NERI OXMAN CALLS HER DESIGN APPROACH MATERIAL ECOLOGY—A PROCESS THAT DRAWS ON THE STRUCTURAL, SYSTEMIC, AND AESTHETIC WISDOM OF NATURE, DISTILLED AND DEPLOYED THROUGH COMPUTATION AND DIGITAL FABRICATION. THROUGHOUT HER TWENTY-YEAR CAREER, SHE HAS BEEN A PIONEER OF NEW MATERIALS AND CONSTRUCTION PROCESSES, AND A CATALYST FOR DYNAMIC INTERDISCIPLINARY COLLABORATIONS. WITH THE MEDIATED MATTER GROUP, HER RESEARCH TEAM AT THE MIT MEDIA LAB, OXMAN HAS PURSUED RIGOROUS AND DARING EXPERIMENTATION THAT IS GROUNDED IN SCIENCE, PROPELLED BY VISIONARY THINKING, AND DISTINGUISHED BY FORMAL ELEGANCE.

PUBLISHED TO ACCOMPANY A MONOGRAPHIC EXHIBITION OF OXMAN’S WORK AT THE MUSEUM OF MODERN ART, NEW YORK, NERI OXMAN: MATERIAL ECOLOGY FEATURES ESSAYS BY PAOLA ANTONELLI AND HADAS A. STEINER. ITS DESIGN, BY IRMA BOOM, PAYS HOMAGE TO STEWART BRAND’S LEGENDARY WHOLE EARTH CATALOG, WHICH CELEBRATED AND PROVIDED RESOURCES FOR A NEW ERA OF AWARENESS IN THE LATE 1960S. THIS VOLUME, IN TURN, HERALDS A NEW ERA OF ECOLOGICAL AWARENESS—ONE IN WHICH THE GENIUS OF NATURE CAN BE HARNESSED, AS OXMAN IS DOING, TO CREATE TOOLS FOR A BETTER FUTURE.
THE NERI OXMAN MATERIAL ECOLOGY CATALOGUE

PAOLA ANTONELLI
WITH ANNA BURCKHARDT

THE MUSEUM OF MODERN ART, NEW YORK
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 reverently 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
THE NATURAL EVOLUTION OF ARCHITECTURE

PAOLA ANTONELLI

EVERYTHING FLOWS, AND NOTHING STAYS THE SAME.
—HERACLITUS

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. Many 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 wise, who regard us as mere beings either resist, pursue, seek to control, or amplify change. We take pride in our ability to invent 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 preeminence 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 antidote to the rush and the rushiness of so many twentieth- and twenty-first-century revolutions—the wind tunnel, the radar, the PET scan, and e-mail among them—Oxman tried her best to avoid being gratuitously seduced by technological developments. At the same time, she was determined to immerse herself in technology, understanding 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 stage 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.

Norton 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 stage 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.

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. 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.’

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Design and the Elastic Mind featured four works from Oxman’s Material Ecology project—Subterrain, Raycounting, Monocoque, and Cartesian Wax (Fall 2007; fig. 4). Each explored natural and cultural 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. 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 macrostructure 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 facial treatments, for instance. In three prototypes built using the Monocoque technique (page 64), “veins” on the skin, rather than an internal structural, 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 shaping 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.
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—creative communities. The groups’ names—Tangible Media, Sculpting Evolution, Fluid Interfaces, for example—combine the familiar tools, techniques, and technologies that they call the Creative Compass.

MMG’s full partner and open to contamination. That purpose is better described by MMG to be attuned to the culture, one that Oxman has designed for the Media Lab, a unique academic sandbox mixing art, design, engineering, and science. Ito argued that the Media Lab needed more teachers and students who could integrate all four disciplines (science on top of design), their tools, techniques, and technologies that they called the Creative Compass. The compass, rendered in four quadrants, includes art and design in additional 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 the 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. 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.

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 Leibniz’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.”

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 entrepreneur, Rich Gold’s 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.

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The results are complex, articulated, fine-tunable demo objects made with one process and often a single material.

Michael Stern, an artist (Ren Ril), 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. 5-16), to name just a few. Broadly stated, as Oxman has described it, the team of researchers is focused on “inventing and developing new design processes, tools, techniques, and technologies that have the potential to redefine the way we make things.” 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.”

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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, thus aligning with the natural history of human exploration into the unknown: the north marks the frontiers of human discovery; 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.

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 to design objects, structures, and interventions to be able to inform and influence the natural ecology, designers must be able to freely move between realms of being and creating in the world and the units that build it: digital units (bits), biological units (genes, metabolic pathways), and physical units (matter, energy, periodic table).

The Krebs Cycle of Creativity III combines the first two iterations into 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 organism (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 actual 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 the planet and its diverse inhabitants, in a bona fide Material Ecology.
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 feedback 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 spider webs (figs. 15, 16), and Agnieszka Kurant, who has deepened her understanding of the future of labor and AI through contemplation of 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, archaeabacteria, 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.

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**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 Cuthoncha Malacosternum—two weeks, and one Tegenaria domestica—four months, turned 4 times 180 degrees on Z axis, 2015. Spider silk, carbon fiber sticks, and plexiglass, 37 ⅝ × 37 ⅝ × 37 ⅝ in. (94.8 × 94.8 × 94.8 cm)

**Fig. 16** Installation view of Tomás Saraceno: Hybird 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. Termites mounds built from colored sand, gold, and crystals, dimensions variable
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 neologism, or state in nine points. The commandments are 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 21st 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 required functions.

