Accelerating Programmable Bio-Matter Architecture.

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Abstract. Building with biology will be the most important platform to transform our planet in the next decades. Since 2006, Synthetic Biology (SynBio) has surfaced as the fastest-growing technology in human history. This field is allowing us to manipulate the genetic code, biology, food, and vaccines and ultimately aiming to reshape the very essence of existence. In this paper, we assess the development of SynBio and its impacts on architectural thinking, materials, and particularly in Architectural fiction. In this paper, we argue that there are at least three waves of impacts of SynBio technology in construction: Biomaterials, Engineered Living Materials (ELM), and Bio-Matter or biobots. We explore architectural thinking's domain, involving architects and engineers in research and startups. We embrace the architectural envisioning role and present our design work utilizing observed biological growth algorithms. Synthetic Biology urges questioning not only biomaterials but also the field's overarching vision.

Keywords: Bio-Architecture, Bio-Matter, Synthetic Biology, Biotechnology, Architecture.

1 Nature, Biology, and Programmable Biology

The concept of nature and biology has evolved radically over the past 200 years. In the 1800s, biology led by pioneers such as Charles Darwin and Alfred Russel Wallace was associated with field expeditions into the almost untouched natural world. In the 1900s, biological studies shifted from travels to laboratory-based investigations eventually leading to the groundbreaking discovery of DNA's structure and function in the 1950s. During the late 20th century, genetic biology gained significant momentum due to groundbreaking advancements in DNA reading and writing technologies.

1.1 Programming Biology with SynBio

SynBio today is predominantly a maker movement (Roosth, 2017) that encourages the active rewriting of biology to gain a deeper understanding of its mechanics. Its evolution has been surprising. Since its emergence in 2006, SynBio has become the fastest-growing technology in human history. SynBio continues to grow exponentially at a staggering rate of 10 times per year, far outpacing the growth of computer technology (Church 2014). This field employs cutting-edge techniques that enable us to design, edit, and engineer diverse living organisms. The remarkable advancements in SynBio have enabled humanity to create a plethora of revolutionary products, including lab-grown meat, bio-grown leather, synthetic milk, wood, fertilizer-free plants, alternative fuels, fragrances, fabrics, novel pharmaceuticals, mRNA vaccines, and even age-reversal techniques. These developments accelerated our comprehension of making genetic techno science (Zwart 2022); however, our understanding of its potential design impact is still in its infancy.

1.2 The Industrialization of our Biosphere

While biology transitioned from nature to laboratories in the 20th century, our industrial production dramatically reshaped the planet. Recent reports from the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Environmental Program (UNEP) warn that critical thresholds in Arctic Ocean warming are nearing (UNEP, 2019). These reports highlight impending tipping points with dire outcomes: ocean acidification, rising sea levels, and permafrost thawing (Schoolmeester, 2019 & Masson-Delmotte, 2018). The paper challenges architects' reliance on incremental industrial fixes for climate change and advocates biology as a transformative solution. Emphasizing a new era in biotechnology also implies reimagining space at a planetary scale to effectively address the conclusions of the IPCC and UNEP.

2 The Technology for Building with Biology

We think there are two generations of possible tactics for the future of Synbio in construction. There is an emerging number of startups developing lab-grown products that already replacing existing materials. However, we think that the real potential of Synbio will involve soon a more advanced narrative of engineered living materials that will allow infrastructures to grow locally and around the world.

2.1 Biomaterials

The first wave of changes is associated with the rapid emergence of lab-grown materials, offering a promising alternative to conventional building resources. These biomaterials involve integrating living cells into a non-living matrix, often genetically engineered for specific traits. They display impressive qualities such as self-assembly, self-repair, and responsiveness to environmental changes. These products target enhanced sustainability, localized distribution, and adherence to regulatory procedures akin to traditional construction items. Companies like BioMASON, Ecovative, Biohm, MycoWorks, Lingrove, Inventwood, Wooddoo, Modernmeadow, Tomtex, and Vitrolansinc are using various methods to grow materials in lab settings such as bio-concrete, bio-bricks, lab-grown wood, and leather, without the need for traditional manufacturing methods. These bio-replacement projects have great value; however, one can speculate that the pace of technology development suggests that the field will develop in a more ambitious direction.

