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Entangled Scales: Structures and Environments of Cellulose Biofilms

The collective imagination of how scale connects the living and nonliving has rarely been so evocatively depicted as in Charles and Ray Eames's short film *Powers of Ten* (1977).[1] This virtual journey through successive scales of matter takes us from the familiar scale of the human body to urban space (10^2), via satellite images of weather phenomena (10^6), and on to the planetary scale (10^7). Returning to the human body, we enter the fibrous structure of tissues (10^{-4}) and finally the finest atomic scale of vibrating particles (10^{-15}). With demonstrative continuity, the film leaves us with the impression that human life, together with the structures and objects surrounding us, occupies an intermediate dimension—neither too large nor too small. The human and architectural scales seem interwoven at the center of these scalar transitions and, at the levels above and below them, matter is less tangible and belongs to disciplinary fields other than architecture.

But what is meant by "scale"? The understanding we are most familiar with is relational—the size or extent of something in comparison to something else. The etymology of the term is more diverse, referring to parts of animal shells, measuring instruments, but also to acts such as scanning, examining, and looking closely.[2] In architecture, as in Eames's film, scale is often associated with human proportions, either in a "cosmological" sense, in diagrams where the human figure stands as a symbolic measure of the world,[3] or in a normative context, where it defines a blueprint required to plan or make something.

This perception of the human scale as the focal point for design—a measure of things existing in the middle of continuous metric space—is a topic we aim to examine critically in this text. We argue that, whether in processes of design, making, or growth, one can speak of *scalar entanglements*, in which structures are influenced by others at different scales that are neither immediately apparent nor clearly ordered. As designers, we usually deal with materials at a scale convenient for human use, though they still depend on relationships and behaviors that go far beyond their own scale or materiality. Microorganisms, for example, are almost imperceptible to the human senses, even though they live and form complex communities in all the spaces we inhabit, from our bodies to the outer environment. Being indiscernible in large-scale building

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1 *Powers of Ten and the Relative Size of Things in the Universe*, directed by Charles and Ray Eames (Eames Office, 1977). The film was based on the earlier version from 1968, which juxtaposed human and earthly space and time scales, https://www.eamesoffice.com/the-work/powers-of-ten-a-rough-sketch/, https://www.eamesoffice.com/the-work/powers-of-ten/.

2 Eric Partridge, *Origins: An Etymological Dictionary of Modern English* (London: Routledge, 2006).

3 Adrian Lahoud, *The Problem of Scale: The City, the Territory, the Planetary*, PhD diss. (University of Technology Sydney, 2013).

 https://doi.org/10.1515/9783110714883-010

practices, however, means that they are unlikely to be seen as active participants in shaping these spaces and their livability.

Based on our experiments with cellulose-producing bacteria, conducted in collaboration with microbiology and materials science,[4] we would like to turn our attention "inward," to the living and growing processes at the microscopic scale, and ask: How does architectural design engage with them? When a design process revolves around the microorganism, how does this differ from dealing with the conventional materials? And, what becomes entangled in the fibrous structure of bacterial cellulose that can be considered across the scales—microbial, material, environmental, and infrastructural?

Engaging with different scales creates uncertainties about their transitions and continuities, as they tend to filter what belongs to a particular frame of reference and what falls outside of it. Architectural theorist Luis Fernández-Galiano notes that, on small scales, the usual distinction between matter and energy no longer applies, one being routinely described in terms of the other. Indifferent to scalar conventions, energies travel across scales and traverse materials, linking them to processes of life, transformation, degradation, and renewal.[5] For architect Adrian Lahoud, the problem of scale is a disciplinary "trap."[6] He draws attention to the unexpected juxtaposition of the small and the planetary, the near and the far, by showing, for example, how the trajectories of aerosol particles are linked to climate changes. Moreover, scalar categories, he argues, have historically emerged around explanations and representations of specific problems, and in turn have partitioned knowledge in accordance with inherited conventions.

Similar ambiguities form part of our interdisciplinary explorations with bacterial cellulose (fig. 1, 2). Starting from cellulosic materials as sites of disciplinary and scalar entanglements, we reflect on novel frameworks required to account for bacterial activity in architecture. In exploring the intrinsic structure and properties of cellulose, we disclose its complex relationships with the environment, and the history of processing of this hierarchical biomaterial, in which bacterial cellulose has only recently gained attention. Some of the practices discussed, such as fermentation and co-weaving textiles with bacteria, go beyond conventional design methodologies and ultimately offer insights on how collaboration with microbiology and materials science can expand the current architectural field of vision beyond the anthropocentric.

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4 Experiments with bacterial cellulose are carried out at the intersection between microbiology, materials science, and architectural design, within the research projects Weaving and Material Form Function, and in collaboration with the Hengge Group at the Department of Microbiology of the Humboldt-Universität zu Berlin, Adaptive Fibrous Materials and Biofilm-based Materials groups at the Max Planck Institute of Colloids and Interfaces in Potsdam.

5 Luis Fernández-Galiano, *Fire and Memory: On Architecture and Energy*, trans. Gina Cariño (Cambridge, MA: MIT Press, 2000), 2.

6 Adrian Lahoud, "Scale as a Problem, Architecture as a Trap," in *Climates: Architecture and the Planetary Imaginary,* ed. James Graham et al. (New York: Columbia University Press, 2016), 111–19.

