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Xenophylum
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DOI 10.1162/ANTI.5CZL 1/18

Xenophylum
Towards a Synthetic Cambrian Explosion

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Abstract

This paper argues for a conceptual shift from biomimicry to xenomorphology in design, proposing a "synthetic Cambrian explosion" driven by techniques such as machine learning, robotics, and synthetic biology. Building on theoretical foundations from Bernard Stiegler's notion of exosomatic evolution, mimetic theories, and assembly theory (developed by Michael Levin, Lee Cronin, and Sara Walker), we show how design has historically aligned with natural forms—a trend we term generalized biomimesis. While this biomimetic paradigm has yielded significant innovations, it constrains creativity by reinforcing nature as a universal model and moral ideal. By contrast, xenomorphology invites designers to explore genuinely alien morphologies unbound by terrestrial adaptation. Drawing on exemplars from the field of evolutionary computing, we argue that computational platforms and modular assembly enable vast new "morphospaces" decoupled from Earth's evolutionary constraints. Ultimately, such a shift paves the way for new forms of anti-fragile design, where emergent resilience and novel behaviors come together to formulate new conceptions of intelligence and adaptation. Embracing xenomorphology opens a radical reimagining of design practice—one with the potential to shape the future of lifelike systems and our evolving relationship with technology.

Keywords

assembly theory (AT); morphogenesis; synthetic biology; evolutionary computation; sustainable design; biomimicry; modular robotics; artificial life; mimetic theory

1 Introduction

Humans are technical beings. While Clifford Geertz is correct in saying that our species compensates for its structural incompleteness through culture, it is unmistakable that we do so through technology as well.[1] As intellectual historian David Bates has argued, there has never been a purely natural human intelligence to oppose artificial forms of intelligence.[2] Early philosopher of technology Ernst Kapp described this process of agency's extension through technology as "organ projection."[3] In turn, Marshall McLuhan emphasized how technology extends the human senses beyond the individual and influences our cognitive life.[4] Such perspectives remain entwined with posthumanist views concerning the integrity of the human.[5] Put differently, in Bernard Stiegler's reading of Alfred Lotka, humanity is "exorganismic": not a sealed biological whole but a species whose capacities and evolutionary trajectory expand through technical instruments—from the simple act of writing to the most complex technological tools. In the Stieglerian reading, exosomatic evolution separates humanity from other species involved in processes of biological and genetically determined evolution.[6] The motor of evolution moves from the natural environment to the technical one: what kinds of technologies—from telescopes to toothpicks—can we deputize to better fulfill functions previously unique to biology?

This paper proposes a framework for explaining humanity's original technicity to ask a speculative question about morphology, behavior, and design in terms of the future of biotechnical evolution. As René Girard and the cohort of thinkers working in the legacy of his ideas about mimetic theory have shown, prefigured by the theories of Gabriel Tarde, humanity is formed by an innate tendency toward mimicry.[7] Thus, sociotechnical innovations inevitably unfold in this predisposition. We have, for example, tended to reproduce the endosomatic operations of animals—their eyes, claws, wings, teeth, kidneys, immune systems, reproductive organs—in technical facsimiles. At present, this tendency unfolds as an invitation to designers to innovate under the aegis of frameworks such as sustainable innovation, which attempts to mirror the planet's "natural" patterns in technologies. We call this paradigm of innovation beginning from mimicry of nature *generalized biomimesis*.

Yet, we contend, humanity is fast approaching an inflection point in its technical evolution. On one hand, the biomimetic paradigm continues, urging us to align design with recognized natural forms. On the other hand, an emerging paradigm—xenomorphology—supplements rather than supplants biomimesis. By suggesting that nature is not an end point, a xenomorphological perspective repositions nature as a malleable reference point, rather than a sacrosanct telos. Drawing on recent work in assembly theory (AT), this paper proposes that what we have conventionally labeled the natural is in fact a cultural projection that enables biomimetic design—but that it is ultimately just one model among many.[8]

