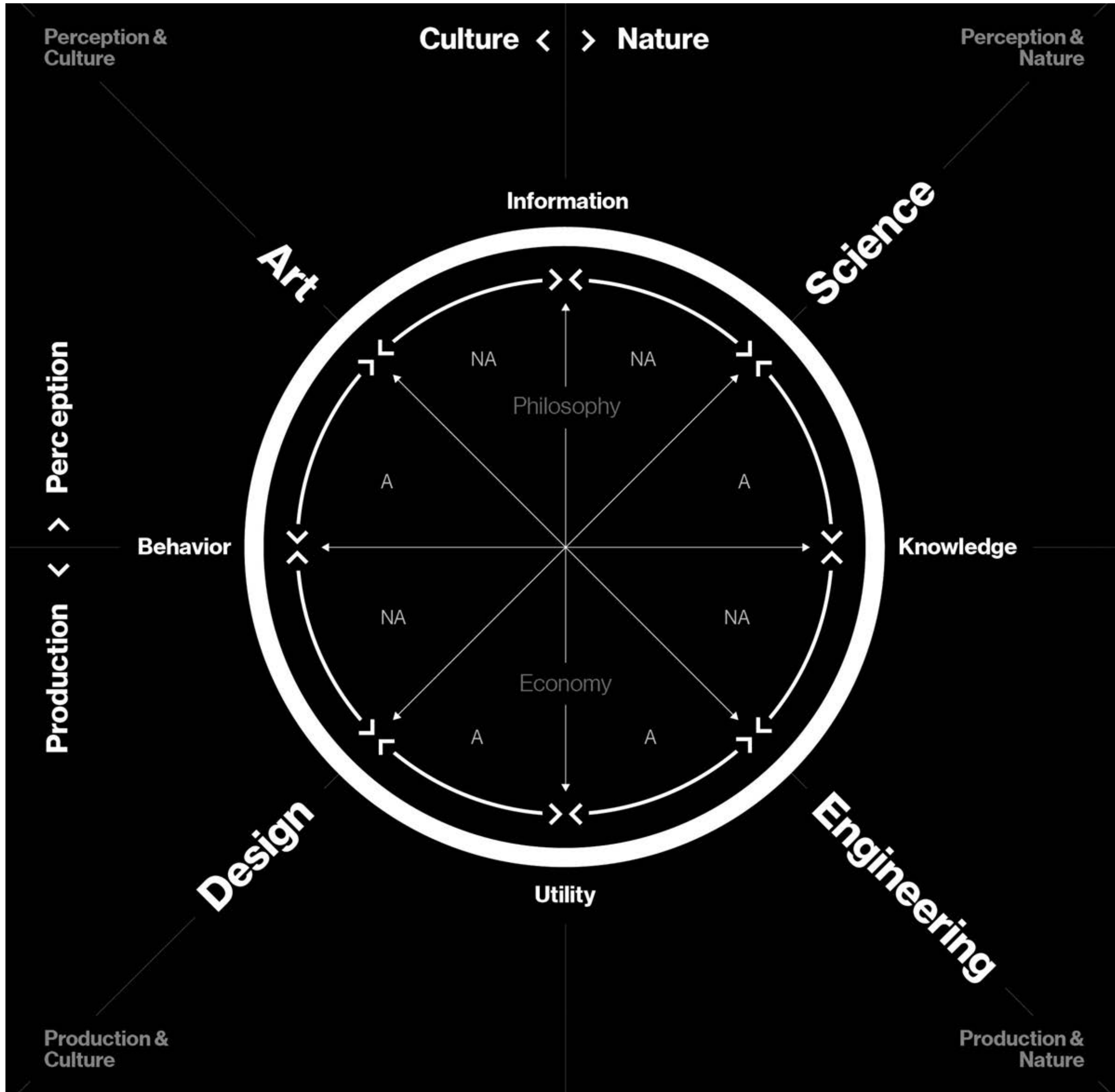


fig. 12 Neri Oxman. The Krebs Cycle of Creativity I (Domains). 2016

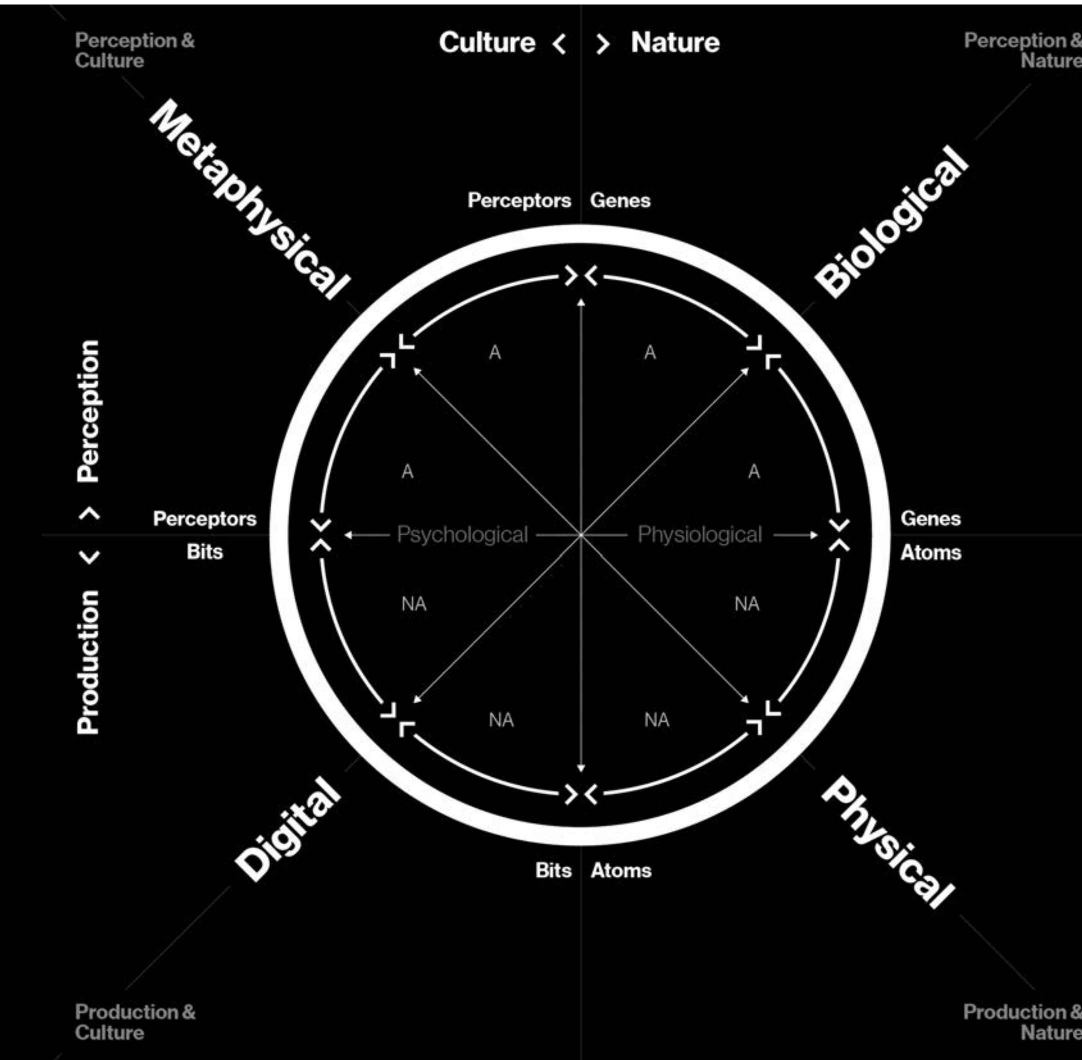
The Krebs Cycle of Creativity is a framework that considers the domains of art, science, engineering, and design as synergetic forms of thinking and making, in which the input from one becomes the output of another. Inspired by and named after the Krebs cycle, which describes the chemical reactions used by organisms that inhabit oxygenated environments, Oxman's version replaces the carbon compounds with the four modalities of human creativity.

The transitions from one domain to another generate intellectual energy, or CreATP. Science explains and predicts the world around us, converting information into knowledge; engineering applies scientific knowledge to the development of solutions for empirical problems, converting knowledge into utility; design produces solutions that maximize function and augment human experience, converting utility into behavior; and art questions human behavior and creates awareness of the world around us, converting behavior into new perceptions of information, presenting anew the data that initiated the cycle, in science.

The KCC's vertical axis leads from sky to earth, from the theoretical (or philosophical) to the applied (or economic). The north marks the climax of human exploration into the unknown; the south marks the products and outcomes this exploration produces. The horizontal axis leads from nature to culture, from understanding—describing and predicting phenomena within the physical world—to creating new ways of using and experiencing it.

fig. 13 Neri Oxman. The Krebs Cycle of Creativity II (Units). 2016

The Krebs Cycle of Creativity II replaces the domains of the first iteration with realms that explain, predict, change, and perceive the world, each of them identified by a unit associated with it. In order for design objects, structures, and interventions to be able to inform and influence the natural ecology, designers must be able to freely move between ways of seeing and making in the world and the units that build them—physical units (such as the elements of the periodic table), digital units (pixels), and biological units (genes).



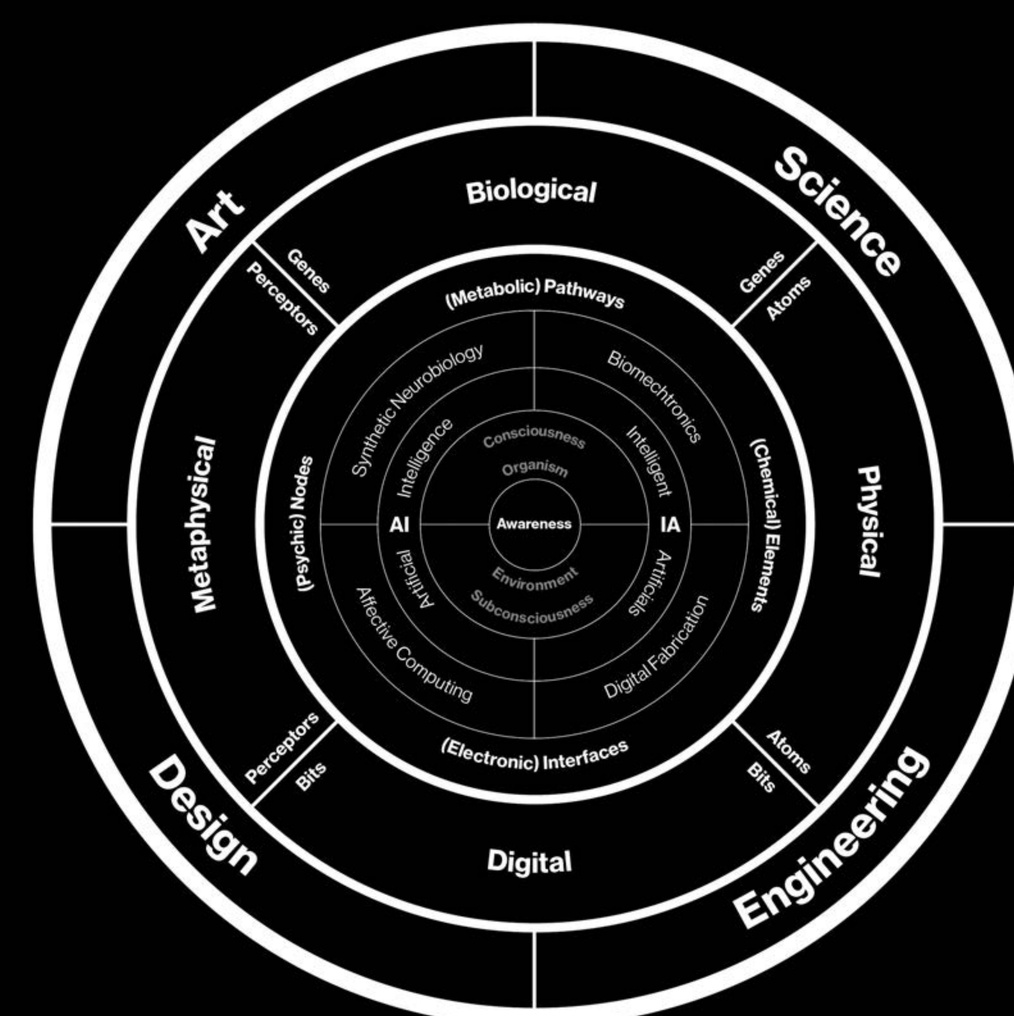


fig. 14 Neri Oxman. The Krebs Cycle of Creativity III (Domains + Units). 2016

The Krebs Cycle of Creativity III combines the first two iterations in a diagram of ideal interdisciplinary design practice, with unencumbered transitions among the realms and domains laid out in KCC I and KCC II. It can be interpreted from top to bottom as it relates to the organisms (top, expressed through metabolic pathways) and/or its environment (bottom, expressed through interfaces) and left to right as it relates to forms of Artificial Intelligence or Intelligent Artifacts.

KCC III was inspired by Walter Gropius's diagram of the Bauhaus curriculum, created in 1922, in which divergent trajectories are represented as a cycle, thus suggesting the school's mission of bringing together students from different disciplines in order to reform art, design, and society. The word *Bau*, in the center, is German for "building"; KCC III replaces that word with "awareness," suggesting that the future of design cannot address only the built environment and the objects designed for and deployed in it; instead, designers must combine the grown and the built, the natural and the artificial, the organism and its environment in novel ways that sustain, augment, and nourish our planet and its diverse inhabitants, in a bona fide Material Ecology.

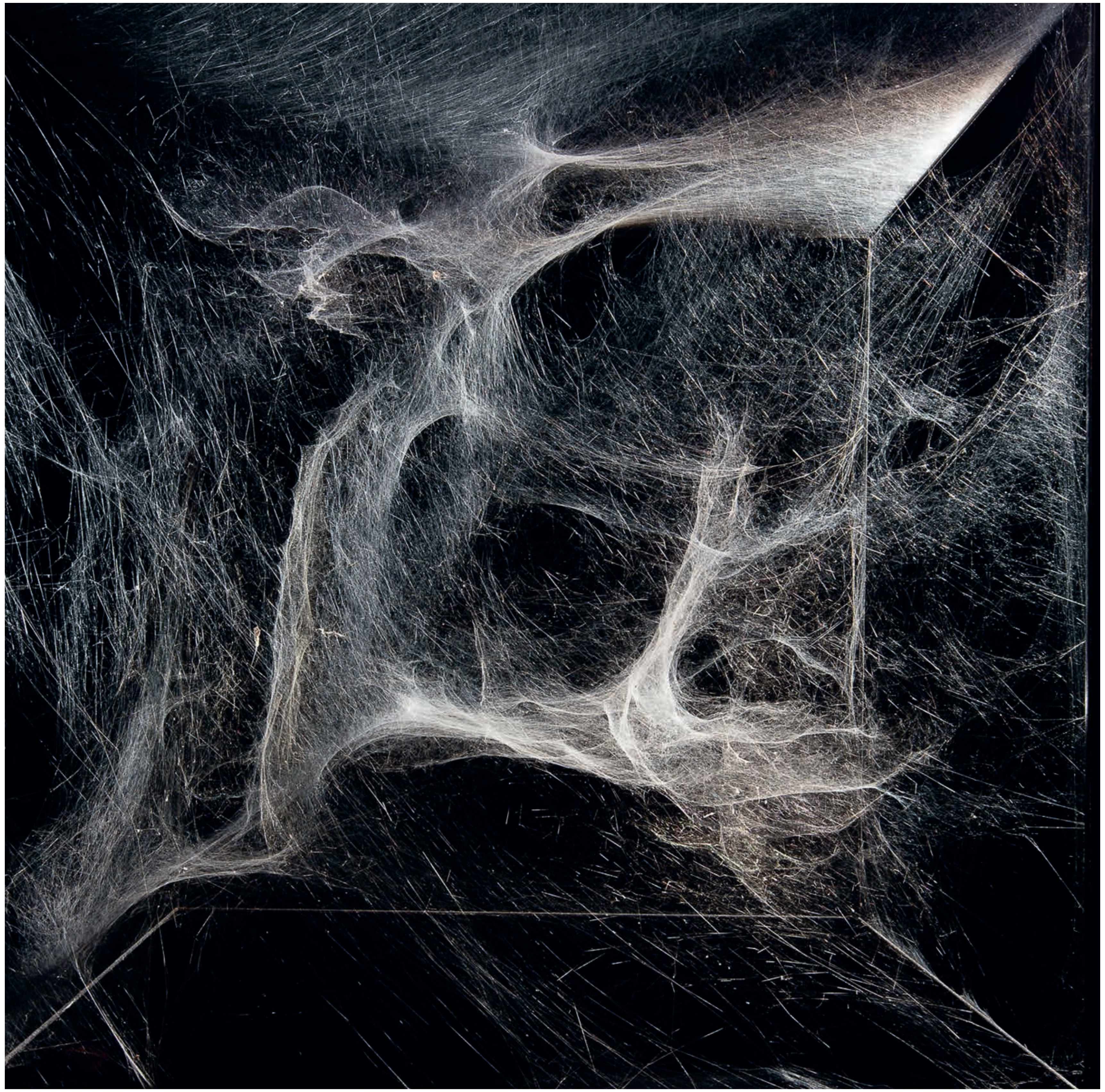


fig. 15 Tomás Saraceno. *Hybrid semi-social solitary musical instrument Arp87 built by: a couple* Cyrtophora citricola*—one month, one* Agelena labyrinthica*—two months, one* Cyrtophora moluccensis*—two weeks, and one* Tegenria domestica*—four months, turned 4 times 180 degrees on Z axis.* 2015. Spider silk, carbon fiber sticks, and plexiglass, 37 ¼ × 37 ¼ × 37 ¼ in. (94.5 × 94.5 × 94.5 cm)

Oxman in fact took the compass a step further in the Krebs Cycle of Creativity (previous pages). In her scheme—which she calls a cartography but which in reality is a philosophy—she postulates not just adjacency and coincidence but entanglement. She outlined a metabolic biofeedback cycle that drives the interdependence of the areas of research necessary for applied creativity: "Knowledge can no longer be ascribed to, or produced within, disciplinary boundaries, but is entirely entangled," she wrote, citing the Krebs cycle—which normally describes the chemical reactions that the cells of oxygen-breathing organisms use to generate energy—as a model.[11] One of the great advantages of the Krebs cycle is that it could be expanded to include the whole MIT community, boarded at different stations by scientists and artists already working in all four spheres—artists like Tomás Saraceno, for instance, who spent time as a visiting artist at MIT's Center for Art, Science, and Technology (CAST) studying spiderwebs (**figs. 15, 16**), and Agnieszka Kurant, who has deepened her understanding of the future of labor and AI through contemplating the collective intelligence of termites (**fig. 17**), or synthetic biologists like Christina Agapakis, who moved from describing cellular organisms to imagining brand-new ones with new functions—and teaming up with designers as a matter of professional course. In a 2017 interview, Oxman offered a revised definition of Material Ecology that also emphasizes universal synthesis. She called it "a holistic approach to design which considers all environments—the built, the natural, and the biological—as one, postulates that any designed physical construct is—by definition—an integral part of our ecology. A practicing material ecologist will therefore engage multiple disciplines—computational design, digital fabrication, synthetic biology, the environment, and the material itself—as inseparable and harmonized dimensions of design."[12]

In 2019, Oxman began a sabbatical from MIT and in early 2020 launched a new practice in New York. The team includes some members of MMG and replicates its diversity, with its members representing six key disciplines: "Two chemists, two biologists, two product designers, two mechanical engineers, two scientists, like Noah's Ark, and architects galore!" There is also a wet lab "with creatures from all six kingdoms"—plants, animals, protists, fungi, archaebacteria, and eubacteria—"and robots."[13] In the Media Lab environment, Oxman and MMG conduct experiments under the gaze of interested and invested patrons. In the new enterprise, patrons will become clients asked to concede their interests to those of the entity that Oxman considers her primary client: nature.

fig. 16 Installation view of *Tomás Saraceno: Hybrid solitary . . . Semi-social quintet . . . On Cosmic webs . . .*, Tanya Bonakdar Gallery, New York, March 26–May 2, 2015

fig. 17 Agnieszka Kurant. *A.A.I.* 2014–present. Termite mounds built from colored sand, gold, and crystals, dimensions variable

[a]	[b]
affirmative	critical
problem solving	problem finding
design as process	design as medium
provides answers	asks questions
in the service of shareholders	in the service of society
for how the world is	for how the world could be
science fiction	social fiction
futures	alternative worlds
fictional functions	functional fictions
change the world to suit us	change the us to suit the world
narratives of production	narratives of consumption
anti-art	applied art
research for design	research through design
applications	implications
design for production	design for debate
fun	satire
concept design	conceptual design
consumer	citizen
makes us buy	makes us think
innovation	provocation
ergonomics	rhetoric
user-friendliness	ethics

fig. 18 Dunne & Raby (Anthony Dunne and Fiona Raby). "A/B Manifesto." 2009

Oxman has crystallized her practice's naturecentric philosophy in a series of principles to which human clients will be asked to commit. The principles have undergone several revisions and are still in flux. The most recent version is "Nine Commandments for a Material Ecology," a nevalogue, or statement in nine points. The commandments are constructive, a declaration of intent for a new design practice. The early versions were descriptive of Oxman's intellectual process and juxtaposed old and new, considering design before and after digital computation and the advent of a so-called Century of Biology at the turn of the millennium. In that, they sympathized with the growing pains of the designers and theoreticians Anthony Dunne and Fiona Raby in moving design away from the problem-solving paradigm and toward criticality and inquisitiveness, a path spelled out in their 2009 "A/B Manifesto" (**fig. 18**), twenty-one juxtapositions highlighting the difference between the past, present, and future of design in the postindustrial, pandigital era.[14] Here is Oxman's nevalogue, followed by selected quotes from previous versions of the principles, along with my own notes in brackets.