2.2 Advanced Living Systems for Material Science

A secondary perspective for SynBio in construction involves engineering fresh living materials orchestrated to exhibit emergent properties and accelerated growth. Engineered Living Materials (ELM) has gained prominence as a well-funded research initiative over the last five years. DARPA has notably backed an ELM program since 2016, envisioning the on-site growth of living materials, responsive to their surroundings and capable of self-healing (Darpa, 2016). Numerous authors have conducted extensive reviews and created taxonomies summarizing projects in this innovative direction (Nguyen, 2018; Gilbert, 2018; and Srubar, 2020). This emerging SynBio generation is poised to transform human space design, enabling on-site habitat growth by delivering bio-ingredients and ecosystems.

2.3 Programmable Matter

A Third era emerges as we design wetware, a bio-matter made of designed of cells that can grow and repair themselves. We employ the term “programmable bio-matter” as an analogy to the concept of “programmable matter” used in computer science, denoting amorphous material that can be coded and manipulated. Early instances of “programmable matter” in computing are projects such as Claytronics, M-blocks, and Computronium, which often envision minuscule robots that assemble and disassemble. However, we contend that biology offers a more intricate means to manipulate matter at the atomic-level matter, given that all living organisms consist of programmed biological material. Current SynBio editing techniques, such as CRISPR or TALENs, are expected to evolve and give way to more versatile methods. Later in the paper we elaborate on the work by the Levin lab at Tufts University and the use of biobots and bioelectricity as novel ways to organize biological matter in space (Levin, 2018).

3 Design Discourses about Building with Biology: from materialism to envisioning

Architecture typically does not directly participate in the basic research tiers that construct the SynBio investigations presented in the previous section. Nevertheless, as consumers of techno-science, Architects repurpose material engineering in research and practice. We think that there are at least three design tactics. The first discourse involves critically engaging with today's first-generation bio-materials (Benjamin, 2018). A second approach supports real-system design experiments in a novel Building Science from an architectural perspective, focusing on understanding through synthesis (Dade-Robertson, 2016). A third option ventures into hypothetical explorations—the fiction of Synbio. While SynBio enterprises pursue various technical paths, the wider population will increasingly encounter artificial biology as a consumer phenomenon in life experiences, between what Jean Baudrillard refers to as reality, simulacra and simulation (Baudrillard, 2005; Baudrillard, 1994). So the design of those bio-experiences is significant. The SynBio researchers we engaged emphasized that we develop an understanding beyond technology. Architecture plays a vital role in envisioning and imagining and we chose to focus on that path. Central to our work was the imperative to grasp the biological processes of growth present in morphogenetics within a spatial framework.

3.1 Jean Baudrillard, Envisioning, and Zeitgeist

Jean Baudrillard in his book “The Systems of Objects,” focuses on understanding reality as a consumption schema surrounding object-signs that defined mid-20th-century life in the developed West (Baudrillard, 2005). He contends that these object-signs surpass mere reflections of reality; rather, the manner in which we consume these signs actively contributes to shaping our reality. In “Simulacra and Simulation,” he elaborates upon this notion, asserting that signs play an active role in molding reality through four stages: reflecting, masking, evolving into detached simulacra, and culminating in “hyperreality” (Baudrillard, 1994). Baudrillard argues that postmodern Western society resides in the “hyperreality” stage, where signs have taken center stage in the creation of meaning.

One could argue that every major innovative period brings forth a design paradox, following the stages of reality and simulacra proposed by Baudrillard. Generally, within design fields, imagining new eras or the zeitgeist (the spirit of its time) proves challenging. In the first stage of a new technological advance, strong references to the immediate past are evident. For example, when automobiles first emerged, they resembled their direct predecessor, the horse carriage. However, over time, the car evolved, reinventing itself every one or two decades. In the 1950s, it embraced the curves of planes, and today, the experience of electric car projects by companies like Tesla, Lucid, and Nio are merging automobiles with the evolving digital media signs. In architecture, we also grapple with this paradox. Will our architectural design imagination in this new era merely involve substituting elements of our contemporary buildings and cities? In our work, we propose that the ultimate zeitgeist of the SynBio era will revolve around weaving our bodies into "pure experiences" within our biosphere (inspired by the epistemic notion of experience pioneered by philosophers William James and Kitaro Nishida). Imagination remains crucial. The subsequent pages detail some of the projects we developed.