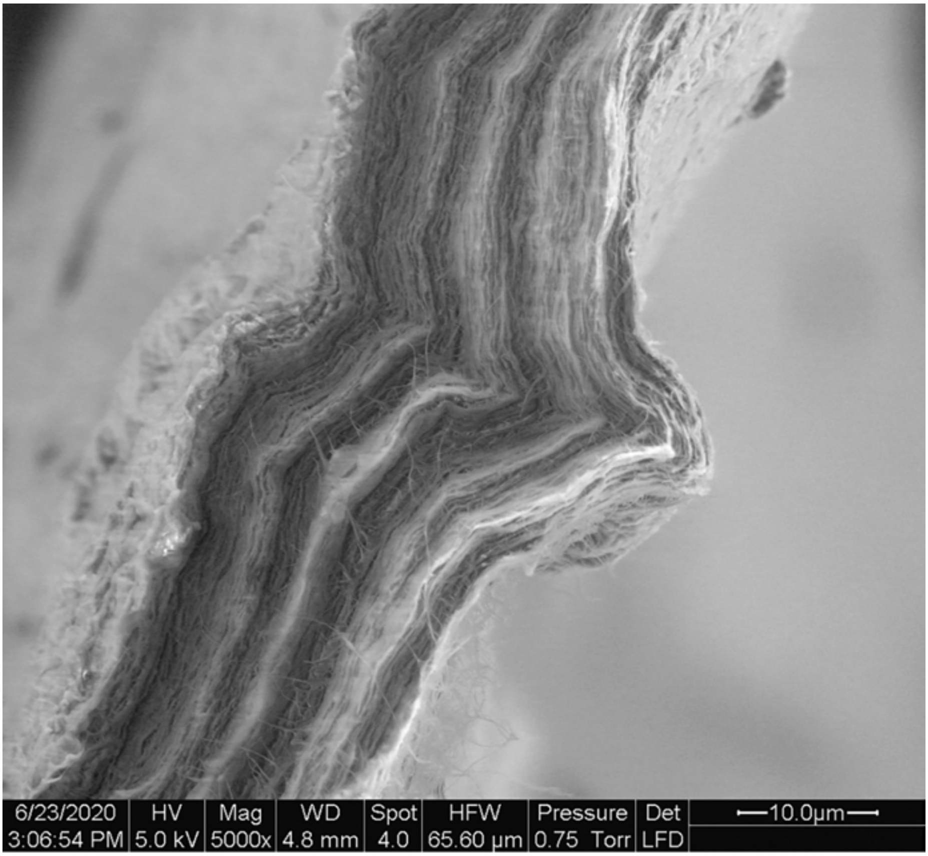

Fig. 1: Microscopic image of the fibrous structure of bacterial cellulose visible in the 10 μm range.

Cellulose: Structures and Processes

Cellulose is the most abundant organic compound occurring in nature—and found in biological materials across their scales. As the skeletal component of the cell walls of all plants, cellulose possesses a unique fiber morphology consisting of elementary fibrils (1.5 – 3.5 nm), microfibrils (10 – 30 nm), and micro fibrillar bands with a lateral dimension of around 100 nm.[7] In plants, in combination with hemicellulose, lignin, and pectin, cellulose is arranged in hierarchical organizations that give these biological materials a range of outstanding properties, such as great yet variable tensile strength. In

7 Dieter Klemm, Brigitte Heublein, Hans-Peter Fink, and Andreas Bohn, "Cellulose: Fascinating Biopolymer and Sustainable Raw Material," *Angewandte Chemie International Edition* 44, no. 22 (2005): 3358 – 93, https://doi.org/10.1002/anie.200460587.

Fig. 2: Open-ended design explorations with bacterial cellulose.

addition to plants, certain bacteria and algae are also capable of synthesizing cellulose. These biological composites differ from the homogenous, monolithic structures: with a few constitutive elements and a multitude of possible configurations, they grow and adapt to changing mechanical and environmental conditions, which are reflected in their structure.[8]

Human culture is deeply intertwined with cellulosic materials. Throughout history, we have built, clothed ourselves, consumed, transported, and communicated using various forms of cellulose, such as wood, straw, cotton, flax, and hemp. In architecture these materials have proved equally important for construction and combustion—both for making structures and for supplying them with energetic flows.[9] Their use has been particularly widespread in societies that rely on plant-tending and on the construction of lightweight and portable, rather than permanent and massive structures.[10]

The knowledge and skills required to manipulate, construct and cooperate with plant matter have developed tacitly through interaction and negotiation with the ma-

8 Peter Fratzl and Richard Weinkamer, "Nature's Hierarchical Materials," *Progress in Materials Science* 52, no. 8 (2007): 1263–1334, https://doi.org/10.1016/j.pmatsci.2007.06.001; Michaela Eder, Shahrouz Amini, and Peter Fratzl, "Biological Composites—Complex Structures for Functional Diversity," *Science* 362, no. 6414 (2018): 543–47, https://doi.org/10.1126/science.aat8297.

9 Fernández-Galiano, *Fire and Memory: On Architecture and Energy*, 7.

10 Mark Jarzombek, *Architecture of First Societies: A Global Perspective* (Hoboken, NJ: Wiley, 2013).

terial.[11] Here, understanding the material on different scales—its internal structure and fiber orientation—was key to working with it successfully.[12] Practitioners, such as carpenters or instrument makers, have perfected this art and developed methods to fine-tune and amplify certain properties of materials. In the example of archery, bows were made of thin strips of wood laminated according to a certain predefined pattern in order to improve their strength and resistance. This marked a profound change in the way plant materials were treated: instead of using structures as they occurred, recomposition and restructuring was introduced to activate their inherent properties.

Industrialization gave rise to a new economy and conception of plant matter as a resource and a raw material involving the manipulation of materials on a molecular level. Wood is no longer perceived and utilized as a complex, grown structure, but broken down into a series of ingredients—lignin, hemicellulose, cellulose—through the development of processes of fractionation (fig. 3). These semi-finished products are then becoming the source of numerous substances (for example, cellulose acetate, cellulose nitrate, methyl cellulose), which in the "formless" state can easily be shaped into a variety of products.