Nature as Client
"The natural environment at large constitutes the 'client' for every commissioned project, as well as its 'site' and material source."

Growth over Assembly
"Nature grows things. We will be able to create objects that will respond to their users, adapt to their environment, and even grow over time after they have been printed." [This principle conceptually moves design and production into the new age of biology, from the assembly line to the wet lab.]

Integration over Segregation
"The typical facade of a building . . . is made up of discrete parts fulfilling distinct functions. Stiff materials provide a protective shell, soft materials provide comfort and insulation, and—in buildings—transparent materials provide connection to the environment. In contrast, human skin utilizes more or less constant material constituents for both barrier functions (small pores, thick skin on our backs) and filtering functions (large pores, thin skin on our face). [In an ideal object,] barrier and filtering functions are integrated into a single material system that can at any point respond and adapt to its environment." [Oxman often describes her work as noncompositional, a whole in which the same material articulates dynamically the required functions.]

Non-Human-Centered Design
"The group considers all living creatures as equals." "The group aims to shift human-centric design to a design culture focused on conserving, improving and augmenting the natural environment though novel technological developments." [The past decade has seen an increasing preoccupation with interspecies design and questioning of anthropocentric values, and Oxman's new practice chooses this position as its baseline.]

Difference over Repetition
"Industrial products generated out of machines . . . consist of repeatable parts with identical properties." "Comprehending difference enables us to design repetitive systems—like bone tissue—that can vary their properties according to environmental constraints. As a consequence of this new approach we will be able to design behavior rather than form." [The form-giving design of yesteryear yields to the new concept of formation, in which a system adapts and performs—behaves.]

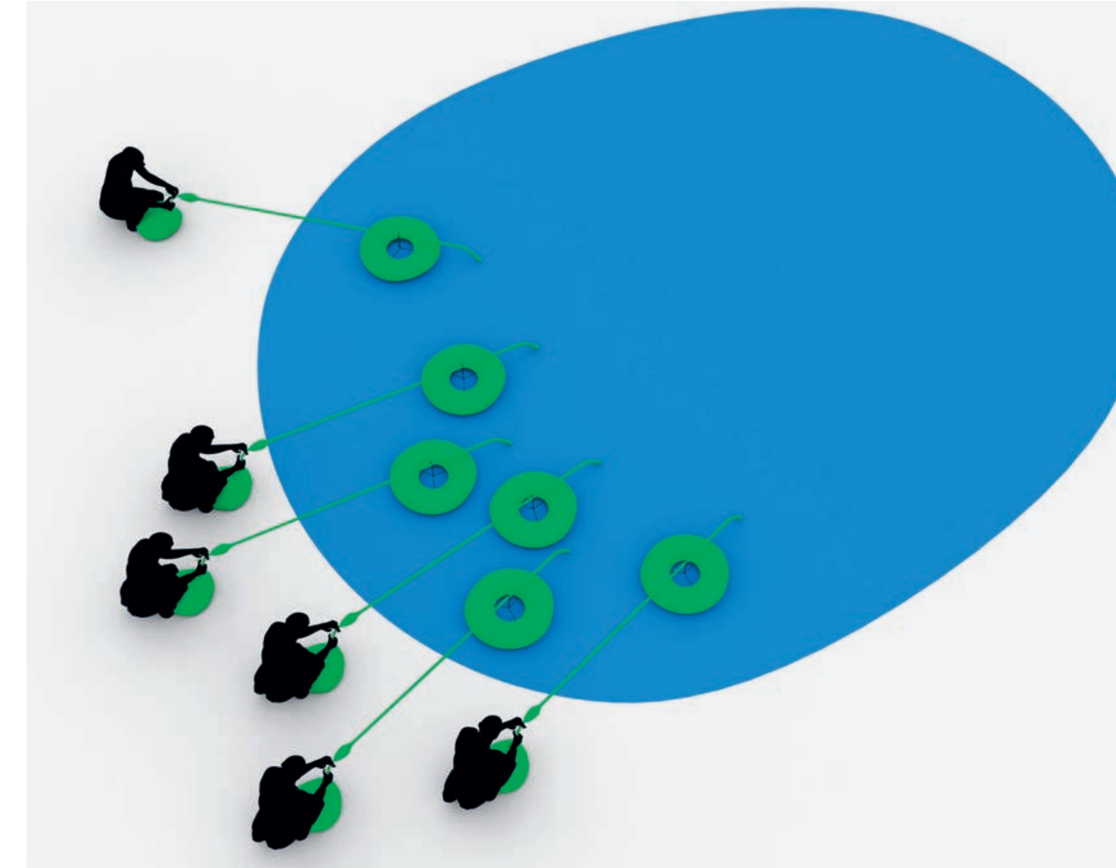
Decay over Disposal
"The Practice implements design workflows in which matter is synthesized by an ecosystem, implemented in human systems, and consumed by the same ecosystem upon obsolescence. . . . Designed decay is the process by which matter is programmed to rejoin an ecosystem's resource cycle and fuel new growth." [An embrace of circularity, this principle affirms the role of the architect within the ecosystem.]

Activist Design
"Any design commission becomes associated with a particular technology—invented or improved upon by the Lab—which embodies the value system associated with the group, and is directly linked to design and construction processes relevant to the commission." [Several enterprises, nonprofit and forprofit, are currently trying to integrate ethics and social and environmental responsibility into their practices, and to pass these values on to their customers—a brand of activism from within the system. Oxman's group will use technology as a vessel for change.]

System over Object
"The product—be it a product, a wearable device, or a building—is considered part of a *system* of interrelations between natural and designed environments including interactions between the entity and the human body as well as the entity and its environment."

Technology over Typology
"Moving away from the taxonomic classification commonly found in buildings and urban places, . . . topology—the way in which constituent parts are interrelated or arranged—is the driving force behind the design process, promoting condition-based programming as the approach for organizing spaces and making places."[15]

The Roots of Material Ecology: Critical Design, New Materiality, Performance-Based Design
This last principle in the "official" nevalogue represents a vow to approach every task at hand without being bogged down by past models, and yet Oxman's multifaceted projects can naturally be situated in various historical contexts. Critical Design, otherwise known—perhaps unfortunately—as Speculative Critical Design (SCD), accommodates the exploratory aspect of her work and the development of new prototypes, materials, and techniques in a speculative environment; these new design tools and technologies, she has said, "have the potential to redefine the way we make things, and *seeding them within speculative design contexts*."[16] Emerging around the turn of the millennium, Critical Design was centered on the Design Interactions course chaired at the Royal College of Art in London by Dunne between 2005 and 2015, at the apex of his and Raby's deep influence on the design world (**figs. 19–22**).[17] The products of Critical Design were, in most cases, objects—from fictional products to interfaces, interiors to buildings and infrastructures—designed in response to scenarios that imagined the possible future consequences of our present choices. They were produced by interdisciplinary teams that included experts on ethics, the life sciences, politics, philosophy, and the economy, among other fields.[18] Their objective was to instigate what the foresight expert Stuart Candy has defined as a "preferable future," in contrast with those that are "probable," "plausible," and "possible."[19]



figs. 19, 20 Dunne & Raby (Anthony Dunne and Fiona Raby). Algae Digesters, from Designs for an Overpopulated Planet: Foragers. 2009. Video and prototypes. The Museum of Modern Art, New York. Gift of The Contemporary Arts Council of the Museum of Modern Art

figs. 21, 22 Dunne & Raby (Anthony Dunne and Fiona Raby). Tree Processor/Digester, from Designs for an Overpopulated Planet: Foragers. 2009. Video and prototypes. The Museum of Modern Art, New York. Gift of The Contemporary Arts Council of the Museum of Modern Art

Much like Italian Radical Design of the 1960s and 1970s, Critical Design began at a moment of pivotal technological, sociopolitical, economic, and cultural change—in this case the ingraining of the digital era—and blossomed until it quickly fizzled into the academic mainstream. After the slow extinction of the RCA course, the Critical Design baton has passed to the Design Academy Eindhoven (already a long-time bona fide runner-up), to the Haute école d'art et de design (HEAD), in Geneva, and to the Aalto University, in Helsinki, among others. Despite its proliferation, much current SCD, sprinkled in design schools worldwide, has featured earnest but inconsequential exercises and clichéd storytelling. Overawed by urgent worldwide environmental and socio-political crises, and by Silicon Valley's gung-ho moonshots into the future, it has lost its bite. Further, it is now clear that there is little patience for fiction (at least in design practice), and no time to waste: the world needs to know that speculations, however far-fetched, can actually happen. The most significant heirs to the SCD approach then are the programs that start from foundations of engineering and science and build a bridge to design. Polytechnic institutions such as Carnegie Mellon University, Cornell University, and MIT model such approaches, and Oxman and MMG are exemplary. Creating "designs that have a profound connection with a specific ecosystem," they choose a preferable future and go for it with all the ammunition in their arsenal, making it first possible (as in an ambitious utopian plan for Tokyo in 2200, commissioned by the Mori Art Museum and the Mori Building Company [**fig. 23**]), then plausible, and hopefully in the end probable.[20]

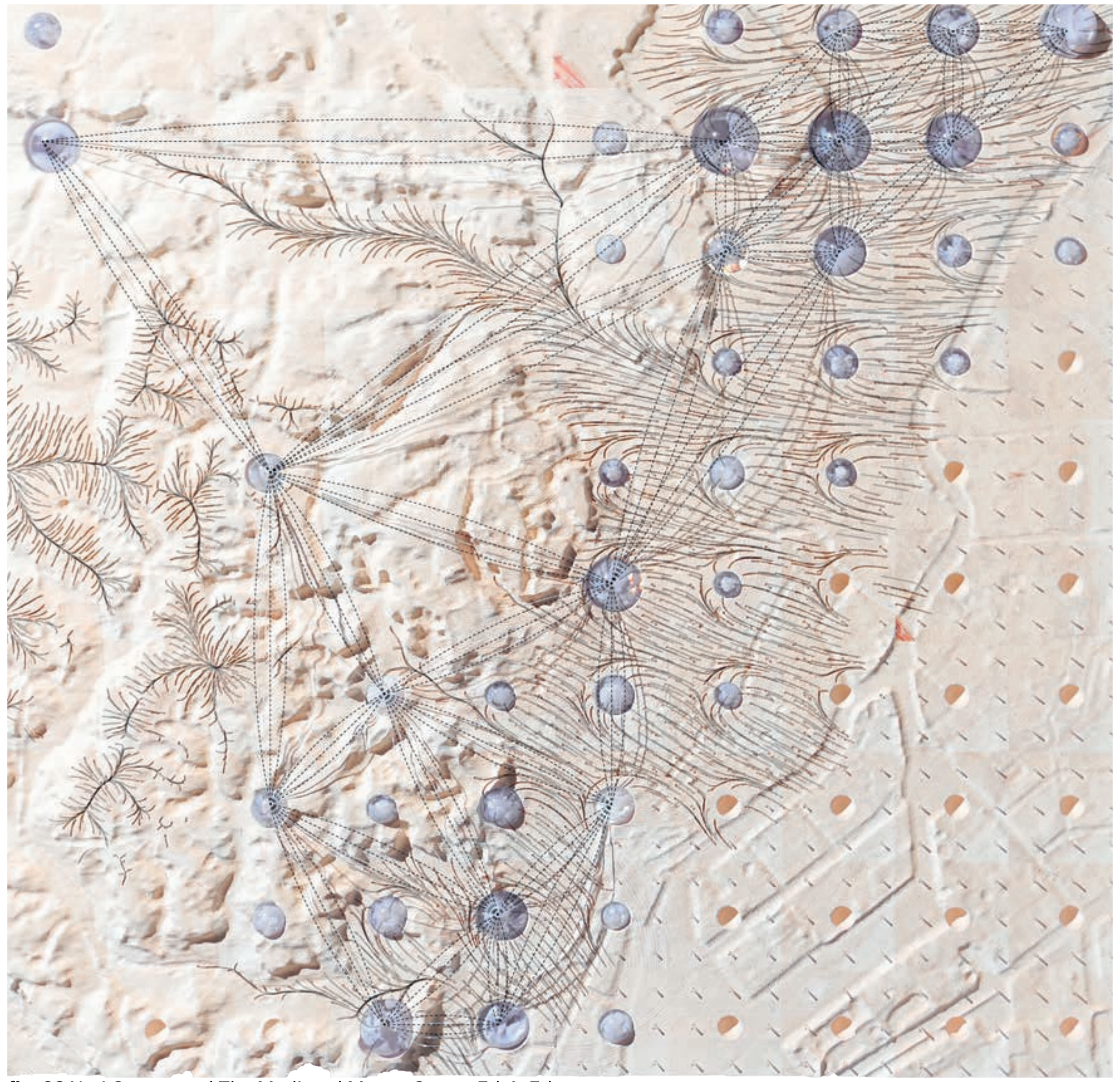


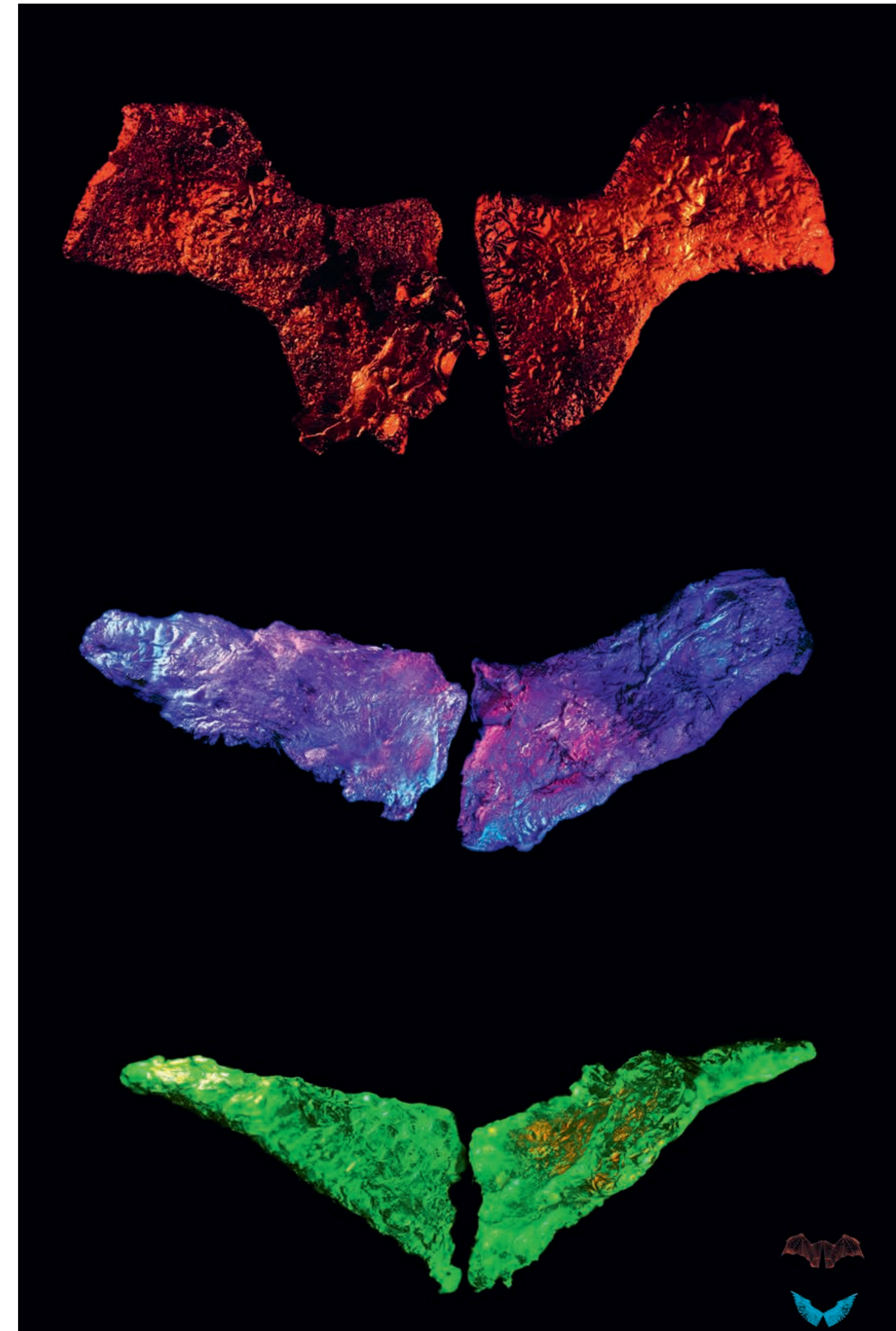
fig. 23 Neri Oxman and The Mediated Matter Group. Edo's Eden: Tokyo 2200. 2019. Wood (hinoki cypress from the Tono region of Japan), acrylic, and photopolymers, 39 ¼ × 39 ¼ × 51 in. (100 × 100 × 130 cm)

A single hinoki tree transformed into an urban-design model, for a future in which a new typology will grow out of the symbiotic relationship between nature- and human-made environments. The meganature is a megastructure with a controlled environment; the model is both time capsule and tree-seed bank.

fig. 24 Installation view of *Mutant Materials in Contemporary Design*, The Museum of Modern Art, New York, May 25–August 22, 1995

Opposite, top:
fig. 25 Oron Catts, Ionat Zurr, and Guy Ben-Ary. The Pig Wings Project, from the Tissue Culture & Art Project. 2000–01. Developed at SymbioticA, The Art and Science Collaborative Research Laboratory, School of Anatomy and Human Biology, The University of Western Australia. Pig mesenchymal cells (bone-marrow stem cells) and PGA and P4HB biodegradable, bioabsorbable polymers, dimensions variable

Wings grown from the mesenchymal cells of pigs and shaped to mimic the wings of a bat, an imaginary angel, and a pterosaur.