In an era of planetary-scale computation, a xenomorphic approach enables us to defamiliarize nature, recognizing artificial intelligences as part of a continuum of strange tools and innovations that stretches back to early hominization and extends to today's technology. Far from being an oddity, these abiotic morphologies may represent the next logical step in cutting-edge design. In describing the theoretical framework, principles, and design possibilities of such alien morphospaces, we introduce the concept of a xenomorphic phylum—or *xenophylum*—to encapsulate the range of generative forms that might arise when designers fully embrace the maximally alien within design. Here we might even speak of a broader *xenosphere*—an emergent domain in which technosphere meets biosphere in radically novel ways. This domain includes advancements in xenorobotics, where existing AI-driven physical morphologies—such as Tesla's Optimus—may be extended beyond strictly biomimetic precedents, expanding the horizon of how we conceive machines and their interplay with organic life.

2 Generalized Biomimesis

In examining nature-inspired innovation—often referred to as biomimetic design or "biodesign"[9]—we observe a fundamental inclination in creative processes that we term *generalized biomimesis*. While biodesign refers to the specific practice of emulating particular biological forms (e.g., modeling structures after plant leaves), generalized biomimesis captures the broader human drive to treat "nature" as a guiding telos in design. This phenomenon reaches back into ancient thought. Plato identified mimesis as a core way that human beings relate to reality.[10] Girard's mimetic theory further describes how desire, agency, and cultural production are profoundly shaped by processes of imitation—whether of real others or of aspirational models.[11] If *mimicry* implies the imitation by an agent of the appearance, behavior, or other characteristics of another agent for survival benefits—such as avoiding predators or

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[1] Geertz, *Works and Lives*.
[2] Bates, *Artificial Intelligence*.
[3] Kapp, *Elements of a Philosophy*.
[4] McLuhan, *Understanding media: The extensions of man*.
[5] Hayles, *How We Became Posthuman*.
[6] Stiegler, *Technics and Time, 1*.
[7] Girard, *Violence and the Sacred*; Dupuy, *Mechanization of the Mind*; Mormino, *Per una teoria*; Palaver, *René Girard's Mimetic Theory*.
[8] Cronin et al., "Assembly Theory."
[9] Polites, *Sustainable Design*; Pawlyn, *Biomimicry in Architecture*.
[10] Belfiore, "Theory of Imitation."
[11] Girard, *Violence and the Sacred*; Blanchard, *Dynamics of Mimesis*.

attracting mates—mimesis, instead, involves a more creative, interpretive, and conscious process by a human agent.[12] In the context of design, such mimetic impulses lead us to look toward nature as the ideal model, projecting our values of purity, sustainability, and authenticity onto the biosphere.

An illustrative example is humanity's long-standing aspiration to master flight. From Daedalus's wax wings for Icarus to Leonardo da Vinci's wing sketches, early conceptions of human flight were directly inspired by the apparent solutions that birds offered to the problem of gravity. While simply observing birds did not yield modern aeronautics, it established nature as a symbolic reference for flight: as both a functional challenge and an aesthetic goal. As Francis Bacon already argued in *Novum Organum*, "Nature, to be commanded, must be obeyed."[13] In Girardian terms, however, nature here serves as a model mediating the human subject's pursuit of a technological object.[14] Over time, such symbolic associations with the biosphere have become deeply linked to an ethical preference for the "natural," arguably taking root in what philosophers have termed the "naturalistic fallacy"—the conflation of the natural with the morally good.[15] This fallacy has been widely criticized since "On Nature" by Mill.[16]

Drawing from the Cornelius Castoriadis's interpretation of the imaginary construction of societies,[17] it can be argued that nature itself operates as an imaginary signification: an abstraction we invest with cultural meaning that shapes how we conceive design and technology. By defining nature negatively—"everything that is not perceived as artificial"—we gloss over how fragile the boundary truly is between bios and techne.[18] The posthuman turn, fueled by developments in AI and genetic engineering, continues to blur the lines between organic and synthetic. Still, a persistent cultural assumption holds that the more "natural" a thing is, the more ethically superior it must be.