Vast industrial landscapes have evolved around cellulose and its extraction that not only involve energy-intensive and chemically laden manufacturing, but also demand deforestation or long-term land use for monocultures. From source materials for extraction to semi-finished products and derivatives, cellulose now occupies an intermediate position—processed from other substances it serves as a raw material for further processing.

To rethink the role of cellulosic materials in the context of architectural design, these dependencies and production methods need to be called into question. Bacterial cellulose has the potential to bypass the logic of extraction: because of its small scale and the fact that it is created by a living organism, this material can remain close to the environments and processes of growth. A new collaborative setting—between species and between disciplines—provides an opportunity to observe and reveal its potential for design.

Microorganism and Biofilm Growth

By familiarizing ourselves with the growth of cellulose at the microscale, we can begin to understand how such a process differs from industrial production. Microbial cellulose does not involve extraction from other materials, as the bacteria produce chemically pure cellulose. Few resources and little energy are needed in the process, which

11 Tim Ingold, "The Textility of Making," *Cambridge Journal of Economics* 34, no. 1 (2010): 91–102, https://doi.org/10.1093/cje/bep042.

12 Michaela Eder, Wolfgang Schäffner, Ingo Burgert, and Peter Fratzl, "Wood and the Activity of Dead Tissue," *Advanced Materials* 33, no. 28 (2021): 2001412, https://doi.org/10.1002/adma.202001412.

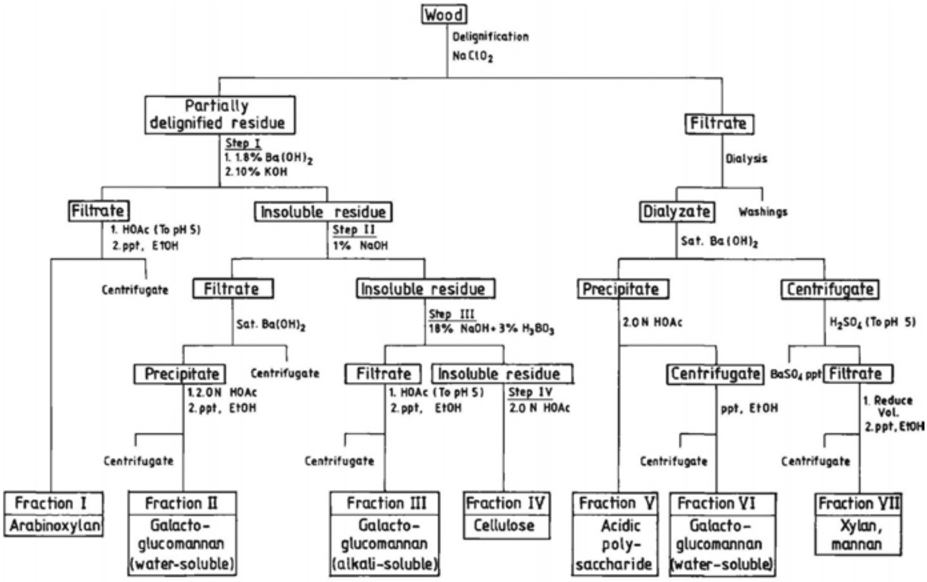

Fig. 3: Pathways of industrial material processing: fractionation of wood.

can be undertaken in domestic or citizen science contexts as well as in the laboratory. Recently, a research landscape in design and architecture has emerged with interest in taking the cellulose growth in various interdisciplinary directions, raising critical questions about care, symbiosis, and cohabitation.[13] Simultaneously addressing bacterial, human, and urban scales, its projects include proposals to use organic waste as a nutrient source for bacterial cellulose, deploying energy infrastructure on an urban scale, imagining growth through community knowledge and within a public space,[14] and actively engaging with the cellulose livingness in making everyday objects and artefacts.

Most of these projects do not obtain cellulose from plants or through industrial processes, but rather grow the material in the laboratory. But how is cellulose grown in a microbiology laboratory? What species, conditions, and scales are entangled in the structure of biofilms and in experiments at the intersection between microbiology and architectural design?

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13 Elvin Karana, Bahareh Barati, and Elisa Giaccardi, "Living Artefacts: Conceptualizing Livingness as a Material Quality in Everyday Artefacts," *International Journal of Design*, 14, no. 3 (2020): 37–53, https://www.ijdesign.org/index.php/IJDesign/article/view/3957/923.

14 Numerous design research projects have been undertaken with bacterial cellulose, see for example the following: "Vibrant Tissue," IAAC, accessed August 31, 2021, http://www.iaacblog.com/programs/vibrant-tissue_-augmented-microbial-cellulose/; "Bio-Fabric," IAAC, accessed August 31, 2021, http://www.iaacblog.com/programs/bio-fabric-microbial-cellulose/; "GrowPak – A step towards closing the loop," accessed August 31, 2021, https://julianajschneider.com/growpak; *Metabolizing Urban Waste into Layered Morphologies*, YouTube video, 4:15, January 24, 2018, https://www.youtube.com/watch?v=Ds9qk3oFIRI.

Bacteria produce cellulose to form biofilms—fibrous assemblages that gather colonies of individual microorganisms. As symbiotic communities of bacteria, biofilms are sites of complex interactions where diverse multispecies act as a collective entity in cooperation and conflict.[15] Bacteria build, maintain, and live in this gelatinous matrix of a fibrous microstructure (fig. 4). The material created during biofilm growth is also termed nano-cellulose, since cellulose particles possess at least one dimension in the nanometer range (1 nm to 100 nm). We have been experimenting with the particular bacterial strain of the genus *Komagataeibacter* called *K. xylinus*, *which* belongs to the group of acetic acid bacteria known for its extensive cellulose production. Unlike that of photosynthetic plants, its growth does not require light, but a warm environment and nutrients. Although the fibrils form on the nanoscale, the biofilms woven by *K. xylinus* are visible on the human scale, allowing for the direct interaction with its growth process and hence for speculation on how it might become part of more symbiotic, bacterial-human design processes.