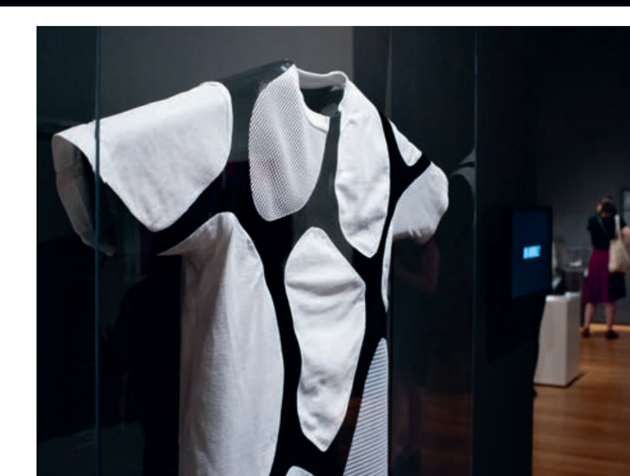


fig. 26 Suzanne Lee and Amy Congdon, Modern Meadow. Zoa. A new animal is born. 2017. Zoa biofabricated leather and cotton, 37 × 31 in. (94 × 78.7 cm). Installation view in *Items: Is Fashion Modern?*, The Museum of Modern Art, New York, October 1, 2017–January 28, 2018

Another root of Oxman and MMG's work can be found in the design of materials. In the modern era, the evolution of the materials of architecture and design has provoked and supported extraordinary mutations in our built environment at all scales. Materials science, moreover, has had a significant impact on design culture at large, freeing not only the floors of buildings and the versatility of objects but also the imaginations of designers and architects—and giving each modern age its own distinct visual and spatial character. In 1995 I organized my first MoMA show, *Mutant Materials in Contemporary Design* (**fig. 24**). The show's thesis was that in a much welcome coup d'état, designers were able to take control of a new generation of materials and begin the design process with the design of the materials themselves, instead of receiving the offerings of engineering and chemical companies. Since 1995 designers' takeover of the material realm has evolved even further, from new resins and composites all the way to biopolymers and living tissues. Taking advantage of the curiosity and openness of synthetic biologists, chemists, physicists, and other scientists, designers like Oron Catts and Ionat Zurr (**fig. 25**), Suzanne Lee (**fig. 26**), Alexandra Daisy Ginsberg, Natsai Audrey Chieza, and Gionata Gatto, among others, have initiated a fertile exchange with science (with biology in particular) and ventured into territories new not only for design but for the whole world.[21] Oxman described this same evolution in her 2013 essay "Material Ecology," in the section "Designing (with) Nature: Towards a New Materiality": "Today, perhaps under the imperatives of growing recognition of the ecological failures of modern design, inspired by the growing presence of advanced fabrication methods, design culture is witnessing a *new materiality*. . . . Examples of the growing interest in the technological potential of innovative material usage and material innovation as a source of design generation are developments in biomaterials, mediated and responsive materials, as well as composite materials."[22] Indeed, Oxman and MMG have put such new materials to powerful use in their projects, freeing both their imaginations and their designs' potential.[23]

fig. 27 Diller + Scofidio (Elizabeth Diller and Ricardo Scofidio). Slow House Project, North Haven, New York. 1989. Plan of lower level and sections. Computer-generated print on frosted polymer sheet with graphite and colored ink, mounted on painted wood with metal, 47 ⅝ × 36 ½ × 1 ½ in. (121 × 92.7 × 3.8 cm). The Museum of Modern Art, New York. Marshall Cogan Purchase Fund and Jeffrey P. Klein Purchase Fund

A final historical thread in Oxman's work comes out of the exquisite synthesis of computation and inspiration that is performance-based design. Asked in 2019 to pick any object in MoMA's collection to discuss in a BBC podcast episode, Oxman chose the most flowing of all architectures—the Austrian architect Frederick Kiesler's legacy project Endless House (1950–60; pages 38–39, **fig. 1**; page 45, **fig. 13**).[24] As Oxman notes in the podcast, so many aspects of Kiesler's intellectual and professional life drew her to him—his spirituality and his nondenominational ease with art and artists among them. But more than anything, she admires the specificity of his architecture—how it adapts locally to changing conditions. The formal, if not conceptual, opposite of a modernist free plan, Kiesler's ideal space is elastic, biomorphic, even intestinal, attuning its curves, the thickness and pitch of the walls, the form and position of the windows, and the slope of the floor to the needs, habits, functions, and feelings of its dwellers. Among the rich pickings from the collection, Oxman was also tempted by Diller + Scofidio's Slow House (1988–90; **fig. 27**). "Conceived as a passage from physical entry to optical departure or, simply, a door to a window," the house is shaped like an acoustic horn opening up to the sea, moving from the smallest intake (the door) through the low ceilings of the sleeping quarters to the air and light of the kitchen and living room, which is open to the water.[25] The architects made sure that the ocean view, replicated in video projections, could be seen in the remote quarters near the entrance. Slow House is a poignant example of dynamic, conditional architecture, conceptual and yet realizable and livable—the video-era evolution of Kiesler's project. Endless House and Slow House both offer an apt introduction to Oxman's brand of performance-based architecture, which carries the conditional paradigm one step further, by integrating it in the technological sphere first, and the biological second.

As Michael Hensel wrote in his history of performance-based architecture, the approach first emerged in the 1960s, at the sunset of modernism, amid the Cold War and the space race, as rockets, space stations, biodomes, and bunkers were adopted as living paragons in both mainstream culture and by architects—the conceptions of Walter Pichler and Raimund Abraham among them, to mention two outstanding works in MoMA's collection (**figs. 28, 29**).[26] These highly technical dwellings guaranteed survival only by adhering to specific, scientifically established parameters and infrastructures; they were parts of ecosystems and constituted an ecosystem in their own right. At that same time, notions of cybernetics and automation made their way into architecture, casting buildings as complex machines that should be devised to support human interaction and functional definition. The great, early manifesto for this kind of approach was Cedric Price's deeply influential 1964 Fun Palace project (**fig. 30**). Inspired by and developed with the avant-garde theater director Joan Littlewood, relying on experts such as the cybernetician Gordon Pask and the psychiatrist Morris Carstairs, Fun Palace has best been described by the architecture scholar Stanley Mathews as "a unique synthesis of a wide range of contemporary

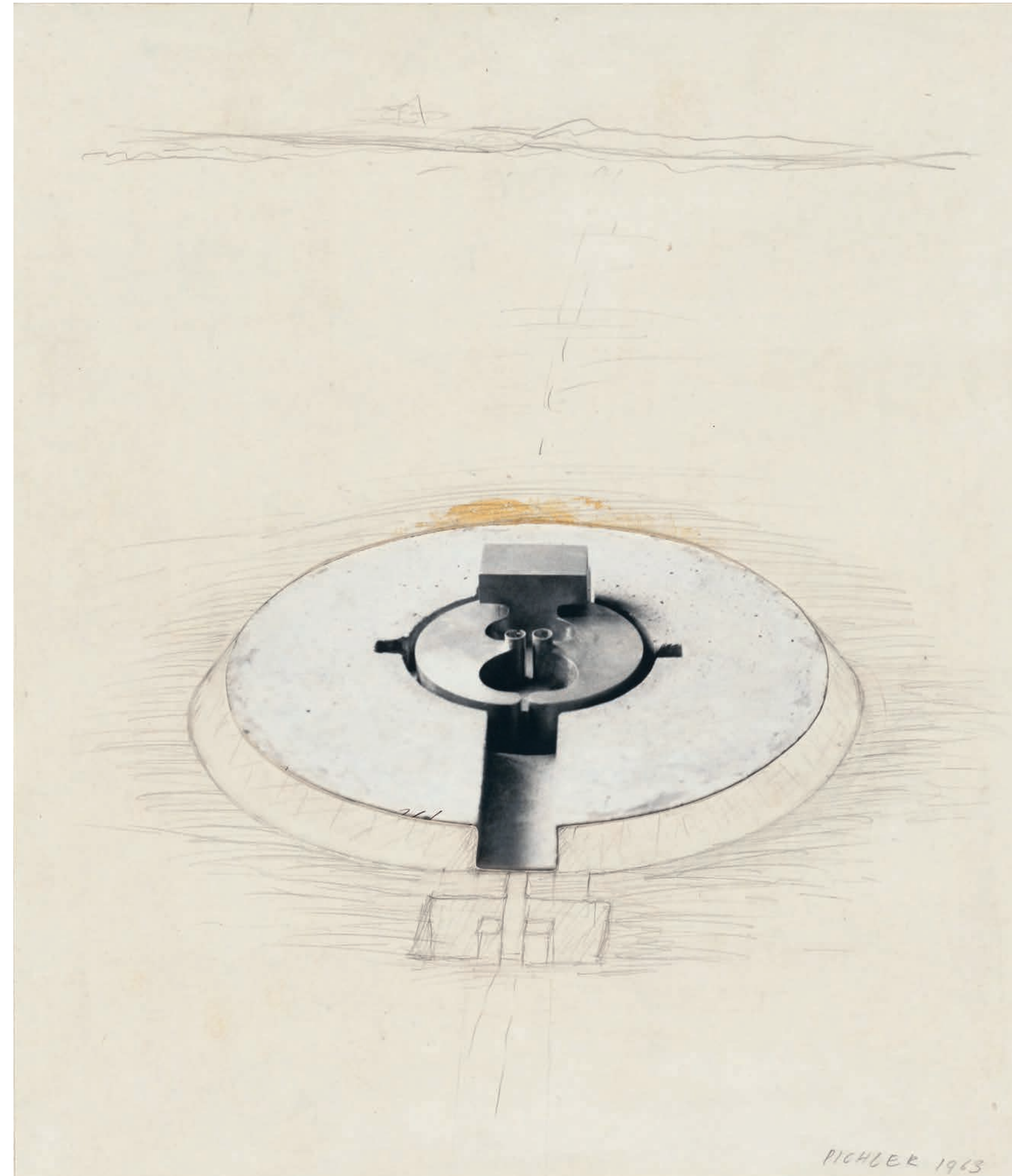


fig. 28 Walter Pichler. Entrance to an Underground City. 1963. Perspective. Photomontage and graphite, 13 ¾ × 11 ¾ in. (34.9 × 29.8 cm). The Museum of Modern Art, New York. Philip Johnson Fund

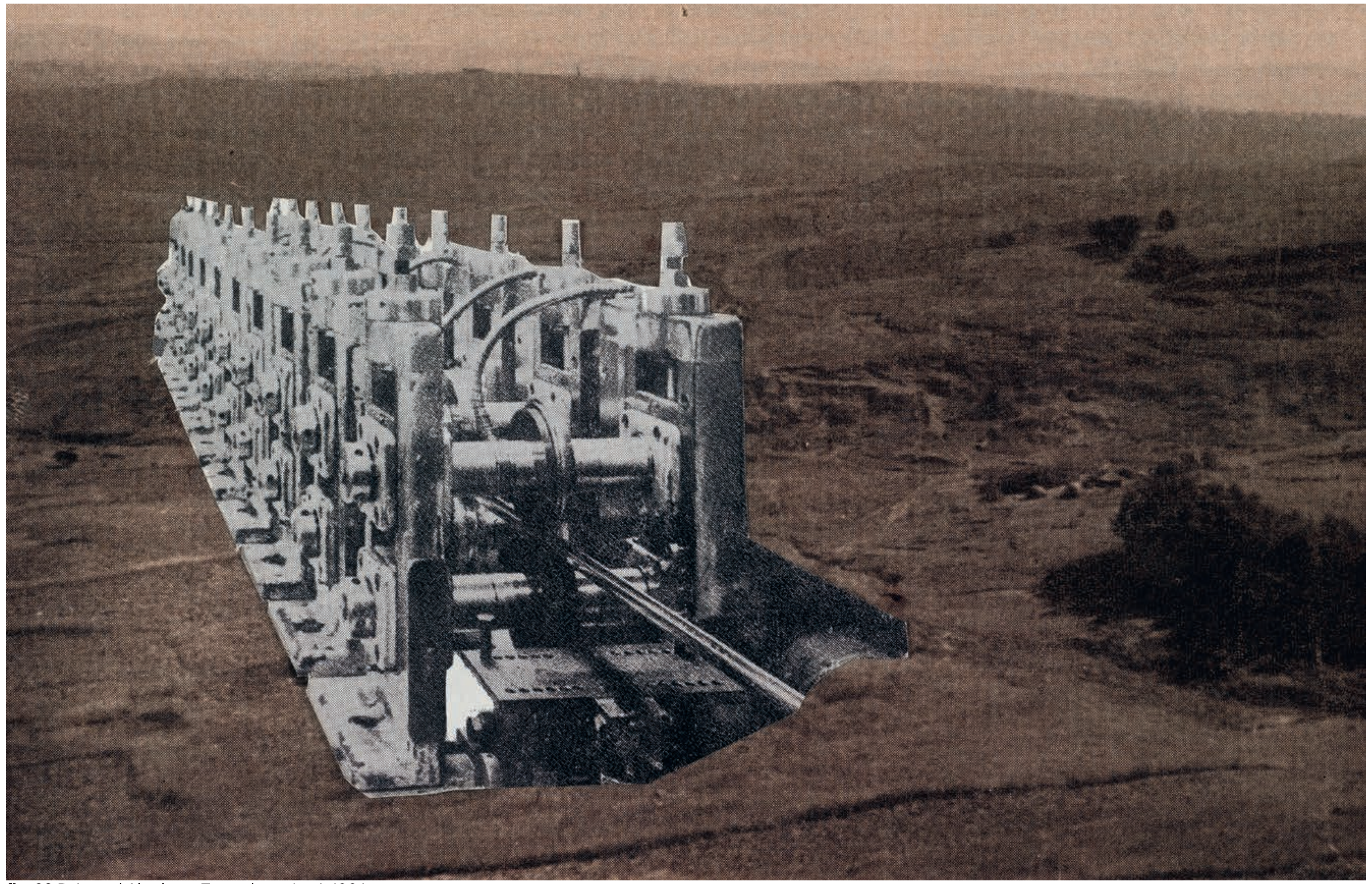


fig. 29 Raimund Abraham. Transplantation I. 1964. Perspective and plan. Collage, 4 ½ × 7 in. (11.4 × 17.8 cm). The Museum of Modern Art, New York. Philip Johnson Fund

discourses and theories, such as the emerging sciences of cybernetics, information technology, and game theory, Situationism, and theater to produce a new kind of improvisational architecture to negotiate the constantly shifting cultural landscape of the post-war years."[27] Indeed, Fun Palace was designed to be activated at the whim of its dwellers, occupied, owned, and used in the way a design object would be. The machine could be inhabited, at last. Flexibility and adaptability were the key-words, and interfaces the new territory of architecture.

In August 1967, the American journal *Progressive Architecture* (**fig. 31**) dedicated an entire issue to the topic of performance design. Hensel notes that the issue focuses on "systems analysis, systems engineering and operations research," as well as "mathematical modelling towards optimization and efficiency." In other words, performance-based architecture is informed not only by the functional program and its formal synthesis but also contemplates a building as a complex system, shifting the focus "from what the building *is* to what it *does*."[28] In 1969 Reyner Banham echoed this call for integration in *The Architecture of the Well-Tempered Environment,* arguing that buildings should not be "divisible into two intellectually separate parts—*structures*, on the one hand, and on the other *mechanical services*."[29] Rather, he suggested, a successful approach to architecture consists in an organic integration and should investigate both external and internal factors, changes in use, changes in users' expectations, changes in the methods of servicing the users' needs and, most importantly for him, the mechanical environmental controls of the building.[30] Banham had in fact already begun arguing for such organic integration in 1965, in an essay for *Art in America* titled "A Home Is Not a House," for which the Canadian architect François Dallegret produced memorable drawings (**fig. 32**).

fig. 31 *Progressive Architecture*, "Performance Design" issue, August 1967. Cover designed by Richard C. Lewis

fig. 30 Cedric Price. Fun Palace for Joan Littlewood Project, Stratford East, London. 1959–61. Perspective. Felt-tipped pen, ink, graphite, crayon, and ink stamp on tracing paper with tape, 6 ½ × 15 ⅞ in. (16.5 × 40.3 cm). The Museum of Modern Art, New York. Gift of The Howard Gilman Foundation

Nicholas Negroponte's *The Architecture Machine: Toward a More Human Environment* (1970; **fig. 33**) was among the first books in the United States dedicated to architectural performance.[31] Highlighting three key concepts—generation, evaluation, and adaptation—the book continued to explore the relationship between human and machine in architecture and design and looked at how emerging technologies facilitated human-machine partnerships. Negroponte's idea of the future was one in which architecture and design embraced these collaborations to the point at which it was not possible to distinguish each partner's contributions.[32] In the decades after the publication of *The Architecture Machine* and with the advancement of computation in architecture, many research projects sought to develop an integrated design system to facilitate performance-based architectural design. The concept was widely adopted toward the end of the twentieth century with the rise of sustainable and green architecture in the United States and, especially, in Europe as a response to environmental concerns.[33] The development of building performance–simulation technologies, which replicate aspects of building performance using a computer-based mathematical model, was also a key factor in this period.

Digital culture and the advent of digital fabrication shifted the focus of architecture's optimization from the mechanism to the algorithm—not only functionally, structurally, and systemically but also expressively. In the book and exhibition *Archaeology of the Digital*, Greg Lynn pointed to a moment in the late 1980s and early 1990s when architects outside of polytechnic schools anointed computation, and when early elements of it could be found in the work of established architects such as Peter Eisenman (**fig. 34**) and Frank Gehry. The introduction of Netscape in 1994 marked the beginning of a new era of "digital normal" for the world at large, during which new tools for creativity and processing led to the proliferation of exuberant new formal languages in all realms—art, literature, popular culture, and architecture and design. Theoreticians and practitioners ran wild with highly exploratory models, driven by the search for a new, "better" way of designing.[34]

fig. 32 François Dallegret. Anatomy of a Dwelling. 1965. Chinese ink on translucent film and gelatin on transparent acetate, 24 ¼ × 19 15/16 in. (61.1 × 50.6 cm). Frac Centre-Val de Loire collection

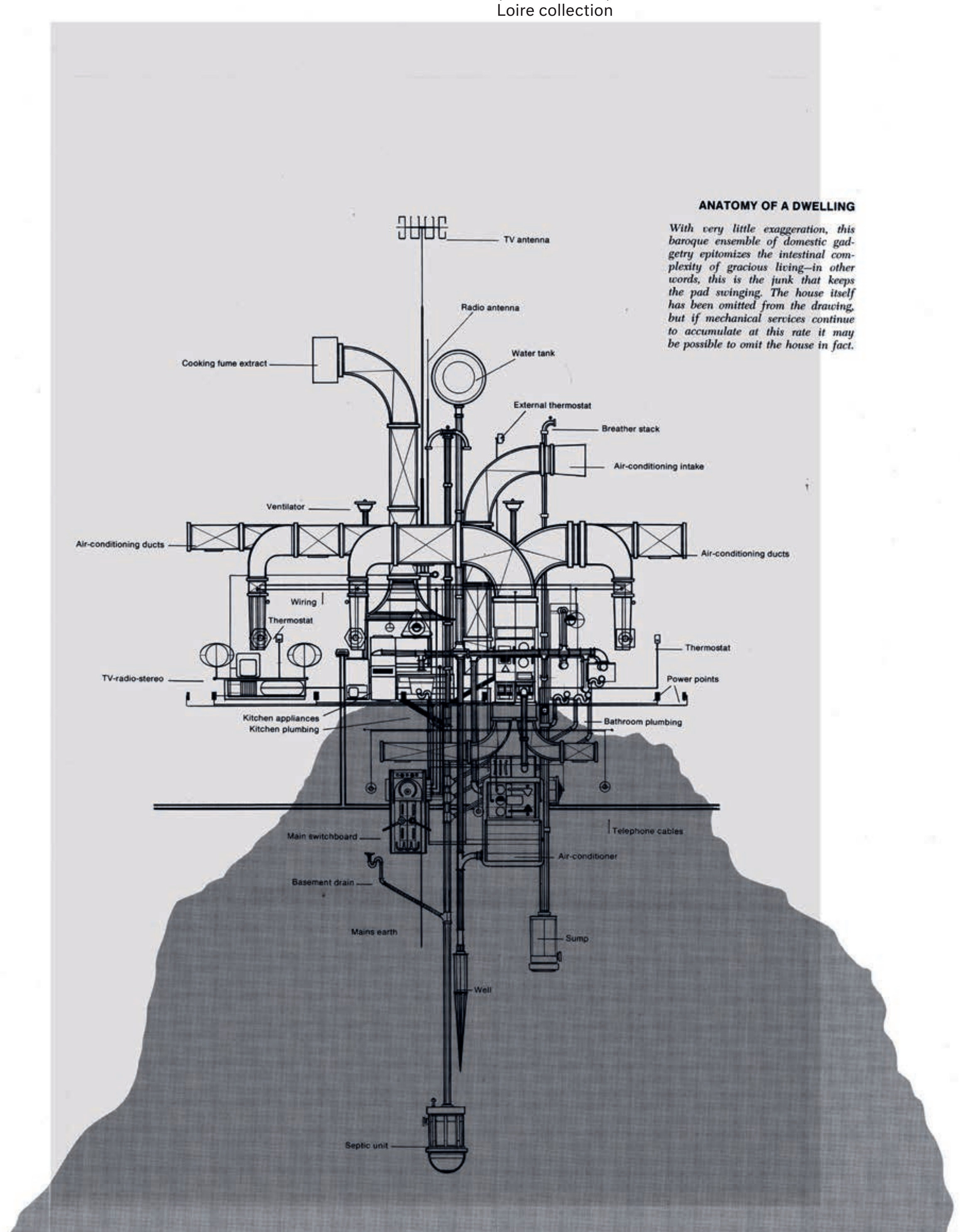


fig. 33 *The Architecture Machine*, by Nicholas Negroponte, 1970. Cover designed by Muriel Cooper