3.2 First Generation of SynBiological Hyperreality: Bio-Food

The first generation of SynBio products (2006-2026) is highly focused on developing viable industrialized biology. For instance, in the food industry, one notable success story has introduced viable plant-based and lab-grown meats, now widely available in the United States. Companies like Impossible Foods, the Not Co., GOOD Meat, and UPSIDE Food create products imitating and replacing conventional foods. Yet, if proteins are capable of assuming any taste or form, why should food be constrained to imitating traditional burgers, bacon, or steaks? Can we redesign food beyond contemporary norms, even altering culinary preparation and social consumption? In our work, we have explored edible buildings—reimagining surfaces with bio-coatings of engineered bacteria to cleanse dirt, neutralize toxins, and detect pathogens.

Food scarcity also affects numerous species, notably dwindling Arctic mammals. In our studio we developed a project for the Arctic Polar Bears, which are encountering increasing food supply shortages and are increasingly resorting to cannibalism to survive. As the impacts of Arctic warming continue to unfold (UNEP, 2019), in conjunction with the emergence of the biotechnological era, our project envisions a “hyper biological reality” that examines the dynamics between humans, wild mammals, plant species, and other biological organisms.

Figure 1. The emergence of lab-grown food in various new forms and consistencies may lead to “hyperreality” in our nutritional experiences. These forms include bio-foods resembling parts of chicken or other familiar dietary components (left), proteins presented in sugar-like forms (center), and abstract spherical shapes (right). Source: Images by the author.

3.3 Desalinization and Sea-Level Stabilization Towers

In our work, we visualize growing large-scale bio-infrastructures capable of absorbing and retaining seawater, similar to sponges and cacti. Utilizing SynBio, we could cultivate desalination towers worldwide (see figure 2). These bio-towers could potentially absorb excess seawater from melting ice sheets and glaciers, helping to stabilize sea level rise. With the ability to manipulate and reshape coastal regions, these sponge towers could incorporate bioreactors and various infrastructures, yielding local sources of food, energy, and raw materials. The Miami desalination tower project is an infrastructure capable of absorbing around 6 million cubic feet of seawater. The design's growth is based on voxels of calcium carbonate that are arranged in Semper knot structural formations as a byproduct of cyanobacteria circuitry. These sponge towers could serve as a sea-level stabilization strategy for the planet. If we gradually establish these infrastructures to absorb the excess seawater, it will be theoretically possible to maintain our current sea levels.

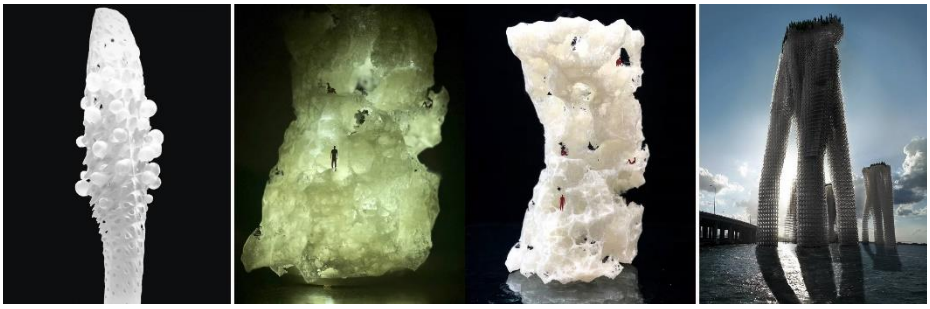

Figure 2. Desalination and retention towers in Miami's Biscayne Bay that integrate growth-through-aggregation methods. Projects by Alison Tapia (left), Rosanna Rodriguez (center), Renzo Lopez (left). Alfredo Andia Design 8 Studio, FIU, Spring 2018 and Spring 2019.