Such thinking undergirds contemporary concerns surrounding ecological sustainability. Biomimetics, whether in architecture, water purification, or materials science, enjoys a halo of moral authority because it draws on a seemingly timeless, "primordial wisdom" of nature.[19] Nevertheless, as Julian Vincent and colleagues[20] have demonstrated, it is undeniable that design based on biomimetic principles has led to the development of several significant and successful devices and concepts over the past fifty years. At the end of the 1990s, indeed, the connection between biomimesis and sustainability became more established. Biomimesis is still *generalized* today: We continue to look to nature—the *bios*—as the primary model to imitate, implicitly accepting the axiom that the more natural a thing is, the healthier, cleaner, and more sustainable it will also be. Yet the extent to which these principles actually hinge on genuinely ecological patterns—rather than cultural ideals about what nature ought to be—remains open to debate.

Thus, *generalized biomimesis* is both a testament to humanity's deep-seated mimetic impulses and a reflection of our cultural investment in nature as a moral and aesthetic ideal. Its efficacy in propelling certain types of sustainable innovation is undeniable. But, as posthumanist thought highlights, our shifting understandings of life—organic or otherwise—compel us to question whether nature should remain the central, or exclusive, prototype for design. If we can move beyond nature's symbolic authority, we may unlock new avenues for invention that neither cling to nor outright reject the bios but incorporate the alien and synthetic on more imaginative terms.

3 Engineering a New Cambrian Explosion

Is it possible for designers to move beyond merely imitating the functional behaviors of biological life—that is, beyond a strictly biomimetic paradigm—and to, instead, create a new xeno-evolutionary environment populated by hybrid artificial and natural forms? We propose that technological developments are positioning us on the brink of what may be termed a synthetic Cambrian explosion, echoing the rapid diversification of species about 540 million years ago. Notably, in this contemporary instance, the driving forces behind evolution need not be genetic. Instead, they can be engineered through modular and combinatorial design principles, unleashing novel capacities and behaviors unbounded by the adaptive latency of organic evolution.

3.1 Xeno-Design via Evolutionary Techniques

One of the most compelling arenas for this diversification is virtual space, particularly through approaches driven by techniques in artificial life (ALife) and evolutionary computation (EC), which feature deeply fertile environments that allow for forms unconstrained by biological path dependency. Systems within ALife and EC solve optimization problems using approaches (e.g., genetic algorithms, differential evolution, particle swarm optimization, ant colony optimization) loosely derived from human understandings of biological evolution. As shown in Figure 1, such systems solve problems by treating

[12] Hui, *Recursivity and Contingency*.
[13] Bacon, *Novum Organum*.
[14] Cerella, "Until the End."
[15] Moore, *Principia Ethica*.
[16] Mill, "On Nature."
[17] Castoriadis, *Imaginary Institution*.
[18] Braidotti, *Posthuman Knowledge*.
[19] Benyus, *Biomimicry*.
[20] Vincent et al., "Biomimetics."

DOI 10.1162/ANTI.5CZL

potential solutions as individuals within a population. Solutions are generated and selected for via a simulated ecosystem consisting of (1) a data-structure-based representation of the solution (the genotype), (2) a way of converting the genotype to a format (the phenotype) suited to the given problem (e.g., the 3D model of a protein), (3) a way of measuring the fitness of the representation according to the problem space, and (4) a logic to handle solution selection ("reproduction") and variation ("mutation") within the population.[21] In this way, "the creativity of evolution need not be constrained to the organic world. Independently of its physical medium, evolution can happen wherever replication, variation, and selection intersect."[22]