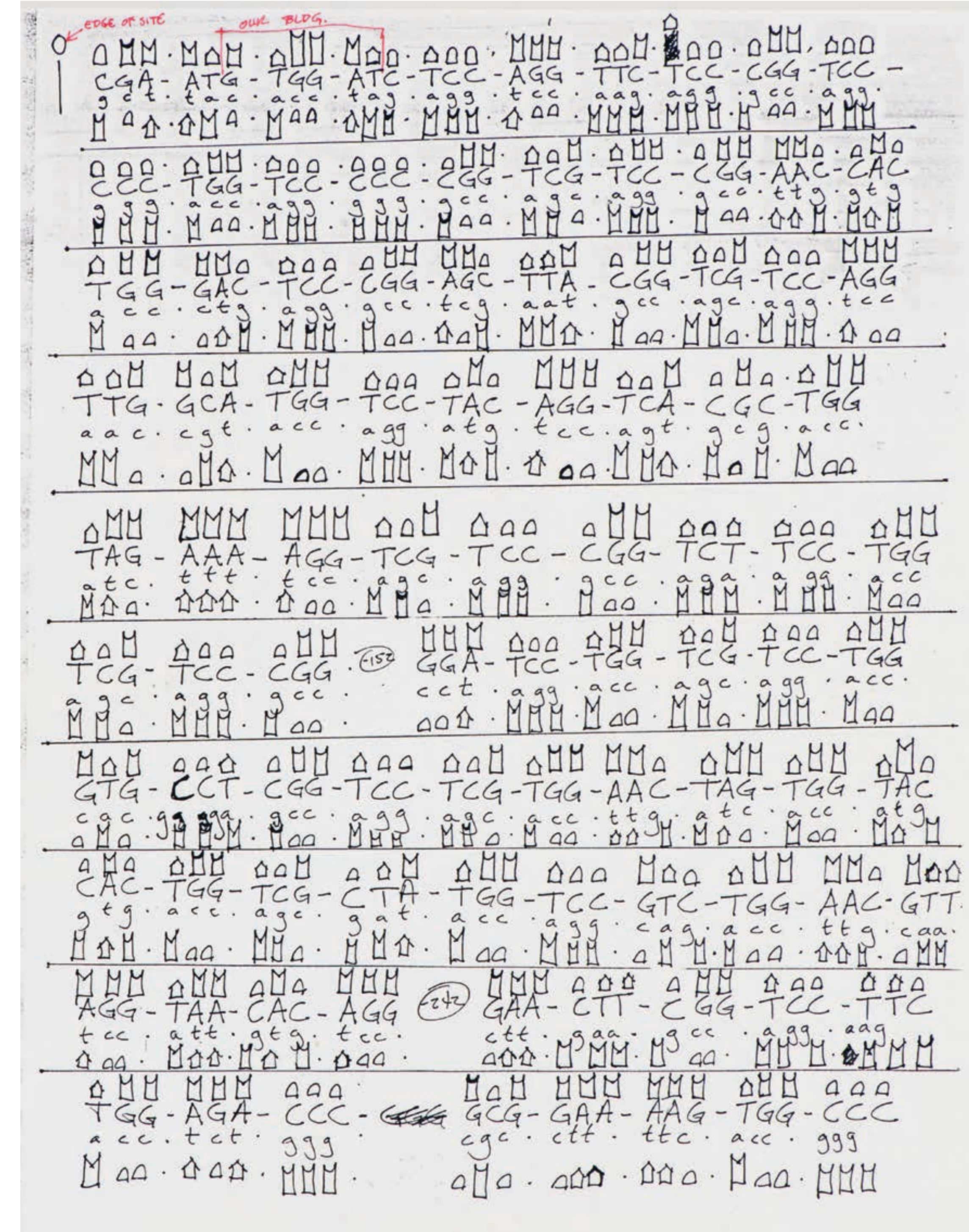


fig. 34 Eisenman/Robertson Architects (Peter Eisenman and Jaquelin T. Robertson). Schematic representation of a DNA sequence for Biozentrum, Biology Center for the J. W. Goethe University, Frankfurt am Main, Germany. 1987. Electrostatic print with ink notations, 11 × 8 ½ in. (28 × 21.5 cm)

The print was included in *Archeology of the Digital*, Canadian Centre for Architecture, Montreal, in 2013, and Yale School of Architecture, New Haven, Connecticut, 2014.

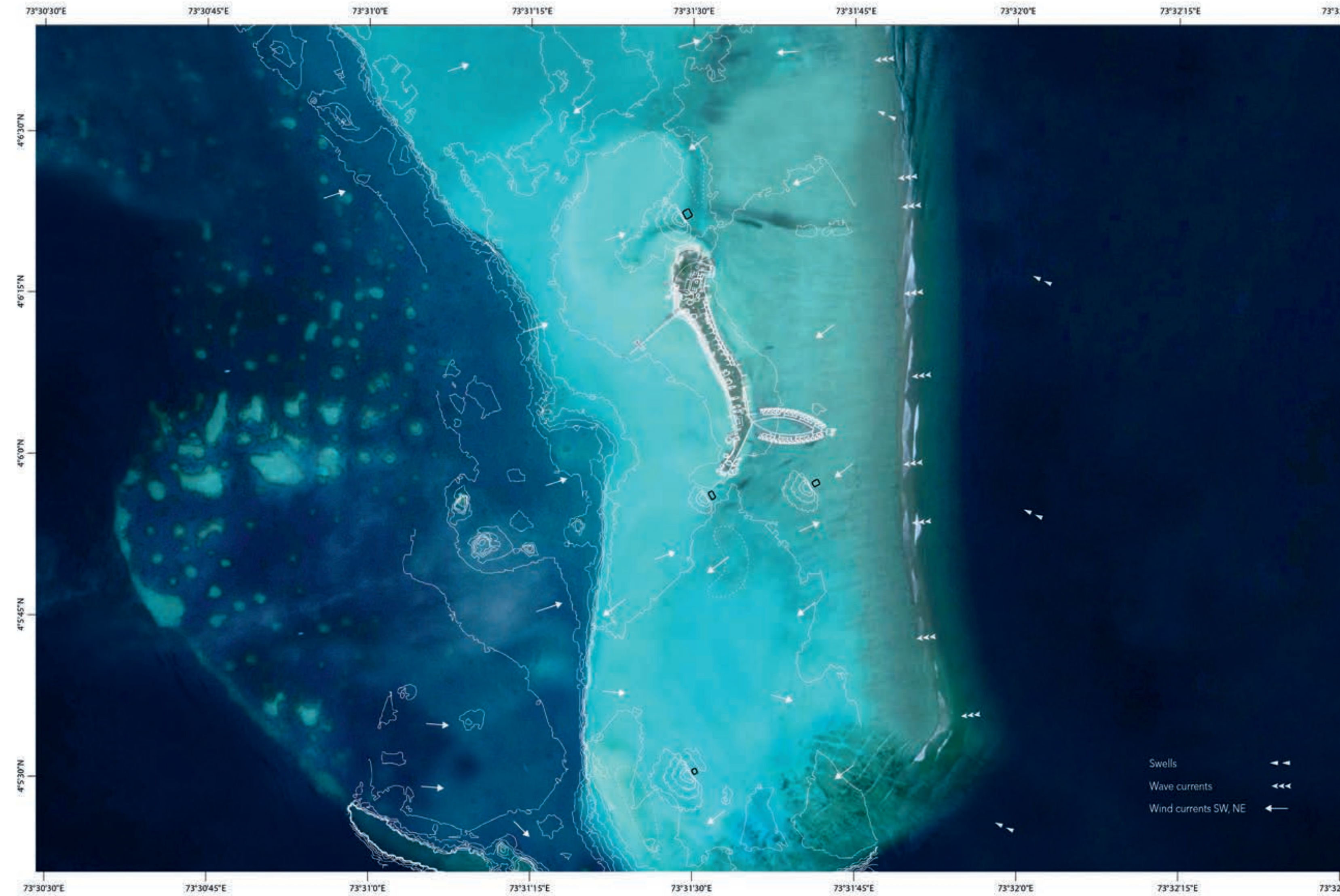
Generative architecture, in which the architect and the computer refine each other's program and design, has emerged over the past decades from this digital Big Bang. Oxman embraced this reciprocal attitude and evolved it into a new organicism, in which the algorithm is a starter for architecturally controlled growth, and the building is no longer a machine but an organism. Just as her description of the creative process had gone from geometric to metabolic, so the generative process in her architecture moved from the purely parametric to the organic. Rivka Oxman has argued that three components are key to performance-based design—the geometric model, the evaluative processes, and the interactivity of the designer.[35] In her daughter's work, however, the interactivity is not between architect and computer but rather between architect and nature, with the computer becoming a tool igniting an interdependency between the two and leading closer to the ideal way of designing and building: "Nature optimizes for a multiplicity of functions across scales: structural load, environmental performance, spatial constraint, and more . . . enabling multi-functionality that matches Nature."[36] This multiplicity leads, in turn, to specificity, the ability of the same design, even of the same material, to respond and adapt to specific conditions, which themselves might be in flux—an object handled by small or big hands, for instance, or a building facade at different times of day, seasonal temperatures, or levels of occupancy. As Kiesler did with his concrete sculptures, Oxman dreams of using one material, or at least one material system—whether silk, glass, or pectin—and taming it to behave differently in different parts of the object, an Endless House in a silkworm's cocoon.[37]

Just when the morphological intelligence of parametric and generative design had engendered a formal style that has become almost dated, Oxman and others introduced a new ingredient—biology—to performative and generative architecture in a way that has reinvigorated the field and diversified its production. Architects such as David Benjamin (**figs. 35, 36**), Skylar Tibbits (**fig. 37**), and Jenny Sabin (**figs. 38, 39**), for example, are each invested in such new expression. Not needing to control the whole process of form making, they let nature run its course, if under specific parameters, some distilling its processes, others integrating it directly in the architecture and infusing it with their own aesthetic along the way. Architects are not alone in embracing biology as the new North Star. Biology is in fact so prevalent in all fields that many intellectuals and opinion makers, including World Economic Forum founder Klaus Schwab, have named the current period the Fourth Industrial Revolution, an era in which every process is informed by organic considerations, in which culture has become wet, infused with an awareness of biology and ecosystems.[38] Oxman herself has noted this precise shift: "Unlike the Industrial Revolution, which was ecology-agnostic, this new approach tightly links objects of design to the natural environment."[39]

Thus the field of performance-based design has moved another notch, from the mechanism to the algorithm and now to the organism. If it seems too good to be true, and if parametric architecture cannot simply be considered sustainable when wet, as Christina Cogdell pointed out in *Toward a Living Architecture? Complexism and Biology in Generative Design* (2019), the effort is nevertheless evolutionary.[40] Despite the distance traveled from the pure volumes of modernism to the intricacy of parametrically enabled neo-organic design, the adaptability Oxman and her contemporaries pursue is not the opposite of the universality that modernist architects had sought. Rather, it is its essence distilled and freed from the homogenized forms of modernism, which were dictated not only by Corbusian dogma—the open plan especially—but also by twentieth-century building materials and techniques. Digital technology has enabled designers to get much closer to nature and its awe-inspiring pluralistic articulations. With that superpower, in the future some of modernism's antagonisms (homogeneity versus specificity, for instance, the former affordable and democratic, the latter pricey and elitist) will be rendered obsolete. New technologies will make specificity accessible. Computation and its expressions—such as performance-based architecture and the generative and parametric design that supports it—are the key to specificity, which is in turn the ability to accommodate different requirements and conditions within the same adaptable, algorithm-based design, perhaps even using the same material. One of the great promises of digital design and fabrication is the ad hoc, the customized, "just in time" production. No waste, no suffocating standardization, no need to differentiate anymore between prototypes and series. The result will be a truly universal kind of design, pluralism without sacrifice.

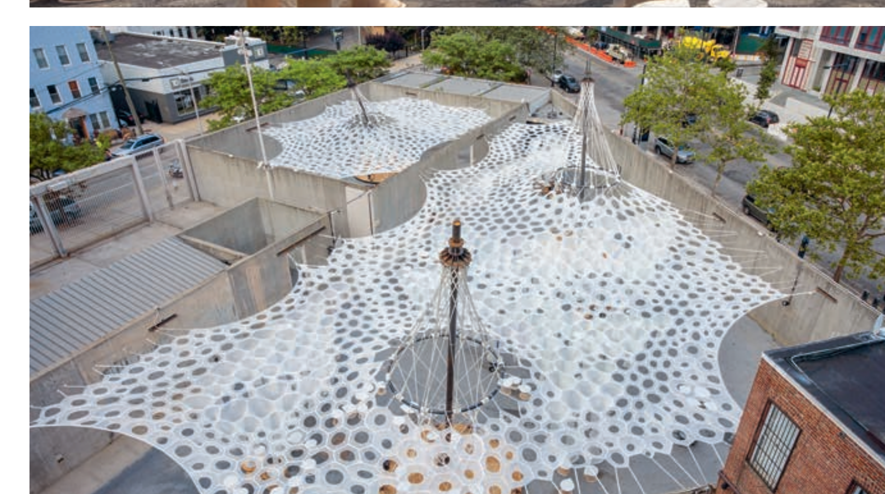
Opposite, top:
fig. 37 Skylar Tibbits, MIT Self-Assembly Lab, and Invena. Growing Islands. 2019. Digital images, drawings, and diagrams, dimensions variable

An exploration of the possibility of replenishing sandbars and protecting coastlines through the careful placement of objects able to harness the natural pattern of waves and tides.



figs. 35, 36 David Benjamin of The Living. Jammed Bio-Welding. 2019. Corn stover and mycelium, dimensions variable

Investigation of the compression of biomaterials in formwork molds as a method of building. The materials grew into each other to form solid or semisolid structures.



figs. 38, 39 Jenny Sabin Studio. Lumen. Installation view in Young Architects Program, MoMA PS1, Long Island City, New York, June 29–September 4, 2017

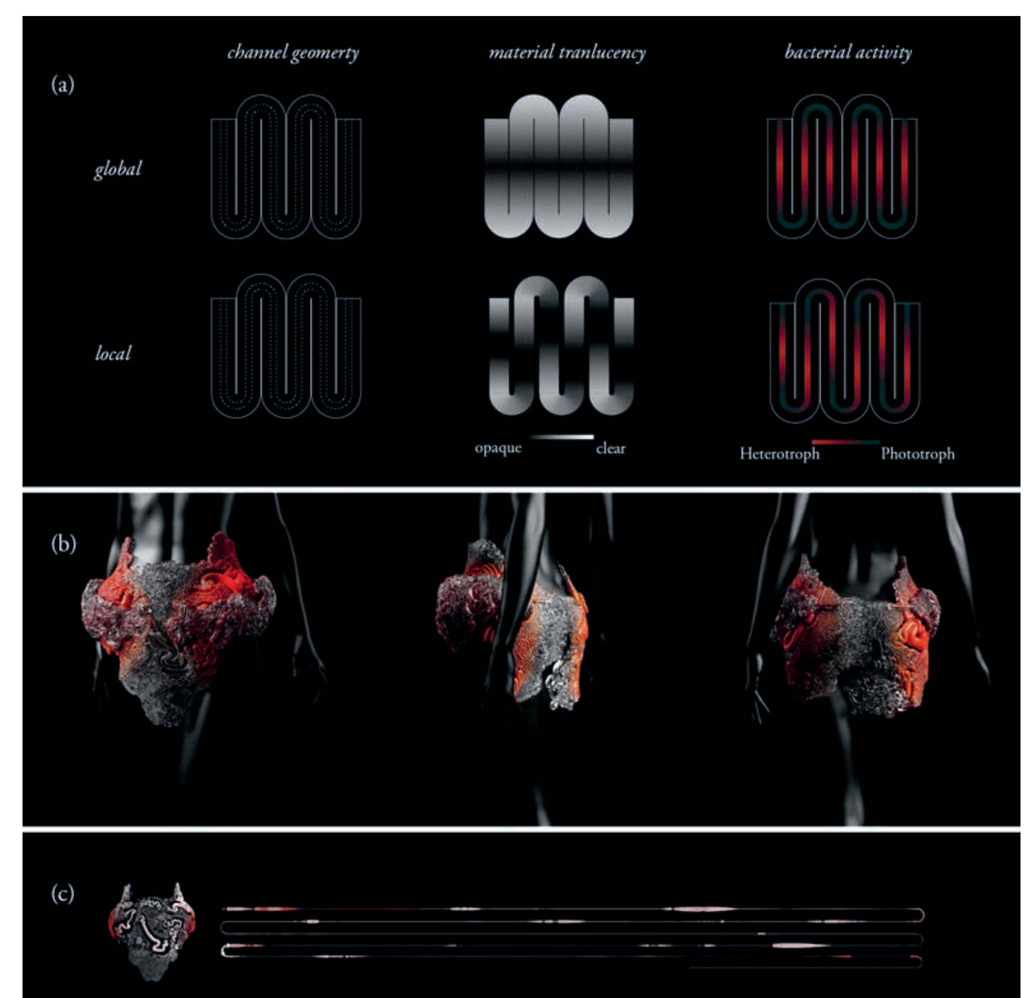
figs. 40 Neri Oxman in collaboration with W. Craig Carter and Iris van Herpen. Anthozoa. 2013. Photopolymers, dimensions variable. Presented at Paris Fashion Week, 2013

A skirt and cape produced with multimaterial 3D-printing technology by Stratasys, which enables both hard and soft materials to be incorporated into a single multifunctional material system.

Material Ecology at MoMA
Material Ecology is an exhibition not only about the future of architecture and design but also about the future role of the designer as the initiator of a process that exists within systems and ecologies, rather than as the form-giver of an object or the follower of functions. MoMA's curatorial team has selected seven projects, some realized by Oxman independently, most of them with MMG, to highlight the impact that her attitude is having on the next generation of designers; of materials-, computation-, and life-scientists; of engineers, clients, and—through her work and her public talks—citizens.