Biofilm growth follows several stages of materiality. When the bacteria are introduced into the culture medium, the film is formed at the interface between two environments: a nutrient-rich liquid and the air. Formation begins with pellicles floating on the surface of the medium and, after a few days, when the hydrogel membrane covers the entire surface, bacterial activity stops or slows down. Once the cellulose is taken out of the medium, it dries and turns into a skin-like, translucent, lightweight structure (fig. 5).

In this process, the biofilm as a living entity undergoes transformation constantly: it changes from a liquid and gelatinous to a dry and solid material. The life within it also fluctuates, since, after the nutrients and oxygen have been depleted, the microorganisms enter a dormant phase. This gradient of nutrients and livingness is not only temporal; it is also spatial and linked to the internal structure of the biofilm and to its fluid boundary with its surroundings.[16] The most active part lies in its contact with the air where the newly-made fibers assemble above already formed layers. Oscillating between wet and dry, living and inert, in many ways the biofilm evolves at the interface of different environments, which in turn become part of its microstructure.

Microbial Environments and Fermentation Practices

One might rightfully ask: how do microbial life and practices of fermentation relate to the field of architecture? How can processes on such a scale, imperceptible to the

15 Alexander May et al., "Kombucha: A Novel Model System for Cooperation and Conflict in a Complex Multi-Species Microbial Ecosystem," *PeerJ* 7 (2019): e7565, https://doi.org/10.7717/peerj.7565.

16 Diego O. Serra, Anja M. Richter, and Regine Hengge, "Cellulose as an Architectural Element in Spatially Structured Escherichia Coli Biofilms," *Journal of Bacteriology* 195, no. 24 (2013): 5540–54, https://doi.org/10.1128/jb.00946-13.

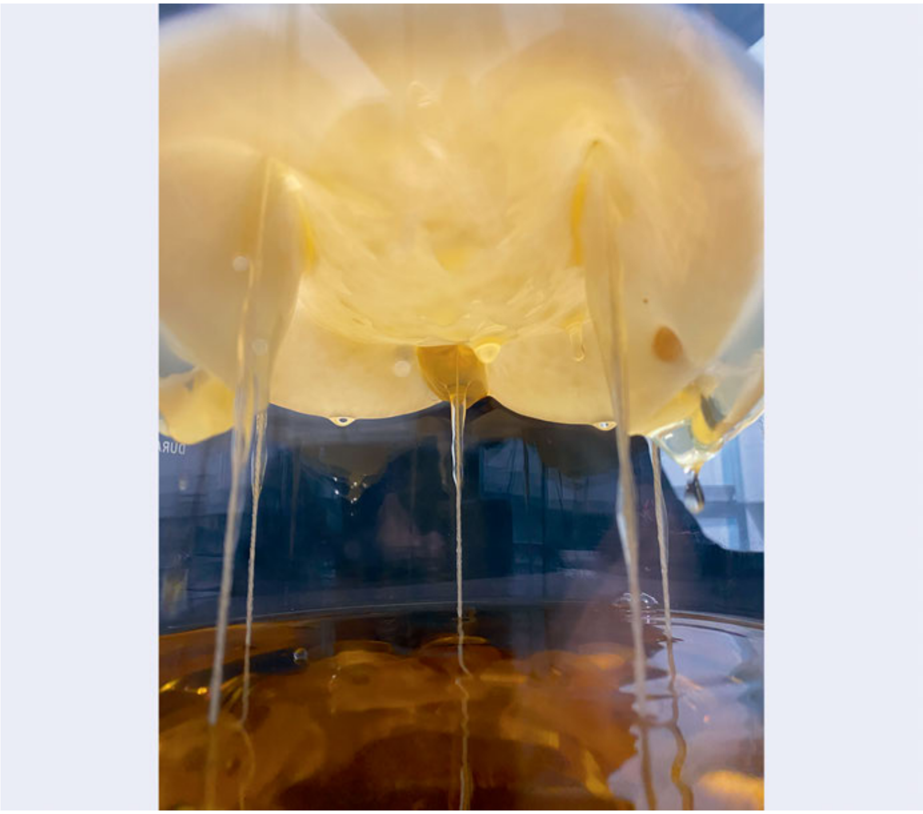

Fig. 4: Gelatinous stage of cellulose biofilm.

human eye, influence the spaces we inhabit? In the field of architecture, microbial activity is generally connoted with negative effects such as rot or mold. By conditioning spaces, by dehumidifying or sanitizing surfaces, we try to prevent, delay, or mitigate these processes. In spite of our efforts, we are still surrounded by a plethora of microbial life—be it in the food we consume or the diverse spaces and environments we move through and inhabit.

If we take these different scales into account, we can see that architecture is in constant microbial exchange with its environment and inhabitants. Every space and building hosts a unique microbiome in constant flux due to its use, as well as with the indoor and outdoor climate.[17] Historically this has been mainly studied in the context of pathogens; more recent research, however, suggests that commensal and benign

17 Simon Lax et al., “Longitudinal Analysis of Microbial Interaction between Humans and the Indoor Environment,” *Gautam Dantas* 15, no. 6200 (2014): 1048 – 52, https://doi.org/10.1126/science.1254529; Jack A. Gilbert and Brent Stephens, “Microbiology of the Built Environment,” *Nature Reviews Microbiology* 16, no. 11 (2018): 661 – 70, https://doi.org/10.1038/s41579-018-0065-5.