The primary bio-material constituting the towers is re-engineered cyanobacteria. Cyanobacteria life forms in the sea, such as Prochlorococcus, algae, and oceanic plankton, are responsible for producing between 50% to 80% of the planet's oxygen. When cyanobacteria die, they can form living rocks in the ocean, akin to the Precambrian stromatolites. A laboratory led by Wil Srubar at the University of Colorado Boulder has already developed bio-concrete using 'synechococcus' cyanobacteria (Heveran, 2020). This bio-concrete exhibits exponential growth and reproduction. For example, by dividing a brick made of this biomaterial into smaller parts while the cyanobacteria are alive, each segment can regenerate into a complete brick within hours. Through the redesign of biological circuitry with cyanobacteria in shallow waters, we could capture excess CO_2 from the atmosphere and create entirely new islands and buildings from cyanobacteria bio-cement in just days. The only requirements are water and redesigned cyanobacteria.

3.4 Bio-Strings and Bio-Fibrous Structures

Naturally produced Spider silk stands out as one of the Earth's most robust materials, surpassing even steel and Kevlar in strength and durability. A growing number of startups, like Spiber, Fibroheal, and Bolt Treads are developing textile-based materials that are similar to synthetic spider silk within their laboratories. The question remains: when will synthetic textiles find its place in architecture? In the realms of art, design, and architecture, our familiarity with string structures remains quite limited.

Figure 3. Cultivating a string structure responsive to both tension and compression through the principles of reaction-diffusion. Project by Maria Perez and Richard Salinas (Alfredo Andia Master Project Studio, FIU, Spring 2021).

Within our studios, we immersed ourselves in the study of synthetic spider silk piping structures and enclosure/façade systems. Figure 3 showcases our utilization of reaction-diffusion and noise offset techniques to shape string-based forms tailored for architectural settings. The growth process facilitates the creation of continuous channels capable of collecting, transporting, and storing nutrients within the structure as plants and trees do in natural settings today.

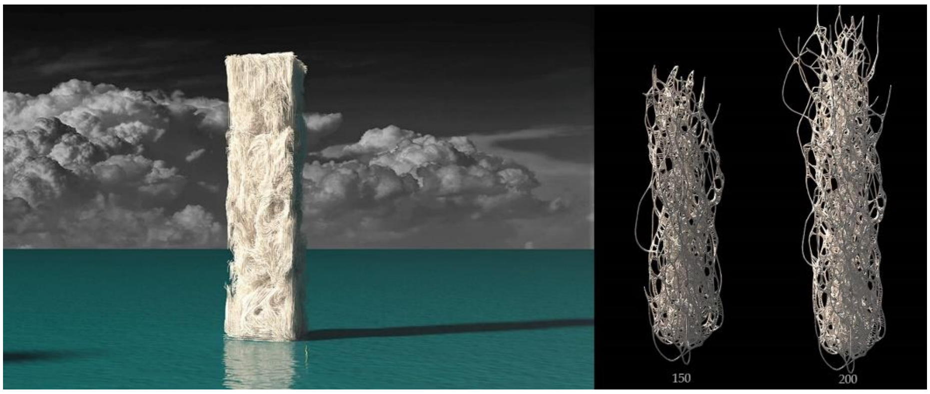

Figure 4. A habitat tower that grows as an ecosystem in the safety valve are in Stilsville, Florida. It evolves through diverse methodologies like curl noise, recursive expansion, and DNA plexus (right image) and develops as fibrous façade above the shallow waters of the bay. Project by Bryan de la Cruz and Juan Moreno (Alfredo Andia Master Project Studio, FIU, Spring 2021).