Every object in the *Material Ecology* exhibition, however finished looking and formally accomplished, is presented as a demonstration of new materials and new processes, as a door into a new way of designing and making. The curatorial team sought to highlight process over product in selecting works, privileging the most processual and speculative experiments over more immediately applicable ones, while also delineating the evolution in Oxman's work. This means we did not include, for instance, the cape and skirt ensemble Oxman designed for the Dutch couture designer Iris van Herpen in 2013 (**figs. 40, 41**), which is seamlessly 3D printed and made of thousands of quills that adapt to the body like a second skin. We did not include Wanderers (2014; **figs. 42, 43**), Oxman's "life-sustaining clothes for interplanetary voyages"—bacteria-infused, photosynthetic gear for space exploration— or Rottlace (2016; **figs. 44, 45**), the spectacular mask modeled on the understructure of Björk's face and worn by the artist on the outside.

fig. 41 Anthozoa. Detail

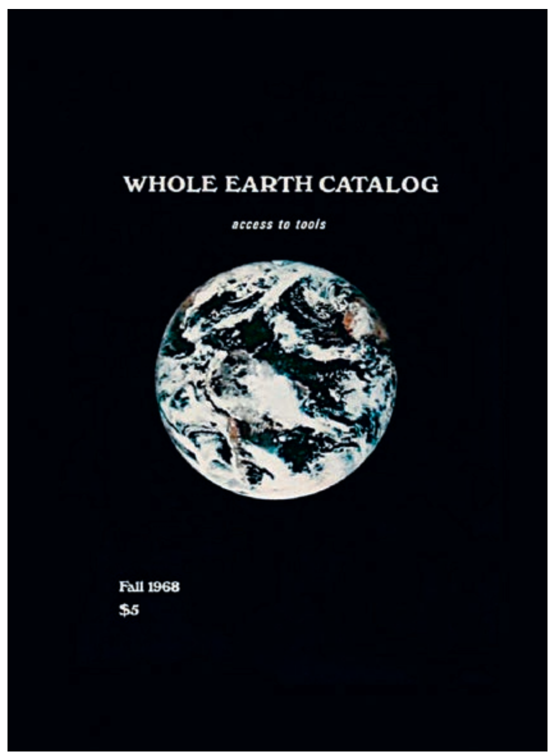


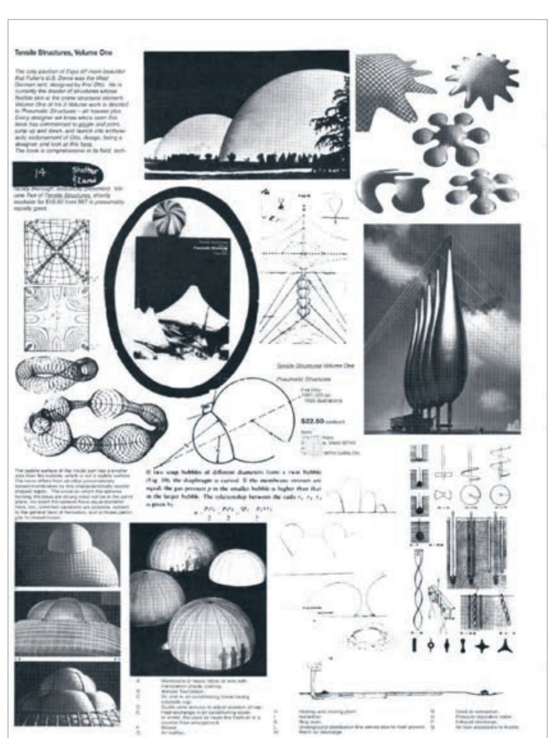
figs. 42, 43 Neri Oxman and The Mediated Matter Group, in collaboration with Stratasys Ltd. Mushtari, from The Sixth Element Collection. 2014. Photopolymers, 35 ½ × 15 ½ × 6 in. (90 × 40 × 15 cm)

This wearable organ system, a physiological augmentation for interplanetary travel, was designed using generative growth algorithms and produced on a Stratasys Objet500 Connex3 3D printer. The computational form generation processes mimic biological growth by generating recursive forms over many iterations of the algorithm.

The effect of material transparency on microbial activity (a); implementation of the global heterogeneous modeling approach on the wearable (b); visualization of the unfolded strand showing how the overall source-based approach influences local changes in opacity along the strand (c).

To stress the prototypical quality and meta-architectural value of the projects in the exhibition, we accompany them with documentation of their development, in the lab and outside, in video and in artifacts. Together with Oxman and with Irma Boom, who designed this book under the spell of Stewart Brand's immortal *Whole Earth Catalog* (**figs. 46–48**), we vowed to make the exhibition and the book "dirty" with process, to convey the feeling of the lab at MIT—which, albeit very clean, is ebullient with ideas, samples, and living beings, from humans to silkworms, ants, and cyanobacteria.[41]





After an introduction to the early Materialecology oeuvre, this catalogue divides the selected works according to the family of techniques that generated them—between Extrusions and Infusions, a division left more loose in the gallery display.[42] If the 2007 Materialecology experiments demonstrated the ability to distill algorithms from natural behaviors in order to apply them to optimizing objects and buildings, the other works featured in the 2020 exhibition describe an evolution toward more complex entanglements with the biological. Extrusions are projects in which the object is obtained from a sometimes biologically augmented material that is extruded by a mechanical or animal nozzle, as in Silk Pavilion I and II (2013 and 2019; pages 96, 106), Aguahoja I and II (2018 and 2019; pages 74, 80), and Glass I and II (2015 and 2017; pages 116, 128). Glass, silk, chitosan, pectin, and cellulose are here excreted by three different printers—the first an innovative printer with a chamber that can function at molten-glass temperature, the second a "massively multiplayer" printer made of thousands of silkworms, and the third a rather traditional robotic arm.[43]
Over this category and over the whole exhibition towers Silk Pavilion II, a site-specific installation designed for the MoMA gallery, which manifests the evolution of the project since it was first installed in the atrium of the MIT Media Lab building, in 2013. One of Oxman's and MMG's best-known projects, the pavilion is an arresting collaboration between humans and insects, powered by computation.[44]

In the Infusions group, a vessel is 3D printed and prepared to accommodate a biological soul in the form of organic elements humans share with the rest of nature—air, bacteria, pigments, and so on. The three series of death masks called Vespers begin with Lazarus (2016; page 144), inspired by Paul Kalanithi's unforgettable 2016 book *When Breath Becomes Air*, in which the young oncologist chronicles his own terminal cancer.[45]
If Lazarus is proof of the concept of capturing a dying person's last breath through data-driven additive manufacturing processes, the three subsequent series culminate with the infusion of bacteria to color the masks, almost in a heat map of life fleeting. Another infusion project, Totems (2019; page 168), focuses on melanin ("the pigment of life," Oxman calls it) as a symbol of both nature's infinite ingenuity—its usefulness, adaptability, omnipresence, and specificity—and of humans' fatal proclivities toward racism and injustice. The project was initiated at Design Indaba in Cape Town in 2018 by the Nelson Mandela Foundation and presented in the 2019 Milan Triennale, *Broken Nature*.[46]

figs. 46–48 Stewart Brand, ed., *Whole Earth Catalog*, Fall 1968. Cover, page 8, page 15

figs. 44, 45 Neri Oxman and The Mediated Matter Group. Rottlace. 2016. Nano-enhanced elastomers, 8 ½ × 15 ½ × 8 ¾ in. (21.3 × 39.3 × 22.3 cm)

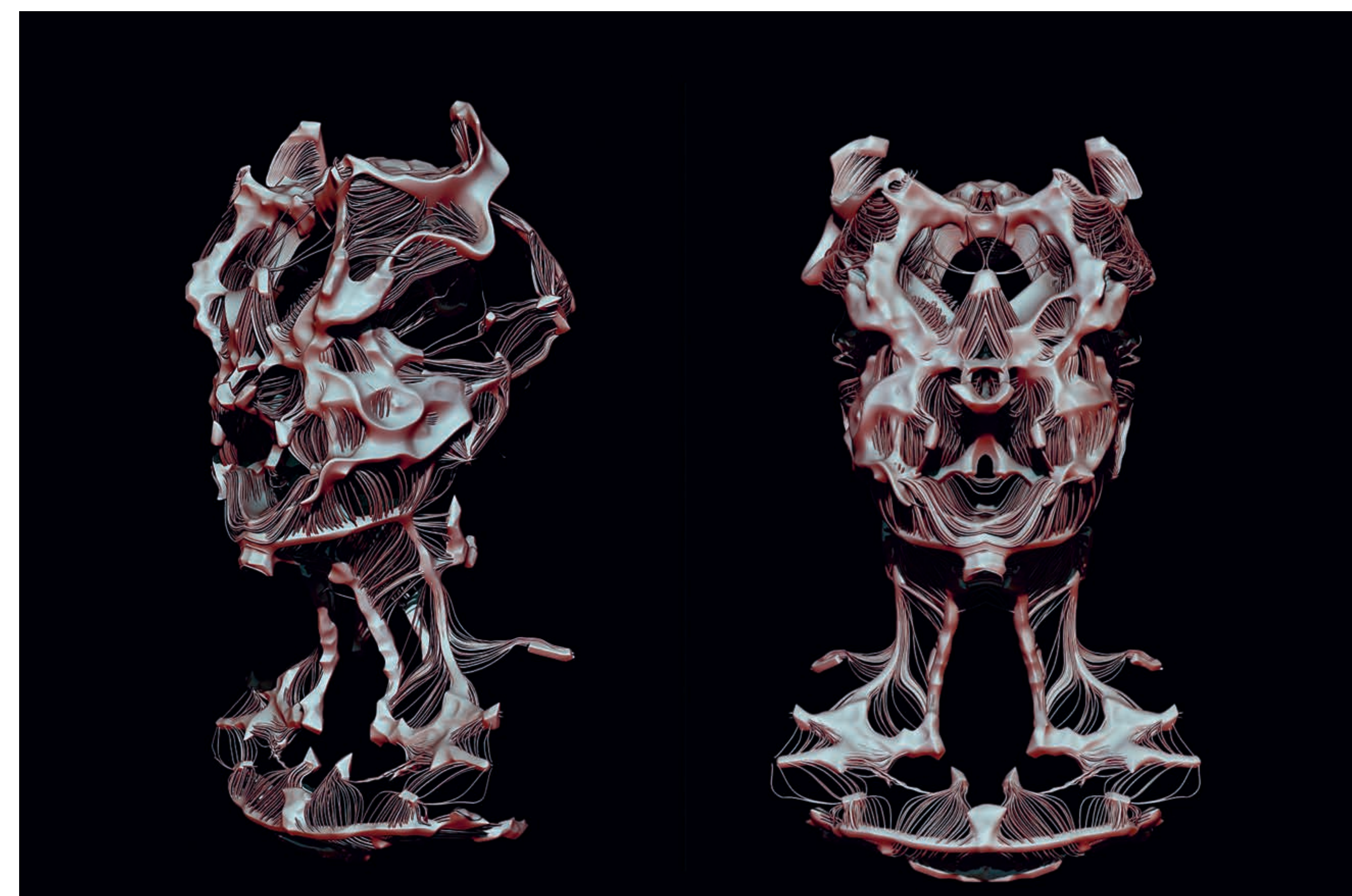
Below, top: Björk wearing Rottlace before performing "Quicksand," Miraikan, National Museum of Emerging Science and Innovation, Tokyo, 2016. The mask's tunable physical properties recapitulate, augment, or control facial form and movement.

Below, bottom: Conceptual rendering. Inspired by their biological counterpart and conceived as muscle textile, the masks are bundled, multimaterial objects, providing formal and structural integrity to the face and neck while also allowing for movement.

Design and Change

One of the major arguments and conclusions of *Design and the Elastic Mind* was that designers play an essential role in aiding and abetting change.[47]
Designers take people by the hand and make change, if not imperceptible, at least acceptable, and even desirable. They have served in this role since the beginning of time, since the first spearhead, the first wheel, and the first brick. Along the way, architects and designers have built wonders and propelled progress, displaying the best aspects of human ingenuity and vision. In some cases, however, they have also offered us glimpses into the darkest corners of human nature. They have turned a blind eye to the exploitation of other human beings, participated in the depletion of resources and in the obliteration of other species, cemented social injustice, celebrated false value systems in order to please and enrich their masters—from tyrants to corporations—and subjugated their neighbors, turning them into citizen consumers. For centuries, they have justified their actions by shifting responsibility onto others, often claiming they were just work for hire.

A positive consequence of our era's many crises, however, is that the ethics of all actions and transactions are now under strict and fundamental scrutiny. For many architects and designers, civic and human values have become a moral compass that guides the design process, even if one occasionally compromised by the need to maintain a practice and cover its overhead costs. One could argue that in design, ethics are sometimes more important than aesthetics and anyway intimately connected to it. It is a local articulation of a widespread movement toward justice, equality, and consideration of the needs and survival of others, in response to the antithetical and equally widespread exacerbation of inequality, conflict, and intolerance. "Without civic morality," Bertrand Russell wrote, "communities perish; without personal morality, their survival has no value."[48]
The values of a morally sound system—the cultural patrimony and mission of an individual, a community, a corporation, a nation—informs behaviors and choices of all kinds. Today, many spheres of human activity and study, from governance to management and economics, have shifted from a dogmatic, pseudoscientific model to value-based systems, although, in



truth, some grand pronouncements coming from corporations and financial institutions have left even the most credulous and optimistic among us puzzled by their well-sounding vows of social and environmental responsibility. Such statements, whether indications of real shifts or merely lip service, are nonetheless a sign of the establishment's need to reckon with public scrutiny and expectations.[49]

One of the most important developments of the past sixty years has been the shift to an approach that takes into account, or attempts to take into account, the polyhedric beliefs and interests of a pluralistic society, as well as the ecological needs of our planet, a shift that is systemic and fluid and embraces complexity. When cultural diversity matters as much as biodiversity, when we treat it as equally fundamental in order to build a better future for all, the joining of science, design, technology, and culture emerges as a promising and constructive approach.

Echoing this conviction, Oxman laid out in a nevalogue draft a principle for her work going forward: "Co-culture over single organism culture." This single tenet highlights and celebrates not only biodiversity but also a deeper entanglement and dependency among individuals and species. It recalls the biologist and evolution scholar Lynn Margulis's important concept of the holobiont, first defined in 1991 as the discrete ecological units formed by groups of biological entities depending on each other and combining their genome in a new, composite version.[50] "Better Together," a promising paper coauthored by Oxman, expands on this idea: "Communities dominate the microbial world; coexisting organisms cannot help but interact."[51] There is strength in unity, and, more precisely, robustness—"the ability to survive perturbation"—which "is an emergent property of microbial communities and is necessary for survival in the wildly fluctuating world."[52] The same can be said about all communities, and this is the most important lesson we can learn from architects and designers who, like Oxman, are looking for new ways forward.

Living in a crucial, complex, and deeply experimental moment, some architects and designers are doing their part by finding new centers of gravity in humans' relationships with other species, with nature, and with one another. They are no longer designing in a vacuum but rather thinking of how their work will be part of ecosystems; they are trying to influence and help manufacturers and developers to define their new powers and responsibilities in a changed context of environmental crisis and social mutations. Those who, like Oxman, engage nature directly, are writing new protocols for their practices. Some selected pairings from Oxman's evolving thoughts help us understand better not only her ideas and her design's evolution but also the essence of her relationship with nature. The "over" proposition that often links the two poles in her nevalogue, as a matter of fact, implies the designer's active role in leading the way, a philosophical choice that becomes a way of life and at the same time an affirmation of the central position of the human species. In Oxman's construct, the role of design is to initiate the reaction and provide interfaces of control. The designer's job, by extension, is "to promote and enable synergy between the built and the grown, the artificial and the natural. . . . The designer then becomes a mediator, a gardener, an alchemist operating across scales and domains to conduct rather than construct."[53] Indeed, it is just this attitude—toward responsive, cooperative, evolutionary change—that we need today.

Notes

1 "Panta chōrei kai ouden menei," attributed to Heraclitus, in Plato, *Cratylus*, trans. Harold N. Fowler (Cambridge, Mass.: Harvard University Press; London: William Heinemann, 1921), 402a. Translation amended by the author.

2 Neri Oxman, statement to the tenure committee, Massachusetts Institute of Technology, 2017. "We have created such frameworks that allow all or most degrees of freedom of the natural phenomenon to be embodied by the object. This advancement and salient feature presents the opportunity to develop material engineering, computational approaches, and digital fabrication techniques that allow us to introduce property gradients with high spatial resolution and multi-functionality across scales."

3 Neri Oxman, "Material Ecology," in Rivka Oxman and Robert Oxman, eds., *Theories of the Digital in Architecture* (London: Routledge, 2013), 322.

4 The series also marked the beginning of a fruitful collaboration with the U.S. 3D-printing company Stratasys, a partnership that is still very much alive today.

5 At the time of writing, the MIT Media Lab is undergoing a deep process of self-examination following the resignation of Joi Ito, its director, in 2019, in the wake of the revelation that the institution had received funds from Jeffrey Epstein, the convicted sex offender and financier, and invited him to tour its premises.

6 Heidi Legg, "Neri Oxman #99," *TheEditorial,* March 2017.

7 Oxman, "Design at the Intersection of Technology and Biology," presentation at "TED2015: Truth and Dare" conference, Vancouver, Canada, March 2015.

8 Oxman, "Material Ecology," 321. See Gottfried Semper, *The Four Elements of Architecture and Other Writings* (1851; Cambridge: Cambridge University Press, 1989).

9 Rich Gold, *The Plenitude: Creativity, Innovation, and Making Stuff* (Cambridge, Mass.: MIT Press, 2007).

10 I contend that nothing will ever be accomplished until we also add design: STEAMD.

11 Oxman, "Age of Entanglement," *Journal of Design and Science*, no. 1 (January 2016). Oxman describes the genesis of the Krebs Cycle of Creativity and puts it in context with other events at MIT Media Lab and beyond.

12 Legg, "Neri Oxman #99."

13 Ibid.

14 Dunne & Raby, "A/B Manifesto," dunneandraby.co.uk/content/projects/476/0.

15 Three juxtapositions that don't appear here resonate as highly symptomatic of Oxman's new approach to design: "Scale over Size" (implying that the ecosystem reigns above all; physical dimension is less important than the impact it has on the system); "Process over Product" (investigating new materials and technologies, with objects produced as "muses" and demos); "Heterogeneity over Homogeneity" (an interest in biomaterials, which can be fine-tuned to behave differently in different parts of the designed organism, and to behave intelligently, varying their behaviors in time and space).

16 Legg, "Neri Oxman #99." In her tenure statement, she articulates this idea in better, although more technical, terms (see note 2). She goes on to say, "Thus, the ideas and principles behind *Material Ecology* inspired the need, and generated a scaffold, for innovation in computational form-generation and digital fabrication *increasing the dimensionality of the design space*. To address this need, my team and I are developing new approaches that enable design and production at Nature's scale to seamlessly vary the physical properties of materials at the resolution of a sperm cell, a blood cell, or a nerve cell. Stiffness, color, transparency, conductivity—even smell and taste—can be individually tuned for each 3D pixel (voxel) within a physical object. The generation of products is therefore no longer limited to assemblages of discrete parts with homogeneous properties. Rather—like organs—objects can be computationally 'grown' and 3D printed to form materially heterogeneous and multi-functional constructs." Oxman, statement to the tenure committee.

17 The term "critical design" was first used by Anthony Dunne in *Hertzian Tales: Electronic Products, Aesthetic Experience, and Critical Design* (London: RCA CRD Research Publications, 1999) and later in *Design Noir: The Secret Life of Electronic Objects* (Basel: Birkhäuser, 2001), written with Fiona Raby.

18 Dunne & Raby, "Critical Design FAQ," dunneandraby.co.uk/content/bydandr/13/0.

19 Stuart Candy, "The Future of Everyday Life: Politics and Design of Experimental Scenarios" (PhD diss., University of Hawai'i at Mānoa, 2010), 35. Futures studies as an academic discipline originated in the 1960s. Several authors have written about different classes of futures. In 1997 Weddell Bell explained that researchers should consider "what can or could be" (the possible), "what is likely to be" (the probable), and "what ought to be" (the preferable). Bell, *Foundations of Futures Studies: Human Science for a New Era*, vol. 1, *History, Purposes, and Knowledge* (New Brunswick, N.J.: Transaction, 1997), 73. Trevor Hancock and Clement Bezold created the "futures cone" in 1994, based on a categorization by Norman Henchey, who considered four different kinds of futures: possible futures (what may be); preferable futures (what should be); plausible futures (what could be); and probable futures (what will likely be). See Hancock and Bezold, "Possible Futures, Preferable Futures," *Healthcare Forum Journal* 37, no. 2 (1994): 23–29; and Henchey, "Making Sense of Futures Studies," *Alternatives* 7, no. 2 (1978): 24–28.