Fig. 5: Dry cellulose biofilm: a heterogenous, skin-like structure with a gradient of opacity.

bacteria also exist in large numbers. In addition to building materials, architectural spaces and surfaces can, in this context, be understood as interfaces between their inhabitants and various microbiota.[18] Recent studies suggest that being exposed to a diverse microbiome can have wide-ranging benefits, from mental health to allergy resistance.[19] The study of these interdependencies and complex relationships between outdoor microbiota, the built environment microbiome, and the human microbiome, transgresses scales and disciplines. Architectural materials—the interfaces—play an active role in this regard as they mediate colonization processes through surface qualities, such as porosity or hydrophilic behavior.[20] This continuum between microbiomes permeates not only built environments but also the human body. We disperse, exchange, and absorb microbiota from our environment through bodily functions such

18 Simon Lax et al., "Our Interface with the Built Environment: Immunity and the Indoor Microbiota," *Trends in Immunology* 36, no. 3 (March 2015): 121–3, https://doi.org/10.1016/j.it.2015.01.001.
19 Andrew J. Hoisington et al., "The Microbiome of the Built Environment and Mental Health," *Microbiome* 3, no. 1 (2015), https://doi.org/10.1186/s40168-015-0127-0.
20 Marcos Cruz and Richard Beckett, "Bioreceptive Design: A Novel Approach to Bio-Digital Materiality," *arq: Architectural Quarterly* 20, no. 1 (2016): 51–64, https://doi.org/10.1017/S1359135516000130.

as breathing or touch,[21] in the exchange that happens mostly unconsciously and unnoticed.

The consumption of fermented food marks an important change though. The fermentation of food relies on the metabolic processes of specific microorganisms to help modify nutrients and improve the taste of food, making it less perishable. This practice has evolved in a symbiotic manner and in the awareness of the positive effects of microbial life and its capabilities. It is a caring relationship where bacteria are given optimal conditions to grow and proliferate, as they become a vital part of our body through food.[22]

Whole building typologies have evolved around this process to provide spaces that are conditioned and designed not necessarily as an environment for humans but to maintain conditions for a specific microbiome to develop—cheese cellars, wineries, or barns for fermenting tobacco or cacao, for example. The products of fermentation, however, are reserved for culinary purposes. Looking at bacterial cellulose, however, suggests a new setting. The result of fermentation processes, it has at the same time recently been explored as an architectural material.

What this brief description of our relationship with microbial life and architecture suggests is that we are confronted with an interdependent fabric of environment, material, and scale, as well as with various life forms which are in constant change and interaction. Our research interest lies precisely in this relationship between nurturing environments, architecture, and microbiology. We have chosen not only to focus on bacterial cellulose as an outcome of fermentation processes, however, but on the changing roles of designer and organism within these shared environments and processes of making.

By seeking to understand bacterial cellulose as simultaneously a material and a living organism, the notion of design and manufacturing changes fundamentally, prompting us to acknowledge its intrinsic activity and aliveness. Instead of relying—as in the case of synthetic polymers—on a predetermined and precisely timed process, designing with fermentation disrupts this procedure and questions our role as designers. This is a shift from simply envisioning a final product and its materialization toward designing boundary conditions in which an organism and its structure evolve (fig. 6). It differs starkly from the common conception of materials as passive and "obedient" entities within the design process. Bio-design calls for a bottom-up approach that guides materials during growth throughout different scales, rather than imposing shapes onto raw materials. In other words, the primary task is to design an environment rather than forms and structures.

The settings for these environments of growth are not limited to the enclosure of a container or an incubator. For instance, observing the development of a biofilm in a

21 Lax, "Our Interface with the Built Environment: Immunity and the Indoor Microbiota."
22 Sandor Ellix Katz, *The Art of Fermentation: An in-Depth Exploration of Essential Concepts and Processes from around the World* (White River Junction, VT: Chelsea Green Pub, 2012).