**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, through novel technological developments.”**

The last principle in the “official” neologism represents a view 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.” Emerging around the turn of the millennium, Critical Design was waxed on the Design Interactions course chaired at the Royal College of Art in London by Dunne between 2005 and 2010, at the apex of his and Raby’s deep influence on the design world (figs. 19-22). 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 the sciences, politics, philosophy, and the economy, among other fields. Their objective was to instigate what the farsighted expert Stuart Candy has defined as a “preferable future,” in contrast with those that are “probable,” “plausible,” and “possible.”

**The Roots of Material Ecology: Critical Design, New Materiality, Performance-Based Design**

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**Differences over Repetition**

Industrial products generated out of machines... consist of repeatable parts with identical properties.”

“**The form-giving design of 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.**

**Technology over Typology**

“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.”

**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, through 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. 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).”

**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**

“Machines, as they are used to classify commonly found in buildings and urban places... the way in which constituent parts are inter-related or arranged—is the driving force behind the design process, promoting conventional programming as the approach for organizing spaces and making places.”

**Fig. 18** Dunne & Raby (Anthony Dunne and Fiona Raby). “9/8 Manifesto” 2009


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, exemplifying “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 possible for designers like Oron Catts and Ionat Zurr to take control of a new generation of materials and begin the design process with the conviction that the materials themselves, instead of receiving the offerings of engineering and chemical companies. Since 1995 designers’ takeover of the material realm has evolved ever further, from new resins and composites all the way to biopolymers and living tissues.

Oxman and MMG have put such new materials to powerful use in their projects, freeing and beginning to biopolymers and living tissues.

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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). 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. 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). 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 Janowitz, Fun Palace has best been described by the architecture scholar Stanley Mathews as “a unique synthesis of a wide range of contemporary
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. 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 keywords, 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.”

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.” 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. 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).
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. 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. 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. 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. Theorists and practitioners ran wild with highly exploratory models, driven by the search for a new, “better” way of designing.

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 organism, in which the algorithm is a starter for architecturally controlled growth, and the computer becomes a tool igniting multi-functionality that matches Nature. This multiplicity leads, in turn, to specificity, the ability of design to respond to the 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.\(^{31}\)

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.\(^{37}\) 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? Complexity 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.
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.
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.43

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.”44

The values of a morally sound system—the cultural patrimony and mission of an individual, a community, a corporation, a nation—forms 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
It is true that some grand pronouncements remain unfulfilled, and corporations and financial institutions have left even the most cynical and optimistic among us puzzled by their endless discourses on their well-being and social and environmental responsibility. Such statements, whether indications of real change or merely aspirational, are nonetheless a sign of the establishment’s need to reckon with public scrutiny and expectations.

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 articulate, the polythetic 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 the way we treat one another is as important as the way we treat the environment, and with one another. They are no longer designing in a vacuum but rather thinking of how their work will impact 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 tensions. 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 work may, in fact, be a misnomer. In order to build a better future for all, the concept of science, technology, and design culture emerges as a promising path.

Echoing this conviction, Oxman laid out in a neologism a framework for a principle: “Co-culture over culture.” This single tendency towards art and nature is not only biodiversity but also a deeper entanglement of all things. For Oxman: “The designer’s job, by extension, is to promote and enable synergy between the built and the natural, the organic and the synthetic. ... The designer is a mediator, a gardener, an alchemist operating across these poles and domains to conduct rather than construct.” Indeed, it is just this attitude—toward responsive, cooperative, evolutionary design—that we need today.

Notes


4. Neri Oxman, “Designing the beginning of a helpful movement with the U.S. 2D-printing industry: a partnership that is still very much alive today.”

5. Oxman’s massive project on Bio Lab 2a undergoing a deep process of self-examination and change (see pp. 247–55 of this work).


9. Neri Oxman, “Material Ecology,” 121. The design’s evolutionary ability will be accomplished until we also add design: STEAM.


15. Elisa DeLanda, “Rivalries between those that often feature the gut as a starting point in the construction of the human, and those that are designed to be compatible rather than the impact it has on the system); “Rivalries between those that often feature the gut as a starting point in the construction of the human, and those that are designed to be compatible rather than incompatible.”


19. “The importance of digit engineering that straddle the two categories.”


MATERIAL ECOLOGY
Material ecology 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-BOOR) was precursor of these technologies—a rethinking of modern construction techniques.

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.

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 1880s, 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. 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.

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

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 Material Ecology 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.
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.

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.

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

Structure 3D printed with acrylic-based polymer.

RAYCOUNTING

Neri Oxman

The method used to generate the design.

Curvature analysis test: Initial surface (left), visual analysis of the curvature (center), and additional surface with distributed thickness function for structural support (right).

Visual analysis of a surface’s curvature (different colors correspond to bowl-like or saddle-like curvature).

Rendition of a phase of the draft angle analysis tool generating the design. 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.

Project using the Raycounting method at Wiesner Student Art Galleries, MIT. The design corresponded to specific light conditions and structural requirements.
Materialecology: Raycounting

Phase of the draft angle method used to generate Raycounting’s design.