20 Oxman, statement to the tenure committee.

21 See William Myers, ed., *Bio Design: Nature Science Creativity* (New York: The Museum of Modern Art, 2012).

22 Oxman, "Material Ecology," 322.

23 Among the many innovative material technologies developed by Oxman and MMG is "high-resolution multi-material modeling and bitmap printing—which enables the design and digital fabrication of structures that can vary their mechanical and optical properties in high spatial and temporal resolutions (ones that often *transcend* the scale of the physical phenomena they are designed to embody)." Legg, "Neri Oxman #99."

24 "Neri Oxman and the Endless House," *The Way I See It* podcast, BBC Radio 3, bbc.co.uk/programmes/m0009bf5. The Endless House project preoccupied Kiesler for a decade, with the first model being built in 1950 and the very last iteration coming in 1960. A commission for MoMA's *Visionary Architecture* exhibition, the last and most important model envisioned the Endless House as a series of cavelike spaces. See also Pedro Gadanho and Phoebe Springstubb, "Endless House: Experimental Archetypes of Dwelling," *Architectural Review*, June 30, 2015.

25 Diller Scofidio + Renfro, "Slow House," dsrny.com/project/slow-house.

26 Michael Hensel, *Performance-Oriented Architecture: Rethinking Architectural Design and the Built Environment* (Chichester, U.K.: John Wiley & Sons, 2013), 23.

27 Stanley Mathews, "The Fun Palace: Cedric Price's Experiment in Architecture and Technology," *Technoetic Arts: A Journal of Speculative Research* 3, no. 2 (2005): 73–91.

28 David Leatherbarrow, "Architecture's Unscripted Performance," in Branko Kolarevic and Ali Malkawi, eds., *Performative Architecture: Beyond Instrumentality* (London: Routledge, 2005), 7.

29 Reyner Banham, *The Architecture of the Well-Tempered Environment* (London: Architectural Press; Chicago: University of Chicago Press, 1969), 11.

30 Ibid., 13.

31 Nicholas Negroponte, *The Architecture Machine: Toward a More Human Environment* (Cambridge, Mass.: MIT Press, 1970), 27. "Our interest," Negroponte wrote, "is simply to preface and to encourage a machine intelligence that simulates a design for the good life and will allow for a full set of self-improving methods. We are talking about a symbiosis that is a cohabitation of two intelligent species." Ibid., 7.

32 Tristan D'Estrée Sterk, "Building upon Negroponte: A Hybridized Model of Control Suitable for Responsive Architecture," in Wolfgang Dokonal and Urs Hirschberg, eds., *Digital Design: 21st eCAADe Conference Proceedings* (Graz, Austria: eCAADe, 2003), 407.

33 Xing Shi, "Performance-Based and Performance-Driven Architectural Design and Optimization," *Frontiers of Architecture and Civil Engineering in China* 4, no. 4 (December 2010): 512–18.

34 Greg Lynn, ed., *Archaeology of the Digital* (Berlin: Sternberg Press; Montreal: Canadian Centre for Architecture, 2013).

35 Rivka Oxman, "Performance-Based Design: Current Practices and Research Issues," *International Journal of Architectural Computing* 6, no. 1 (January 2008): 3–4.

36 Oxman, statement to the tenure committee.

37 Toward realizing this dream, Oxman and her team have recently developed Hybrid Living Materials (HLMs), which they describe as a "fabrication platform, which integrates computational design, additive manufacturing, and synthetic biology to achieve replicable fabrication and control of biohybrids." Rachel Soo Hoo Smith et al., "Hybrid Living Materials: Digital Design and Fabrication of 3D Multi-Material Structures with Programmable Biohybrid Surfaces," in *Advanced Functional Materials*, published ahead of print, December 18, 2019, onlinelibrary.wiley.com/doi/10.1002/adfm.201907401. The HLMs combine living and nonliving components to harness the biological capabilities of organisms within structural materials, thereby producing a new class of uniquely responsive and multifunctional products.

38 The term Fourth Industrial Revolution is commonly attributed to Schwab, who first used it in his book of that same name (London: Penguin Books, 2017). See also Schwab, "The Fourth Industrial Revolution," *Encyclopedia Britannica*, May 2018, in which he predicts that "the Fourth Industrial Revolution heralds a series of social, political, cultural, and economic upheavals that will unfold over the 21st century. Building on the widespread availability of digital technologies that were the result of the Third Industrial, or Digital, Revolution, the Fourth Industrial Revolution will be driven largely by the convergence of digital, biological, and physical innovations." Its theoretical framework, however, has been laid out throughout the end of the twentieth century and the beginning of the twenty-first by academics and entrepreneurs, such as Craig Venter and Daniel Cohen in "The Century of Biology," *New Perspectives Quarterly* 1, no. 4 (2004).

39 Oxman, statement to the tenure committee.

40 Christina Cogdell, *Toward a Living Architecture? Complexism and Biology in Generative Design* (Minneapolis: University of Minnesota Press, 2019).

41 Stewart Brand launched the *Whole Earth Catalog* at the height of the counterculture movement in San Francisco, inspired by R. Buckminster Fuller, DIY culture, and the belief that information, above everything, wants to be free. The first issue was published in the fall of 1968. Its now instantly recognizable covers featured some of the first images of Earth viewed from space, taken during the early space missions, along with the catalog's slogan and mission statement: "access to tools." Inside its pages, readers were offered Brand's vision of a new social order and were given the skills and tools necessary to embrace such a future. The catalog recommended everything from agricultural and mechanical equipment to books like Melford Spiro's *Kibbutz: Venture in Utopia* or Norbert Wiener's *Cybernetics, or Control and Communication in the Animal and the Machine*, to new digital technologies such as the Hewlett-Packard 9100A. Even though the publication had a short life span—it was published quarterly from 1968 through 1971, and then occasionally thereafter—it left a lasting impression, influencing everyone from Steve Jobs (who once described it as "Google in paperback form") and Steve Wozniak to *Wired* magazine founder Kevin Kelly.

42 The early works (Raycounting, Subterrain, Armour, and Cartesian Wax) and the Imaginary Beings series—poetically themed pretexts to fine-tune techniques, materials, and goals—represent moments of free experimentation that straddle the two categories.

43 This is an off-label use of a term from the video games world: a massively multiplayer online game is a game with thousands of players active at the same time on the same server.

44 Here, silkworms are treated the way an artisan would be treated by an Italian architect: counting on the artisans' skills and expertise, the architect would not insult them with too many details in the drawings. After all, silkworms are already highly accomplished builders.

45 Paul Kalanithi, *When Breath Becomes Air* (New York: Random House, 2016).

46 The XXII Triennale di Milano, titled *Broken Nature: Design Takes On Human Survival*, was organized by me, with Ala Tannir, Laura Maeran, and Erica Petrillo. The exhibition highlighted the concept of restorative design and studied the state of the threads that connect humans to their natural environments. Oxman's Totems was one of four projects commissioned for the show.

47 "One of design's most fundamental tasks is to help people deal with change. Designers stand between revolutions and everyday life. . . . [They] have the ability to grasp momentous changes in technology, science, and social mores and to convert them into objects and ideas that people can understand and use." Paola Antonelli, "Design and the Elastic Mind," in *Design and the Elastic Mind* (New York: The Museum of Modern Art, 2008), 14–15.

48 Bertrand Russell, *Authority and the Individual: The Reith Lectures* (1949; London: Routledge, 2009), 75.

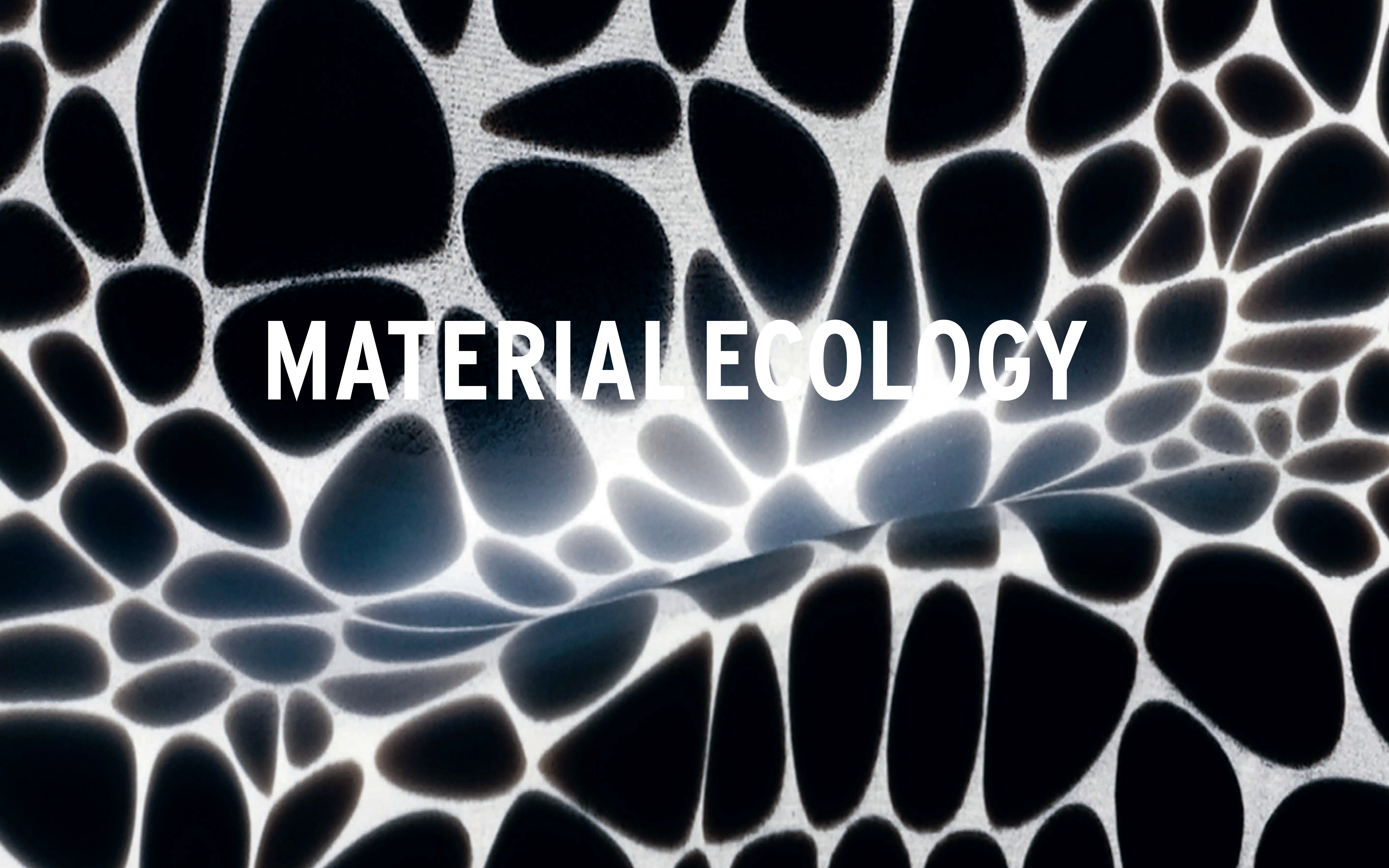
49 See Jamie Dimon, the CEO of JPMorgan Chase, in Elizabeth Dilts, "Top U.S. CEOs Say Companies Should Put Social Responsibility above Profit," Reuters, August 2019.

50 Lynn Margulis and René Fester, eds., *Symbiosis as a Source of Evolutionary Innovation* (Cambridge, Mass.: MIT Press, 1991).

51 Stephanie G. Hays et al., "Better Together: Engineering and Application of Microbial Symbioses," *Current Opinion in Biotechnology* 36 (August 2015): 40. "Interactions include touching, using dedicated signals, horizontal gene transfer, 'competitive or cooperative' scenarios where microbes compete for a provide resources, and alteration of environment to influence the growth of neighbors."

52 Ibid.

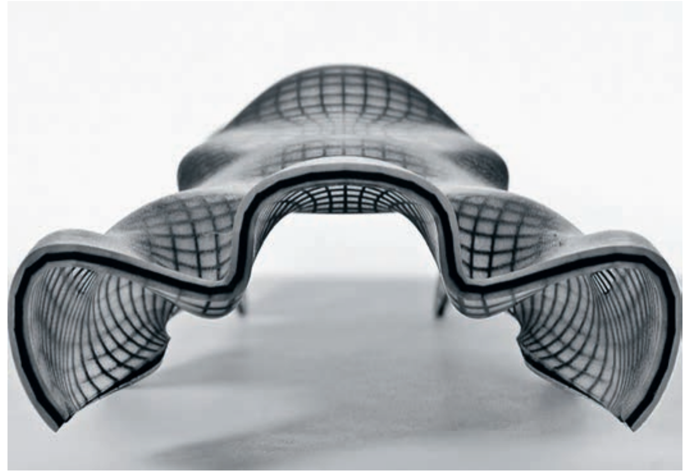
53 Oxman, e-mail to the author, July 7, 2019.

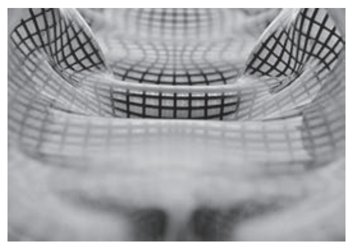

MATERIAL ECOLOGY

ARMOUR / METAMESH

Neri Oxman
Armour. 2007
Photopolymers
17 ½ × 7 ½ × 5 in.
(44.5 × 19.1 × 12.7 cm)
Produced by Stratasys Ltd.
Collaborators and contributors:
ARRK Product Development Group Ltd., Tangible Express

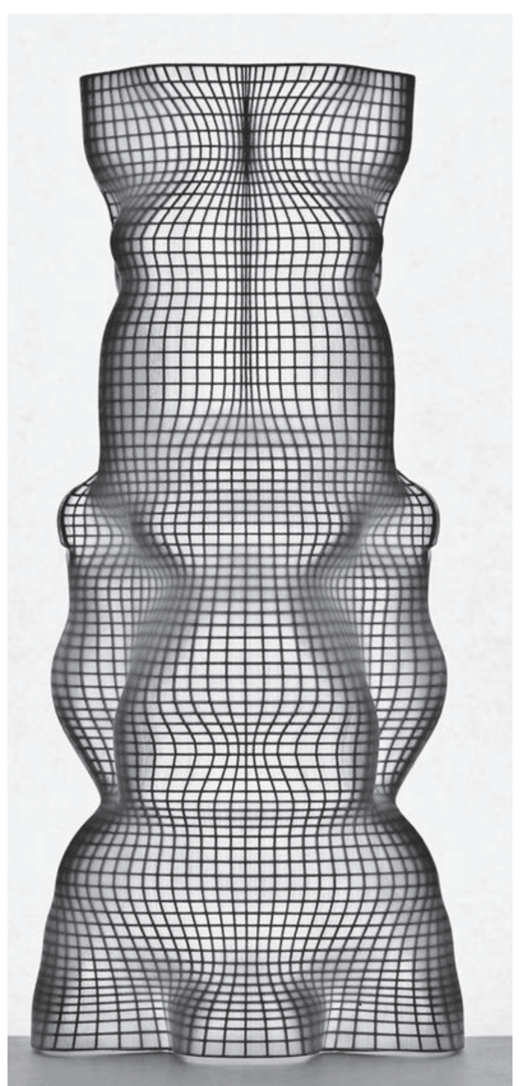
Neri Oxman and
The Mediated Matter Group
MetaMesh. 2015
Computational model
An MIT Media Lab project
Research team: Jorge Duro-Royo, Katia Zolotovsky, Laia Mogas-Soldevila, Swati Varshney, Mary C. Boyce, Christine Ortiz, Neri Oxman
Collaborators and contributors:
Institute for Collaborative Biotechnologies, MIT Institute for Soldier Nanotechnologies, National Security Science and Engineering Faculty Fellowship Program, Stratasys Ltd.



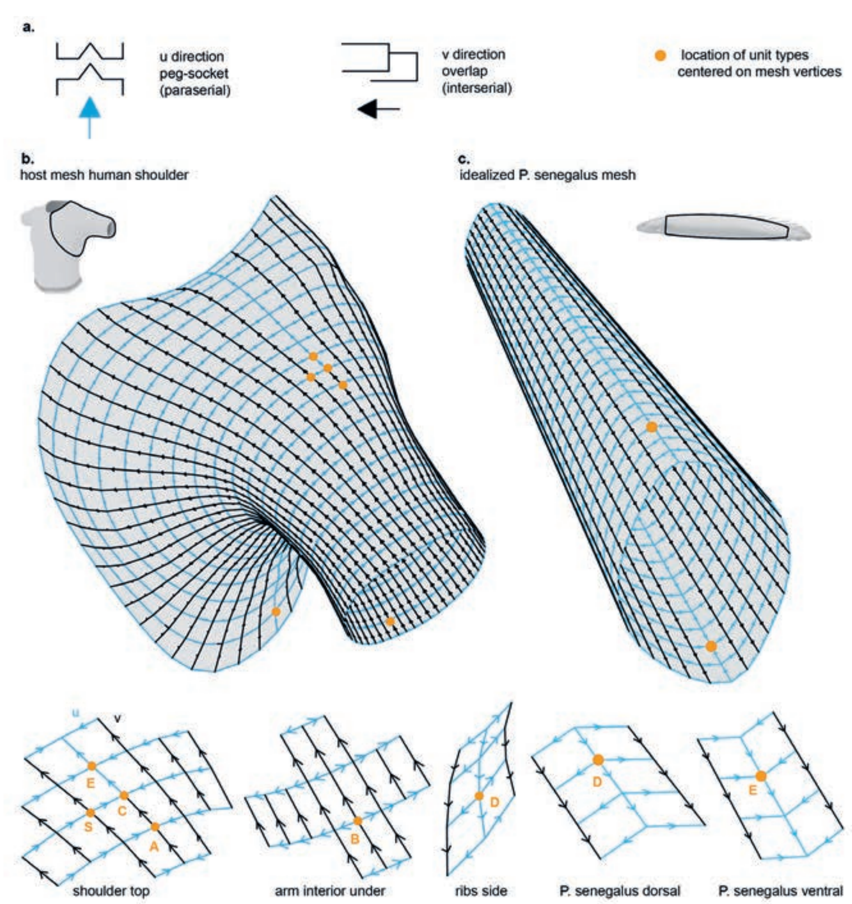


The structures of organisms in the biological world perform a multiplicity of functions at different scales, simultaneously managing structural load, environmental pressures, and spatial constraints: a living tree is the equivalent of any engineering masterpiece. In the designed world, however, human-made materials and the technologies necessary to create them have not matched the refinement and sophistication of natural ones. Bricks are dumber than cells, and synthetic fibers have yet to fire electrical signals into the textiles they inhabit.

With the design approach we call Material Ecology, we created a set of principles and technologies that promote and enable the production of smart objects that respond to their environment and function more like bodies than manufactured entities, accommodating multiple functions rather than just one. With such technologies, designers can create relationships between artificial structures and their environments at a resolution that will match and eventually outperform nature.

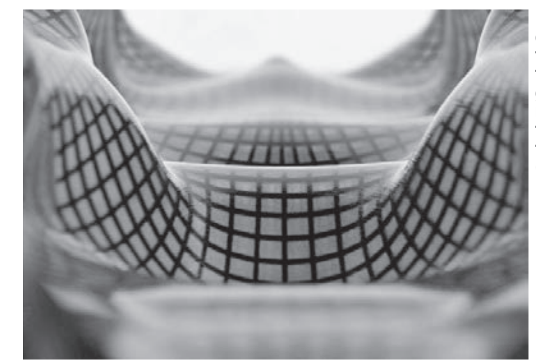


Materialecology is the name of a series of prototypes in which individual technologies explored how a design object might relate to its environment. Using multifunctional materials, high spatial resolution in manufacturing, and computational algorithms, we experimented with ways to create environmentally informed and responsive objects and buildings. Armour (pronounced ar-MOOR) was precursor of these technologies—a rethinking of modern construction techniques.