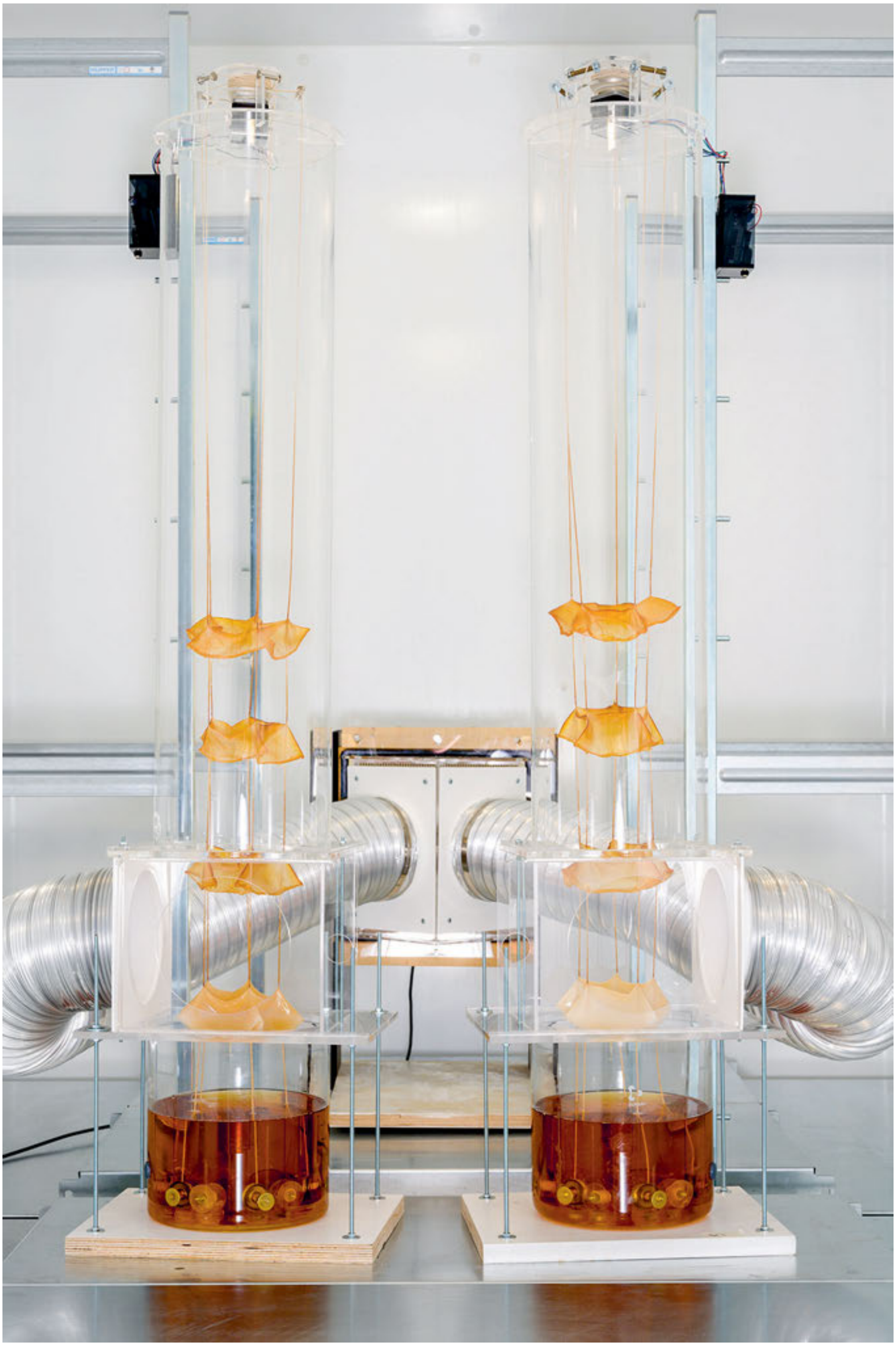

Fig. 6: Environment of growth: designing with boundary conditions in the laboratory.

Petri dish, one would assume that it is a contained process, a closed system with defined and rigid boundary conditions: the glass sides of the Petri dish, the medium with its nutrient composition, and a lid that should seal everything off. But this is hardly the case: even though the Petri dish may appear encapsulated, it is in fact embedded in an environment and permeated by energy flows that affect its temperature and humidity. Air circulates through minute gaps between the dish and its lid while radiation and light permeate the system. Variable levels of nutrient, temperature gradients, and microstructural changes in the growth medium all influence the growth of biofilm to a certain degree. Instead of viewing these boundary conditions as geometrically defined and enclosed, they can be understood as fluid zones of exchange, where different scales intersect and guide the growth process.

Donna Haraway describes these relations as “sympoietic,”[23] or more specifically as a “holoent” condition, so as not to privilege “the living but to encompass the biotic and abiotic in dynamic sympoietic patterning.”[24] Processes of growth are intrinsically interdependent and their environments fluctuate. As designers we are also part of that environment. Compared to working with conventional materials, the degree of control and influence we have over such conditions is often limited. Instead of imposing forms onto materials we start to think about designing environments of their growth. Instead of approaching additive assembly using screws and bolts and subtractive processes with drilling and milling, the toolset shifts to preparing a nutritious broth on which microorganisms can feed and multiply. It is the way of guiding growth and structure through nutrients, viscosities and temperature. This interaction with a living organism and the environment resembles more closely the cheese- or wine-making practices we mentioned earlier: it is more a task of care than of control.

Textilic Milieus and Co-Weaving

We understand the biofilm as a textile entity, composed of grown nanocellulose entangled in a fibrous network. For us, therefore, “weaving” and the “textilic” start on the microscale through microbiological activity. From this microbial textile, a microenvironment emerges that actively supports the development of the bacterial community.[25] It provides a buffer zone, and its permeability allows for nutrients and bacteria to travel within what is a *textilic milieu.*

23 Donna Haraway, *Staying with the Trouble* (Durham, NC: Duke University Press, 2016), 25, https://doi.org/10.2307/j.ctv11cw25q.

24 Ibid., 26.

25 Karin Krauthausen and Regine Hengge, “Das Ereignis der Faser / The Event of a Fibre,” *Gropius Bau Journal* (article accompanying the exhibition *Kosmos Weben* by Hella Jongerius), 2021, 1–8.

For anthropologist Tim Ingold, the notion of "textilic" encompasses a negotiation process with the material during the process of making.[26] Ingold emphasizes that making and textility are not a question "of imposing preconceived forms on inert matter but of intervening in the fields of force and currents of material wherein forms are generated."[27] Both the designer and the bacteria play a crucial role in the fields of force and currents in the material: we set boundary conditions in which the microbiological "weaving" can take place.

In our experiments, a scaffold—another textile entity on a different scale—is introduced to this setting that not only structurally mediates between the nano-cellulose and a macroscopic fiber structure, but similarly allows for new microenvironments to emerge during growth (fig. 7). In contrast to the biofilm, this secondary textile scaffold follows a designed pattern and a geometry on a macro scale to provide a support for the biofilm to develop. The two textile systems, the biofilm and the thread, intersect in certain areas or fully integrate with one another. During growth, a gradient between the fuzzy boundary of the threads and the biofilm emerges, where the fibers of the scaffold intertwine with the nanocellulose to form a structural bond. Rather than being glued to each other, these structures grow together, intertwining the human-made and the bacterial: in this web-like milieu, we observe the reciprocal and fluid relationship between the nano-, micro-, and mesoscale in a nurturing and active environment.