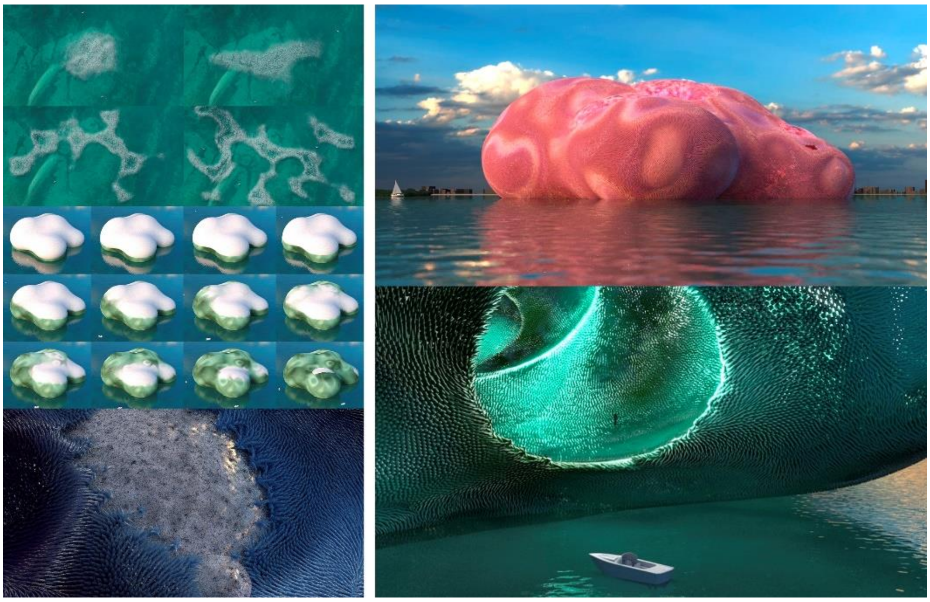

Figure 5. An island/concert hall with a fibrous façade that grows at the Biscayne Bay. Project by Carmen Alvarez and Steve Rivera (Alfredo Andia Design 8, FIU, Spring 2021).

In addition, a series of fibrous-based skin habitats were developed based on the ability of fibrous infrastructures to capture CO_2 from the air. These fibrous structures can be infused with synthetic micro-fluidics, akin to those pioneered by Tobias Erb at the Max-Planck Institute. This augmentation enhances carbon sequestration using synthetic chloroplasts, several orders of magnitude more efficient than natural chloroplasts found in plants (Miller et al., 2020).

Figure 4 presents a fibrous façade of a housing facility in the Stilsville area of Florida. The work employed growth processes such as curl noise, recursive growth, and DNA plexus. Figure 5 depicts an island/concert hall emerging from the shallow Biscayne Bay. The surface features synthetic biological fibrous organisms capturing CO2, generating energy, and providing dynamic illumination. The fibrous skin is an advanced iteration of the glowing nanobionics plants developed at MIT's Strano Research Group (Lew et al., 2020). Plant nanobionics integrate nanotechnology and plant biology, imparting novel functions like a high-bandwidth plant-technology interface for real-time monitoring. We foresee façade systems with a plant-based communication network, benefiting environmental solutions, ensuring food security, enabling energy applications via biofuel cells, and potentially replacing conventional electronics.

3.5 Bio-Matter and Biobots

We have also explored the concepts of Bio-Matter, as described in section 2.3 above. In visual fiction, the T-1000 shapeshifting android from the movie Terminator 2 serves as a dramatic representation of programmable matter. The T-1000 is depicted as a liquid metal nanorobotic substance, a malleable form that has been a long-standing aspiration in computer science. Its latest version includes a ductile material with viscoelastic properties, manipulated by tiny magnetic particles (Sun et al., 2022; Wang et al., 2023). An organism in our biosphere that bears biomechanical resemblance to the T-1000 is physarum polycephalum, also known as the true slime or many-headed slime mold. These diverse ameboid organisms are found across various phyla in the Protista kingdom. They exhibit advanced cooperation skills, beginning as single-celled microbes and later merging to optimize food location. Their behavior offers innovative principles for bio-computing (Adamatzky et al., 2012).

Another example of computable bio-matter is the biobot project called Xenobots, developed at the Levin lab at Tufts and the University of Vermont (Kriegman et al., 2019). These tiny living robots, under 1 millimeter in size, consist entirely of cellular material. They are novel lifeforms programmed to perform specific tasks. Constructed from frog skin and heart cells, their patterns are designed using an evolutionary algorithm. The most suitable configurations, after about 100 test runs, become a new life form. These cells possess high emergence intelligence, enabling them to construct complex bodies, heal, exhibit cooperative behavior, but cannot reproduce (Blackiston et al., 2021).