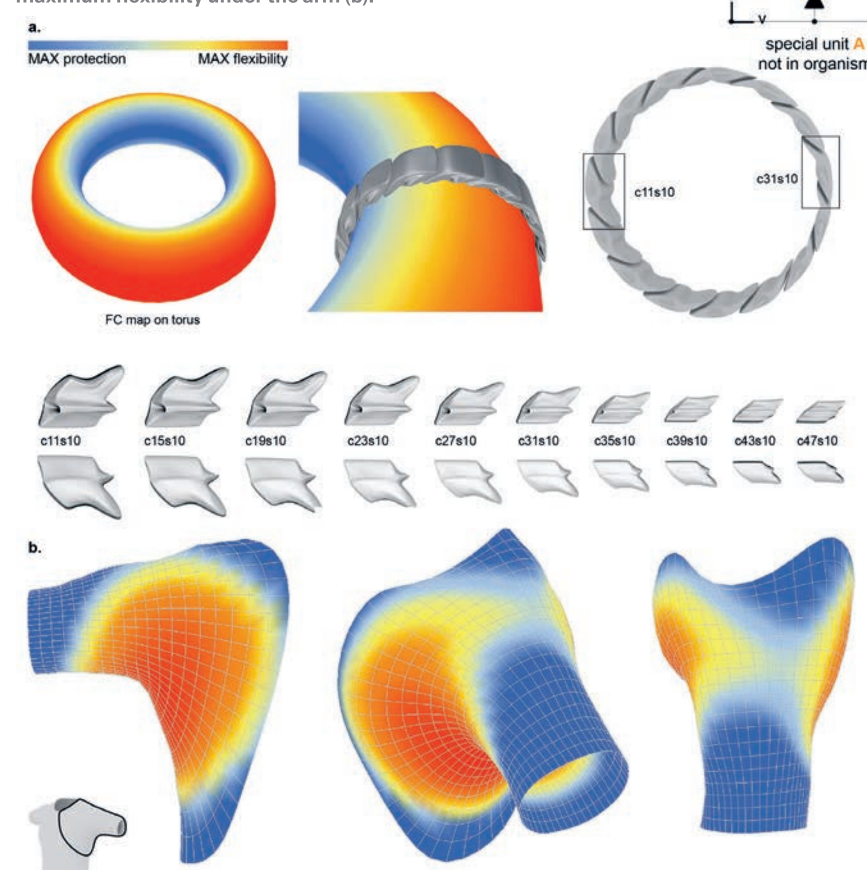
For MetaMesh, individual units were analyzed according to the predicted mobility of the areas they would cover. Directionality model analyzing mesh for a human shoulder (left) and for the ancient armored fish *P. senegalus* (right).

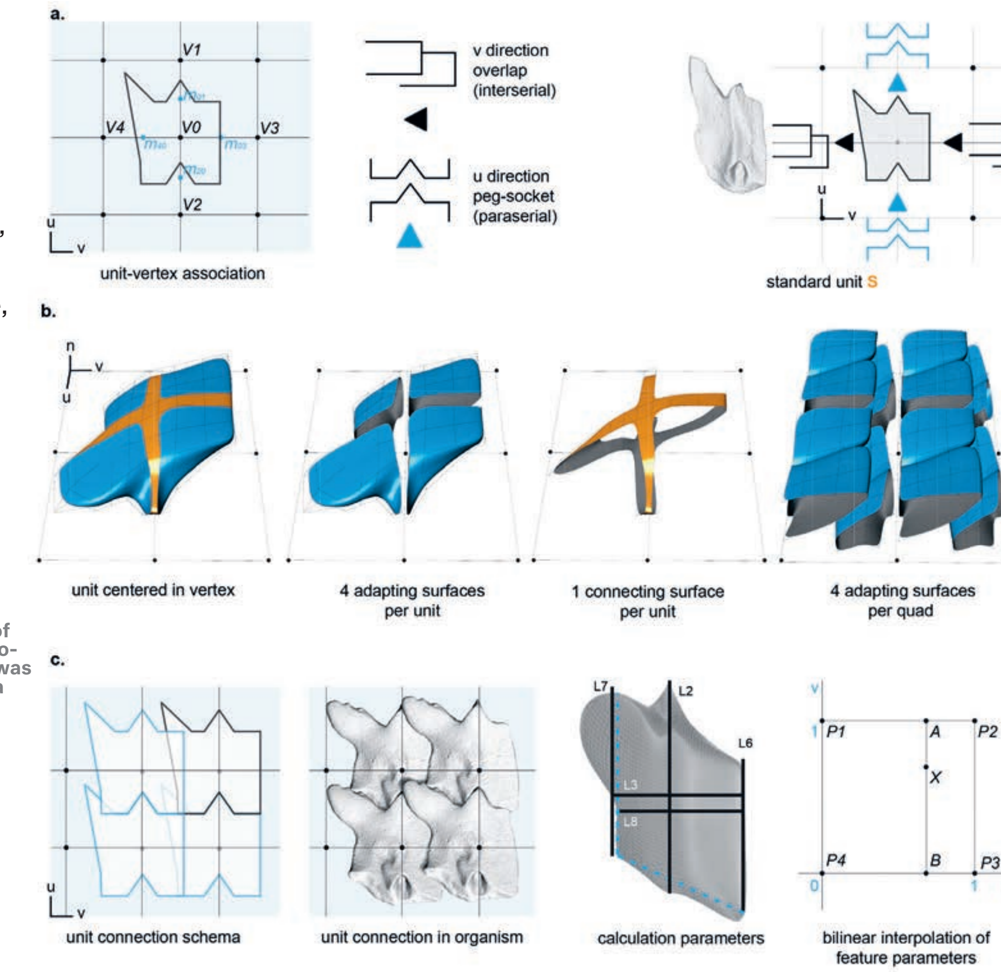
Unlike nature's strategies for material distribution, architectural design and construction have primarily been based on strategies of material assembly and property assignment. The I-beam—one of the quintessential structural components of the modern movement in architecture and a hallmark of the Industrial Revolution—originated in 1850s, with a single piece of steel rolled into a beam with an *i*-shaped cross section. Its horizontal elements (known as flanges) resist bending, and the vertical element (the web) resists shear forces. Because I-beams are not as effective in resisting torsion, they tend to be used as vertical structures in, for example, curtain-wall facades. Armour is a small-scale prototype of a beam designed to act as skin and structure at the same time. Stiff structural components are embedded in a soft skin, creating a composite that is able to carry vertical, horizontal, and rotational loads. The beam's sectional profile and structural thickness can be varied depending on the anticipated load. The black elements represent anticipated trajectories of structural forces, and the translucent skin represents the curtain wall (or skin) containing them.

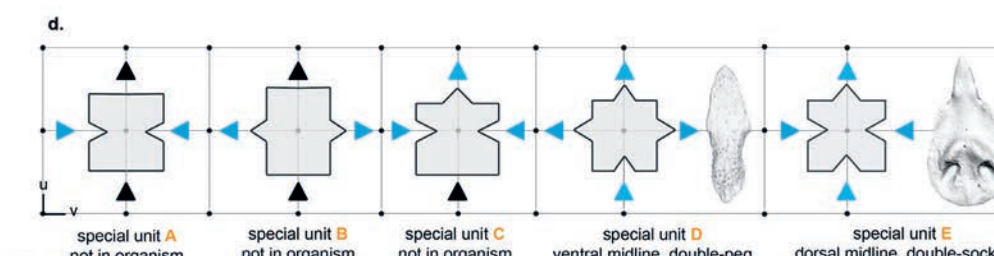


Photographs of different views of the Armour prototype. Its design was generated with a method similar to the one used for Raycounting (page 52).

The armor's properties were optimized to suit various bodies and body parts. *P. senegalus*'s armor (represented by a torus and optimized for swimming) provides maximum protection near the head and maximum flexibility near the tail (a); human shoulder armor provides maximum protection above the shoulder and maximum flexibility under the arm (b).

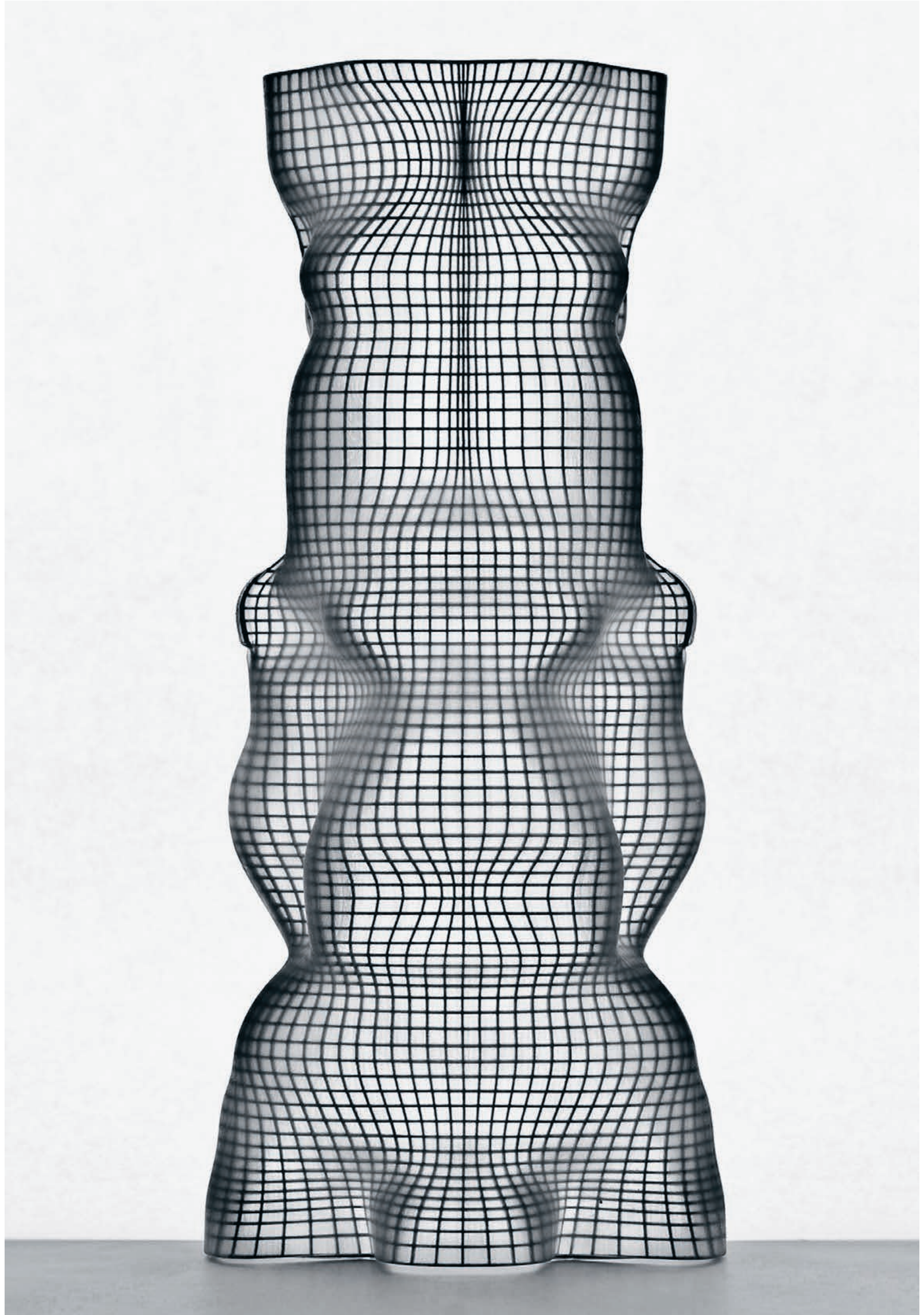


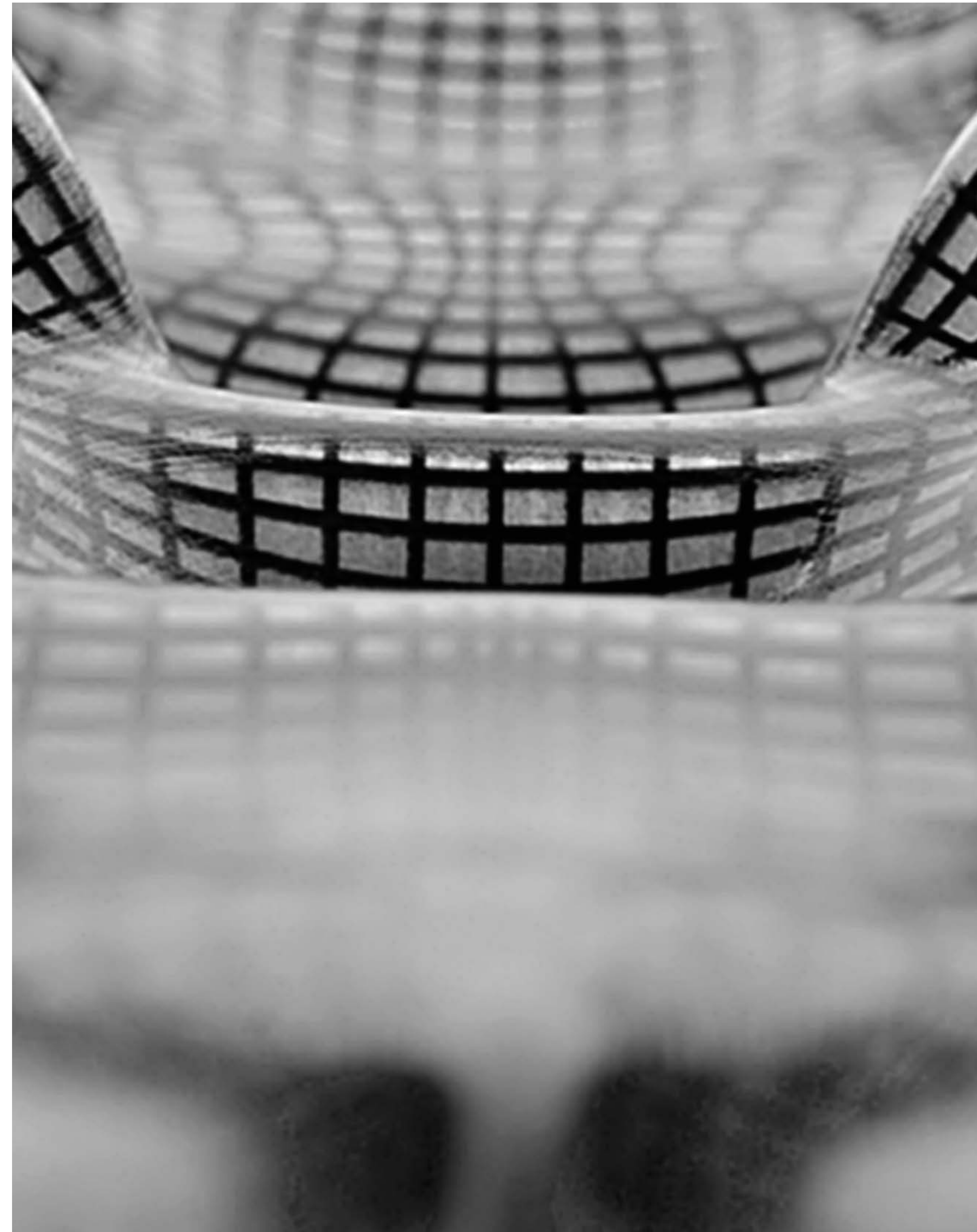




Standard armor units were defined in terms of how they connect to each other. Centering a scale unit over a mesh vertex (a), constructing a unit from connecting surfaces, and contact surfaces (b), calculating how multiple units connect (c), specialized unit types (d).

Using the research behind Armour, we developed processes that move beyond the questioning of existing construction. MetaMesh, based on a similar design method, is a functional exoskeleton created by adapting the configuration of fish scales, with a combination of protective rigid components and a flexible underlying skin that enables sophisticated articulation. As was true in other Materialecology projects, MetaMesh demonstrates the heterogeneity and differentiation of material properties in a structural skin, with shear stress and surface pressure distributed over the object in components of varying thickness. The 3D-printing technology developed for the project can print parts and assemblies from multiple materials in a single build as well as create composite materials based on preset combinations of mechanical properties.


Materialecology: Armour

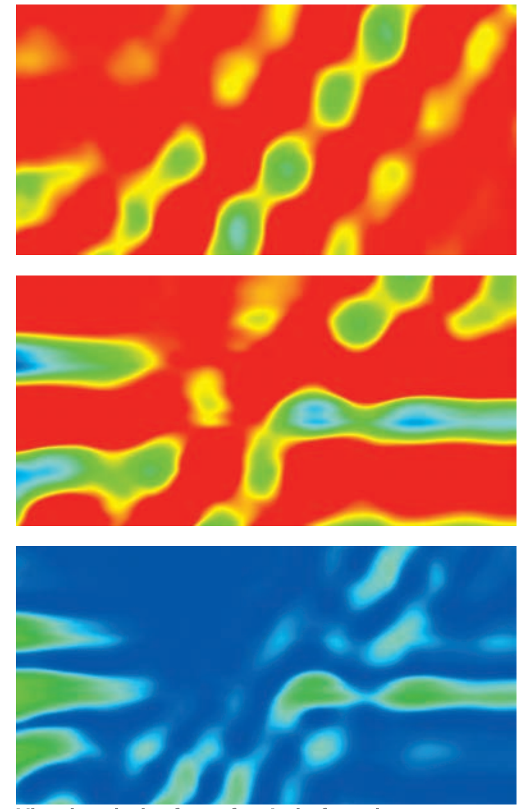


RAYCOUNTING

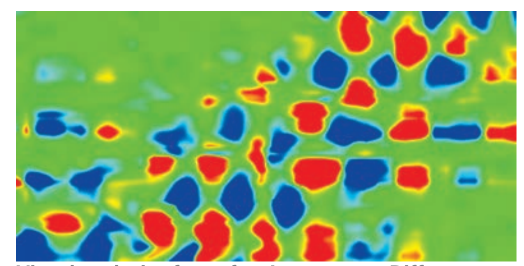
Neri Oxman
Raycounting. 2007
Silk-coated nylon and acrylic-based polymer
17 × 11 × 10 in. (43.2 × 27.9 × 25.4 cm) and 19 3/16 × 10 × 6 in. (48.7 × 25.4 × 15.2 cm)
Collaborators and contributors:
Tangible Express, AARK Product Development Group Ltd.

In Raycounting, we registered the intensity and orientation of natural light to compute the form of a 3D-printed construction. The project was inspired by nineteenth-century photo-sculpture, in which three-dimensional replicas were created by projecting photographs of objects taken from different angles onto sheets of wood and then carving and assembling them. For our version we created an algorithm to calculate the intensity, position, and direction of one or more light sources and then assigned curvature values to points in space. The models explore the relation between geometry and light performance from the perspective of computational geometry; the results are sunshades perfectly suited to their environmental conditions.

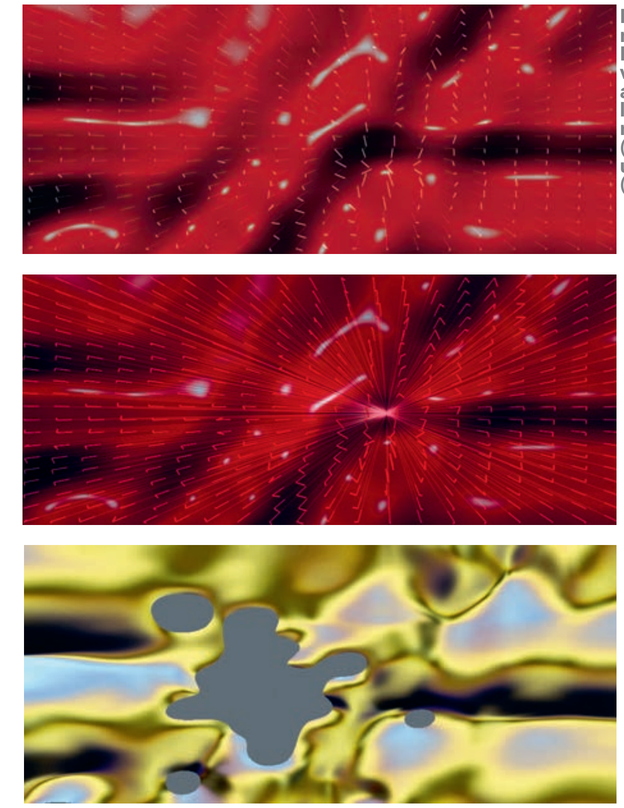
Structure 3D printed with silk-coated nylon.