Even after growth, we notice that the exchange with the environment continues to contribute to the "fields of force" as a generative impulse for transforming material structures and configuring their relationship to their surroundings. In studies of the morphologies of drying, for example, both the shape and internal structure of the biofilm are reconfigured through several wetting and drying cycles (fig. 8). Through rehydration, the cellulose returns to its original shape, but the fiber alignment remains in the "memory" of the material. All these changes take place on the level of the fiber: swelling causes the biofilm to temporarily become gelatinous before returning to the dry state, where the fibrous structure reappears. In the drying process, both elastic and thermal energy pass through the material and are exchanged with the environment: elastic energy is stored and released during the shape-change, while heat escapes by evaporation—a phase transition of water from liquid to gas. In these processes, environment and structure intermix and become part of each other's composition, so that the environment acts not as a passive, immaterial domain surrounding the structure, but is incorporated into the material (figs. 9, 10).

Again, if we consider how Ingold differentiates between the "fields of force" through which artifacts are shaped and "morphogenetic fields" that give rise to biological form, we need to take a closer look at this duality as it affects our experiments.

26 Tim Ingold, "The Textility of Making," *Cambridge Journal of Economics* 34, no. 1 (2009): 93, http://doi.org/10.1093/cje/bep042.
27 Ibid., 2.

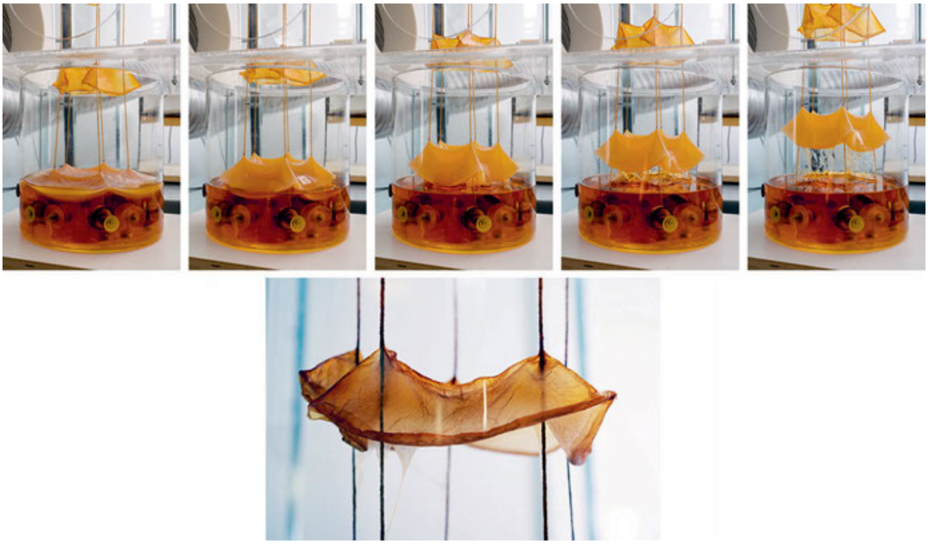

Fig. 7: Experimental setup with a perpendicular thread.

Fig. 8: Morphologies of drying.

Ingold states that "[b]oth kinds of field cut across the developing interface between the object (organism or artefact) and an environment which, in the case of the artefact,

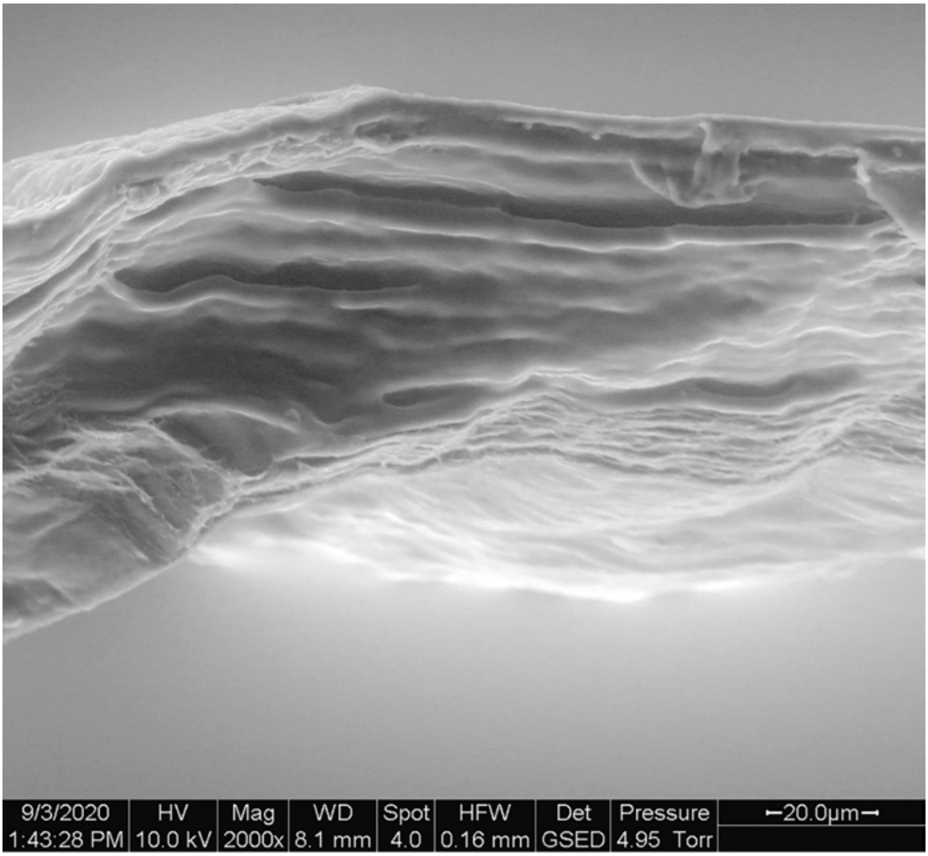

Fig. 9: Wet, gelatinous internal structure of the biofilm exposed to moisture.

critically includes its 'maker'."[28] While he distinguishes between "organism or artifact," in our experiments, these dualities start to blur, since they form a continuum. In fact, we can observe an overlap between what Ingold describes as "fields of force" and "morphogenetic fields," where the growth of the biofilm is guided by the textile structure.