Biobots, such as Xenobots referenced above, raise fundamental ethical, philosophical, and biological questions, but for us, it has been a catalyst to rethink design (Levin, 2020). They signal the emergence of agent-driven bio-matter. All living organisms are composed of programmed biological matter. In our studios, we envision a future with a type of generic bio-matter—a highly intelligent biological entity made of living cells capable of bio-computation, data storage, retrieval, and DNA-encoded data processing. We experimented with bio-matter utilizing form-finding workflows through recursive growth (figure 6). One group studied façades employing recursive growth bio-matter, propagating based on solar radiation and structural stiffness. Other works have used bio-matter to grow skin structures over scaffolding made from fast-growing shrubs that dissolve over time.

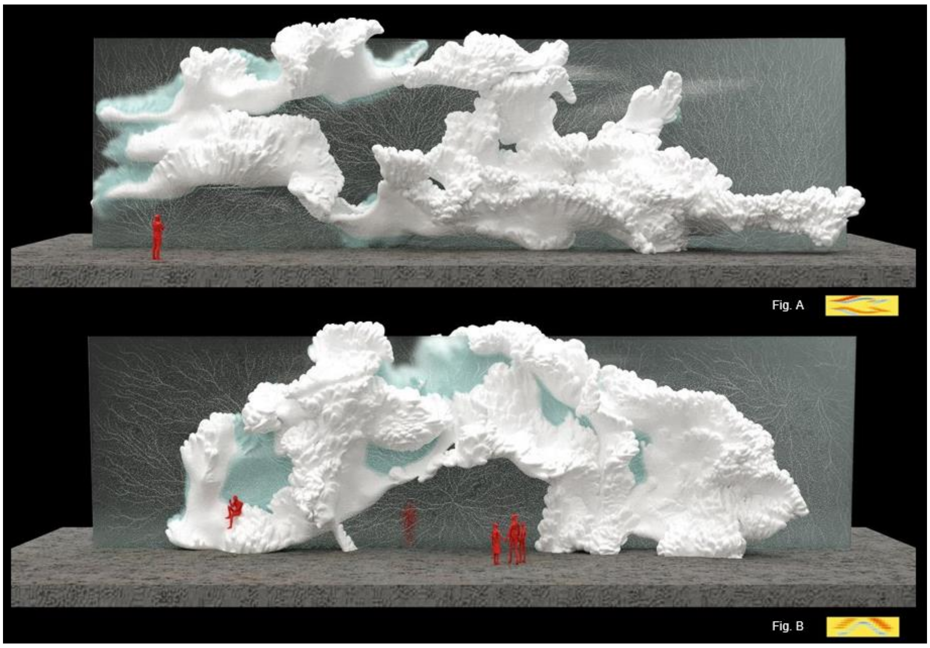

Figure 6. Programmable Bio-Matter. A series of walls designed that react to stiffness and solar radiation levels and wind forces of the site. Project by Maria Perez and Richard Salinas (Alfredo Andia Master Project Studio, FIU, Spring 2021).

4 Conclusion

The integration of emerging SynBio technology with architectural design is still in its early stages. We emphasize that this technology is unfolding in three phases: 1) Lab-grown construction products; 2) Engineered living materials that challenge material science by expediting large-scale infrastructure growth; 3) Biologically programmable bio-matter achieved through more plastic methods that are not fully mature yet such as bio-electricity and biobots. In this paper, we inquire about where architectural thinking should reside. We observe architects innovating with novel biomaterials like mycelium, lab-grown wood, and bio-cement. An increasing number of architects and engineers actively partake in research, grant proposals, and establish important startups in this realm. In our presented work, we opt for a different epistemic domain from the traditional architect-construction-material science nexus. We use Jean Braudilliar's analysis to observe that consumption rather than production is the main driver of the construction of reality (including simulation, simulacra, and hyperreality), extending beyond mere technological material substitution. So in our approach, we propose that the next plateau of SynBio is envisioning, fiction, not just the technology production that could act as as material bio-replacement. Fiction can be a taboo in architecture. However, it has also served as a springboard for significant narratives in architectural history, spanning from early modernists and Russian constructivists to metabolists, and encompassing practices like Archigram, Archizoom, and Haus-Rucker-Co. A transformational platform like Synthetic Biology necessitates architects, designers, and artists to challenge not only biomaterials but also the broader vision of the field.