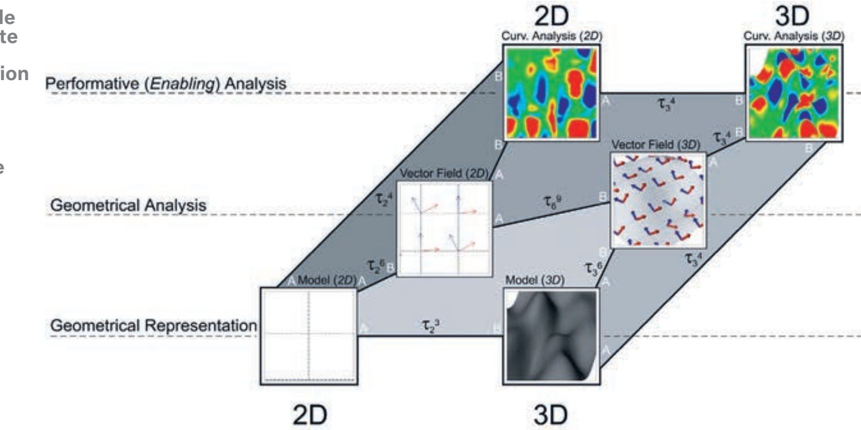
Visual analysis of a surface's draft angle (curvature in relation to a viewing point).



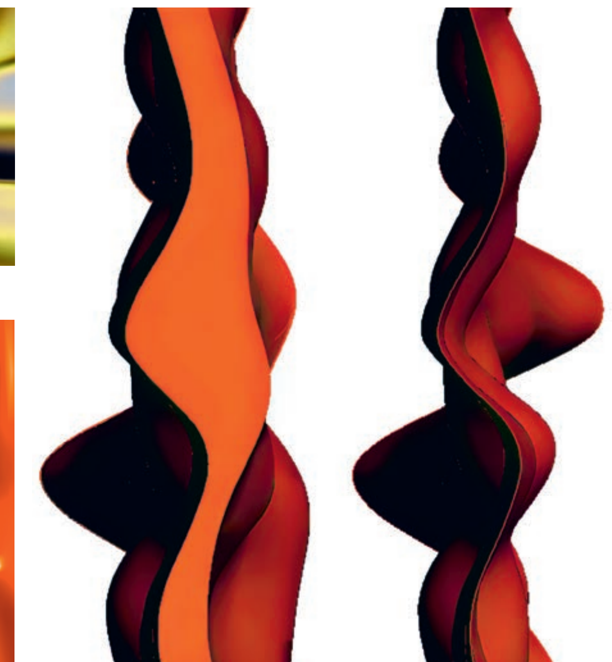
Visual analysis of a surface's curvature. Different colors correspond to bowl (or saddlelike) curvature.



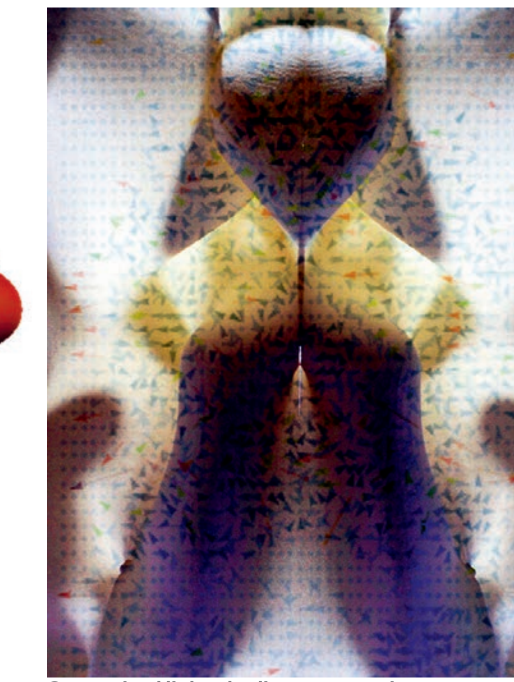
Phases of the draft angle method used to generate Raycounting's design: vector reparameterization and computation of light-source angles relative to the surface (top and center); final user-generated surface (bottom).



Above: Diagram of two- and three-dimensional reciprocal transformations, which increase in complexity from geometrical representation (bottom) to analysis (middle) to performative analysis (top).

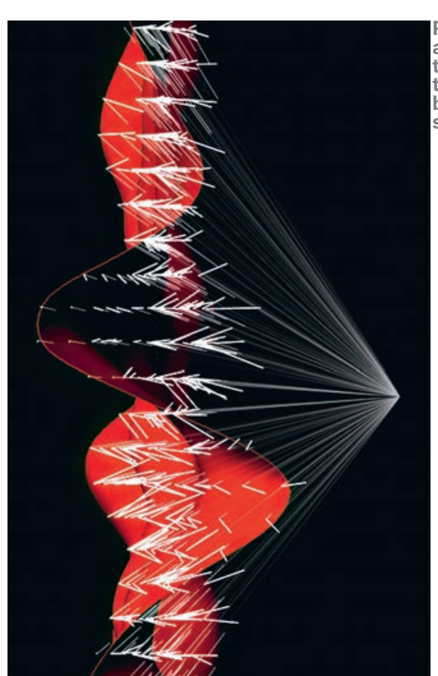


Renderings of a surface with and without thickness.

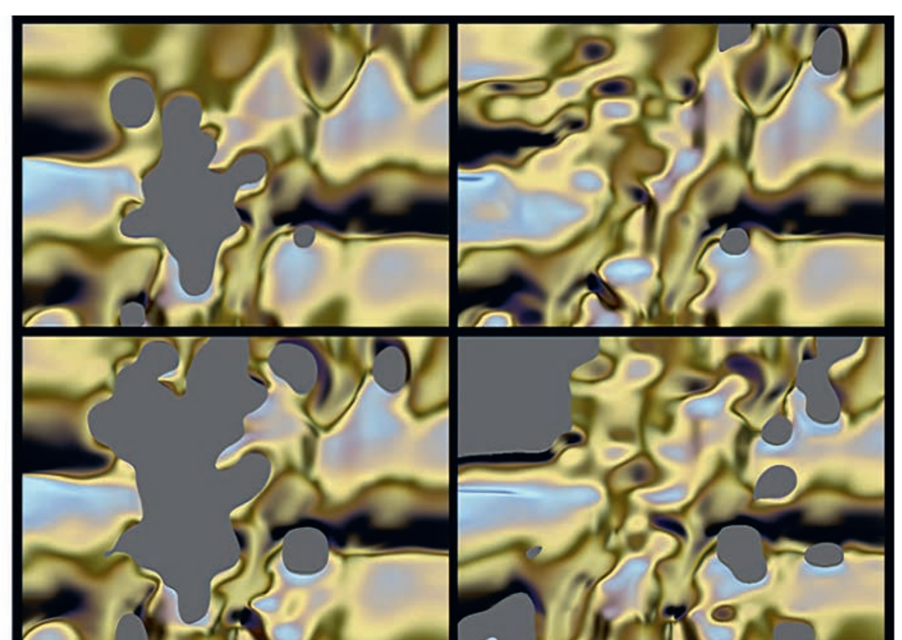


Customized light-shading constructions were generated by registering the intensity and orientation of light rays in a given environment.

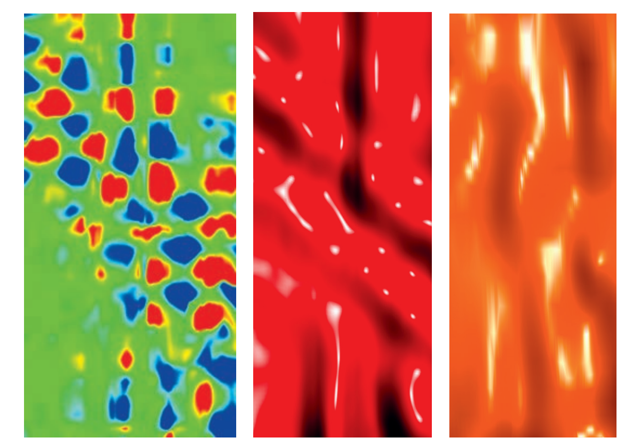
The method used to generate the design.



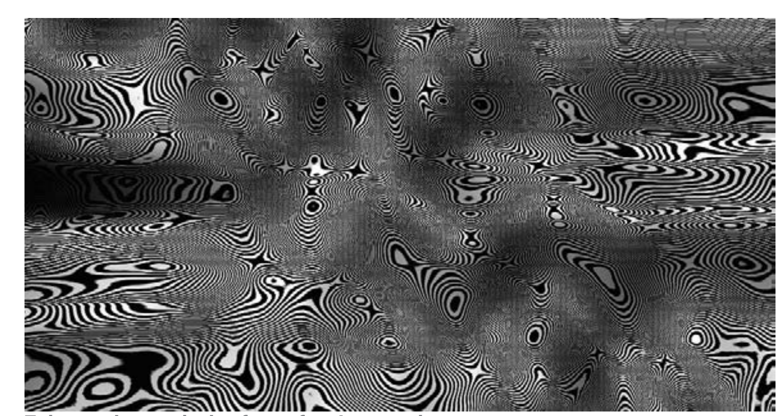
Rendering of a phase of the draft angle analysis tool generating the design of the object. The computation took into account the angles between the surface and a light source (coming from the right).



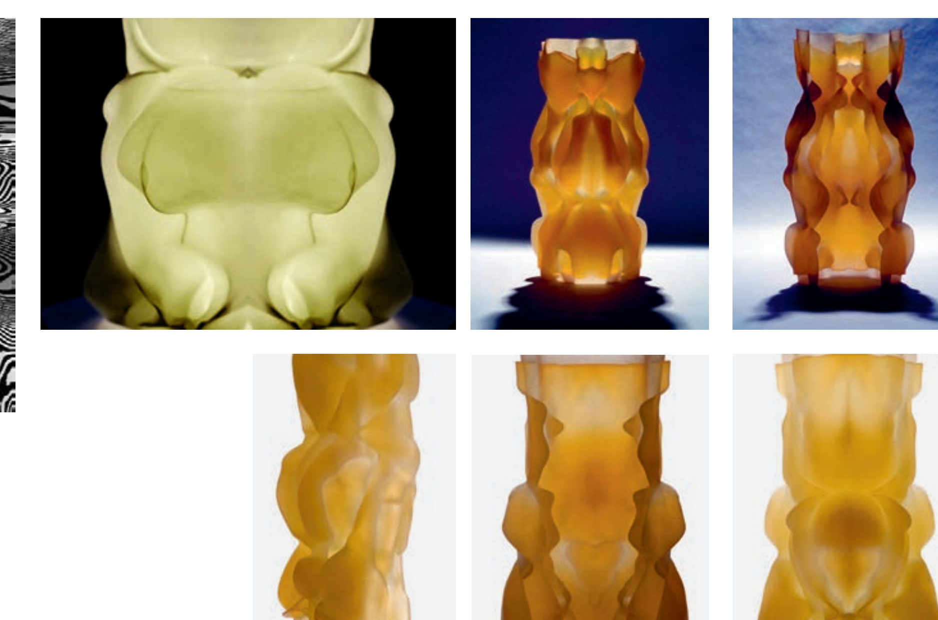
Results of four iterations of the draft angle method. Holes in the surface of the object appeared when the angle between the light source and the surface approached a minimal threshold value.



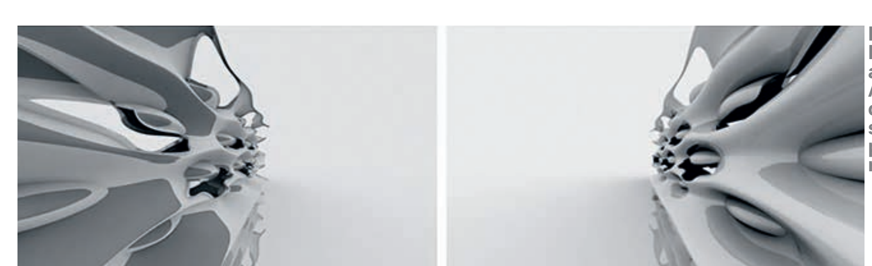
Curvature analysis tool: initial surface (left), visual analysis of its curvature (center), and additional surface with distributed thickness function for structural support (right).



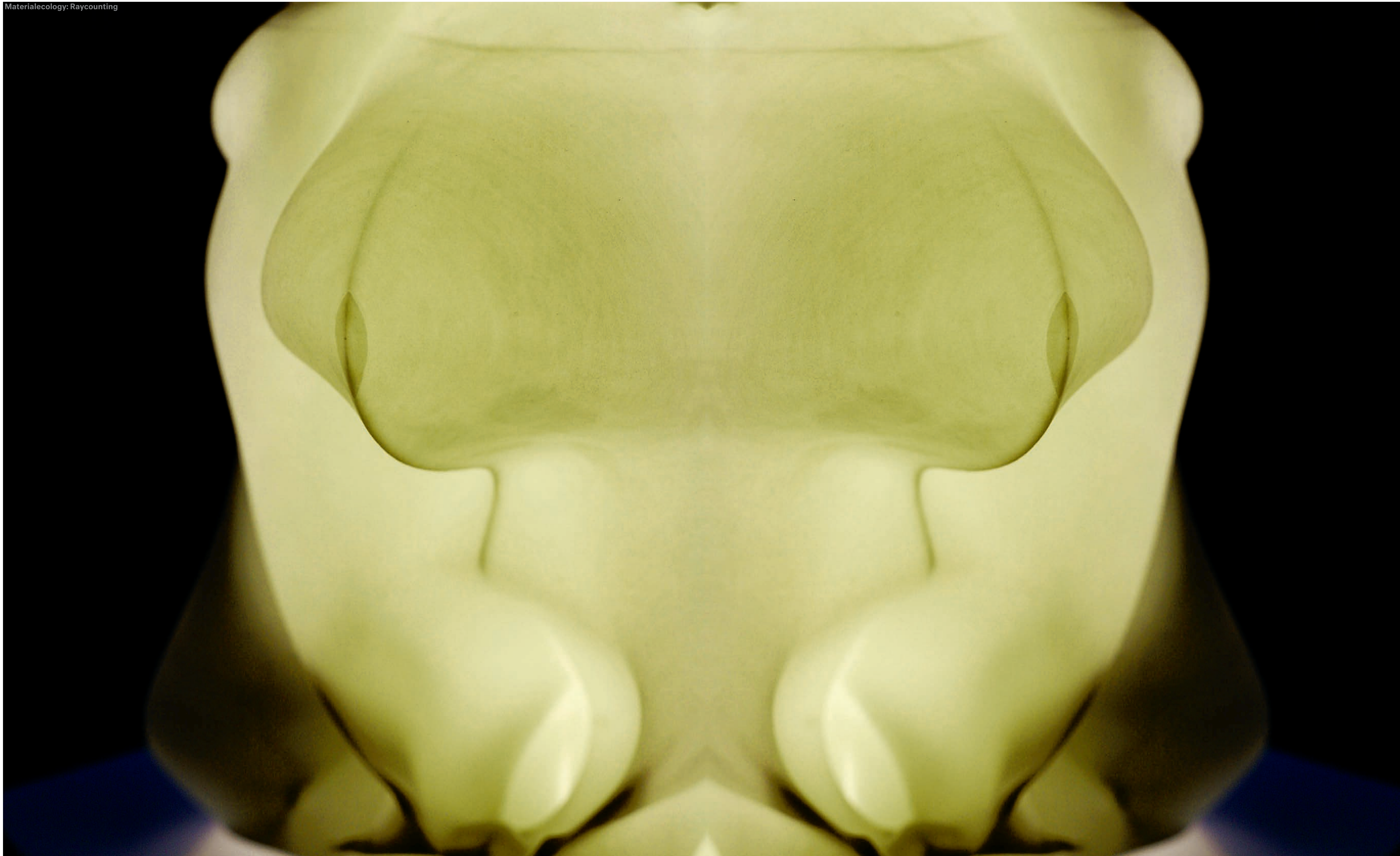
Zebra-stripe analysis of a surface's smoothness.

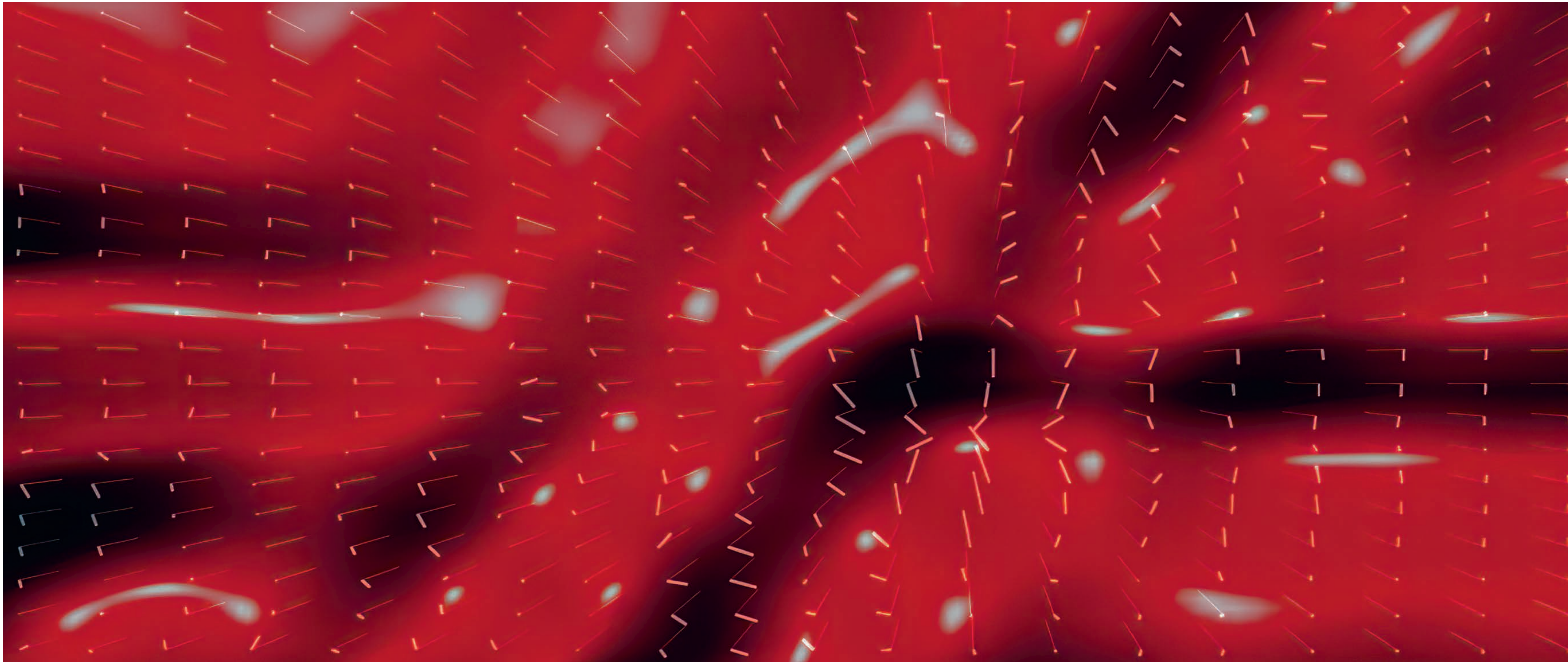


Structure 3D printed with acrylic-based polymer.



Project using the Raycounting method at Wiesner Student Art Gallery, MIT. The design corresponded to specific light-condition parameters and structural requirements.





Materialecology: Raycounting
Phase of the draft angle method used
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The Natural Evolution of Architecture

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Limbs of Nature

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Armour/MetaMesh

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Raycounting

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Cartesian Wax

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Monocoque/Beast

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Aguahoja I and II; Silk Pavilion I and II

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Glass I

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Vespers I

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