In his essay "The Textility of Making," Ingold discusses the craft of woodworking, describing how the "blade enters the grain [of wood] and follows a line already incorporated into the timber through its previous history of growth."[29] The act of making is described as temporarily disconnected from the process of growth. Through direct interaction with bacteria during the processes of growth, a simultaneity between growth

28 Tim Ingold, *The Perception of the Environment: Essays in Livelihood, Dwelling and Skill, Mind, Culture, and Activity*, vol. 9, 2002, 345.
29 Ingold, "The Textility of Making," 92.

Fig. 10: During drying, spontaneous folding occurs along the textile threads and the entire biofilm structure.

and making takes form and it suddenly becomes possible to co-weave structures together with the organism and to guide what Ingold refers to as "lines" in their becoming (fig. 10).

Weaving Scales

In researching and seeking to understand microbial structures, our disciplinary lenses instinctively tend to separate out the material from the biological activity, observing each at their respective scales. In materials science laboratories, we investigate and measure fibril diameters, tensile strength on the micro or macro scale, and material behavior upon wetting or drying (fig. 11). Meanwhile, in the microbiology laboratory, the focus is on the bacteria, on their genomes and metabolism. Even though the data and insights we gain from these distinct disciplinary methodologies are important in understanding parts of the complex workings of the biofilm and its materiality, the individual pieces can scarcely provide a sense of the intertwined ecology of a biofilm. The relationship between microorganism, structure, and environment is complex yet fascinating and can hardly be described through discrete scientific viewpoints and scales.

The interplay of these viewpoints is far from linear. Charles and Ray Eames's visual journey through the successive scales of matter offered a systematic and ordered picture of the hierarchy of scale, each clearly framed within its own microcosm. But this separation—a "trap" of scale—together with independent disciplinary scientific views, does not capture the simultaneity and fuzziness of the scalar encounters in the design process, nor the tactility of their weaving.

Stepping away from the field of architecture, where the default measure is the human, our attention has shifted towards the seemingly imperceptible processes of textile-making on the microscale. This change of perception leads us to recognize the multitude of lives and structures beyond the human, which, even though not visible, shape and influence our bodies as much as the spaces surrounding us. Our attempt to leave the convenience of a solely anthropocentric view of materials and processes has presented us with new opportunities for designing through growth, but likewise with challenges and limitations. Whenever we encounter contaminated cellulose in Petri dishes in the laboratory, our understanding of control and collaboration is challenged: our design intentions are confronted with the unpredictable reality of the culturing practice that defies isolation and containment. Working with biofilms has shown the fluidity and simultaneity of biological processes, where fibers on different scales emerge and intersect in dynamic environments of growth. To co-design these environments means to acknowledge the dynamic relationships of bacterial cellulose, its structure, and life, together with their entanglement across scales.

Rather than seeking control over these intricate relationships, which Ingold refers to as "fields of force," our approach guided us toward crafting environments that foster and nurture growth. In addition to bacteria, these environments required careful consideration of factors such as nutrients, temperature, and airflow. Our role as designers shifted from thinking about finished objects to creating settings in which bacteria might act independently. This shift calls for a different approach to design that moves away from imposing predefined shapes onto passive materials and towards embracing roles of care and responsibility that more closely align with practices of fermentation.

As we engaged with bacteria, a novel collaborative environment unfolded for us, fostering not only interdisciplinary connections but also forging collaborations between different species. While our documentation shows the outcomes of this attempt at "collaborative weaving," it is merely a static representation of the dynamic process that takes place between bacteria and its textilic milieu, where making unfolds in a constantly changing environment of entangled scales.

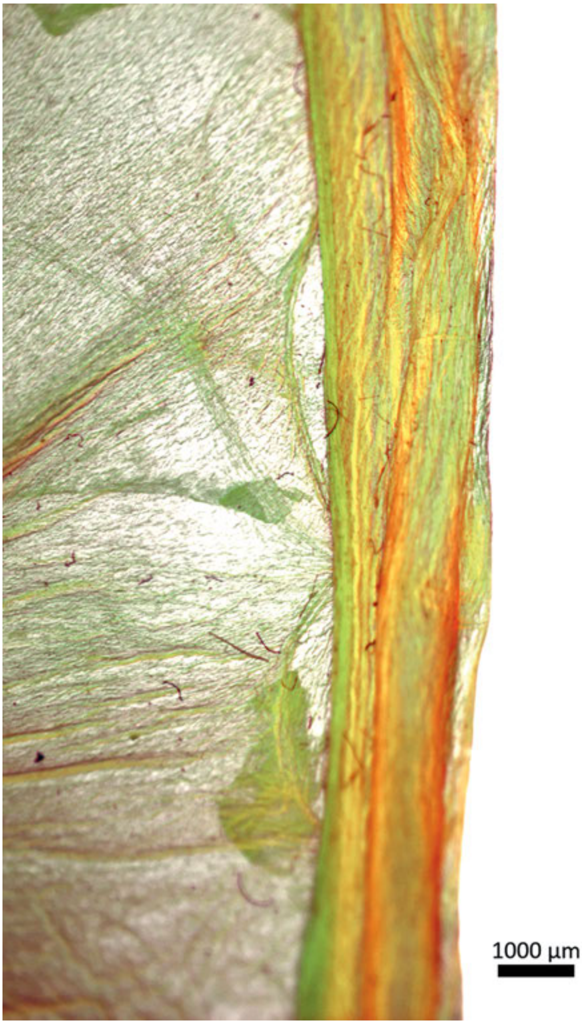

Fig. 11: Microscopic image showing the “guided growth”: the alignment of cellulose fibers to the textile scaffold and to the edge of the glass enclosure.

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