References

Roosth, S. (2017). Synthetic: How life got made. University of Chicago Press.

Church, G. M., & Regis, E. (2014). Regenesis: how synthetic biology will reinvent nature and ourselves. Basic Books.

Zwart, H. (2022). Continental philosophy of technoscience (p. 245). Springer Nature.

UNEP. (2019). Temperature rise is ‘locked-in’ for the coming decades in the Arctic. UN Environment, Press release: Nairobi, March 13, 2019. Retrieved May 30, 2021, from: https://www.unep.org/news-and-stories/press-release/temperature-rise-locked-coming-decades-arctic

Schoolmeester, T., Gjerdi, H. L., Crump, J., Alfthan, B., Fabres, J., Johnsen, K., & Baker, E. (2019). Global linkages—A graphic look at the changing Arctic. Nairobi and Arendal: UN Environment and GRIDArendal.

Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P. R., & Waterfield, T. (2018). Global warming of 1.5 C. Intergovernmental Panel on Climate Change (IPCC).

DARPA. (2016). Living Structural Materials Could Open New Horizons for Engineers and Architects. Retrieved May 30, 2021.

Nguyen, P. Q., Courchesne, N. M. D., Duraj-Thatte, A., Praveschotinunt, P., & Joshi, N. S. (2018). Engineered living materials: prospects and challenges for using biological systems to direct the assembly of smart materials. Advanced Materials, 30(19),

Gilbert, C., & Ellis, T. (2018). Biological engineered living materials: growing functional materials with genetically programmable properties. ACS synthetic biology, 8(1)

Srubar III, W. V. (2020). Engineered living materials: taxonomies and emerging trends. Trends in Biotechnology.

Levin, M., & Martyniuk, C. J. (2018). The bioelectric code: An ancient computational medium for dynamic control of growth and form. Biosystems, 164, 76-93.

Benjamin, D. (2018). Now we see now: architecture and research by The Living. The Monacelli Press.

Dade-Robertson, M. (2016). Building Science: Synthetic Biology and emerging technologies in architectural research. arq: Architectural Research Quarterly, 20(1), 5-8.

Baudrillard, J. (2005). The system of objects (Vol. 3). Verso.

Baudrillard, J. (1994). Simulacra and simulation. University of Michigan press.

Heveran, C. M., Williams, S. L., Qiu, J., Artier, J., Hubler, M. H., Cook, S. M., ... & Srubar III, W. V. (2020). Biomineralization and successive regeneration of engineered living building materials. Matter, 2(2), 481-494.

Miller, T. E., Beneyton, T., Schwander, T., Diehl, C., Girault, M., McLean, R., ... & Erb, T. J. (2020). Light-powered CO2 fixation in a chloroplast mimic with natural and synthetic parts. *Science*, *368*(6491), 649-654.

Lew, T. T. S., Koman, V. B., Gordiichuk, P., Park, M., & Strano, M. S. (2020). The emergence of plant nanobionics and living plants as technology. *Advanced Materials Technologies*, *5*(3), 1900657.

Wang, Q., Pan, C., Zhang, Y., Peng, L., Chen, Z., Majidi, C., & Jiang, L. (2023). Magnetoactive liquid-solid phase transitional matter. Matter, 6(3), 855-872.

Kriegman, S., Blackiston, D., Levin, M., & Bongard, J. (2020). A scalable pipeline for designing reconfigurable organisms. Proceedings of the National Academy of Sciences, 117(4), 1853-1859.

Adamatzky, A., Erokhin, V., Grube, M., Schubert, T., & Schumann, A. (2012). Physarum chip project: growing computers from slime mould. Int. J. Unconv. Comput., 8(4), 319-323.

Blackiston, D., Lederer, E., Kriegman, S., Garnier, S., Bongard, J., & Levin, M. (2021). A cellular platform for the development of synthetic living machines. Science Robotics, 6(52), eabf1571.

Levin, M., Bongard, J., & Lunshof, J. E. (2020). Applications and ethics of computer-designed organisms. Nature Reviews Molecular Cell Biology, 21(11), 655-656.