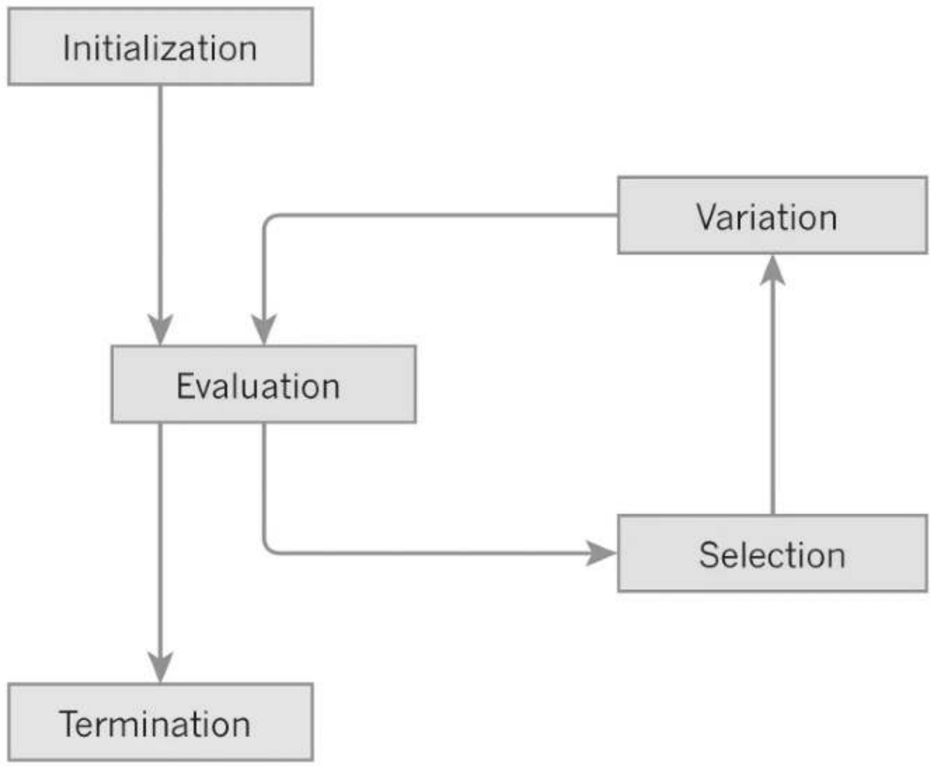

Figure 1 Evolutionary algorithms typically follow an optimization process that consists of seeding the system with random genotypes, evaluating the resulting phenotypes according to a fitness function, introducing subsequent variation, and iterating until a certain stopping condition is met. Source: Eiben and Smith, "From Evolutionary Computation."

The evolutionary approach has been found to be particularly useful for discovering solutions in problem spaces where absolute optimization is second to obtaining a menagerie of approximate solutions, or where the potential search space is simply too vast for individual human comprehension and manual optimization. EC techniques have been co-opted and applied in spaces as diverse as machine learning, design space exploration, computer vision, computer graphics, and robotics. Indeed, the output of such systems seems to have no limit in terms of form or function. Practitioners have leveraged EC to produce better neural networks, decision trees, and machine learning (ML) models,[23] improve protein structure estimation,[24] optimize 2D and 3D geometries,[25] design controls for mechatronic systems,[26] and produce novel evolutionary physical designs,[27] and robotic forms and behaviors.[28] In the pursuit of xenomorphological design that goes beyond biological precedent, we find the latter set of scenarios most relevant for further discussion. To speculate on the xenomorphic and xenobehavioral potential of generative computation, it can be helpful to review instances of existing work that has successfully produced unconventional, yet bioderived attributes and behaviors. Such exemplars may serve as a useful jumping-off point for further extrapolation.

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21 Eiben and Smith, "From Evolutionary Computation."
22 Lehman et al., "Surprising Creativity," 275.
23 Yao, "Evolving Artificial Neural Networks"; Barros et al., "Survey of Evolutionary Algorithms"; Telikani et al., "Evolutionary Machine Learning."
24 Widera et al., "GP Challenge"; Lei et al., "MO4."
25 Arias-Montano et al., "Multiobjective Evolutionary Algorithms."
26 Alattas et al., "Evolutionary Modular Robotics."
27 Sawada et al., "Evolutionary Generative Design."
28 Nolfi and Floreano, Evolutionary Robotics.

DOI 10.1162/ANTI.5CZL

3.1.1 Karl Sims's Evolutionary Morphologies

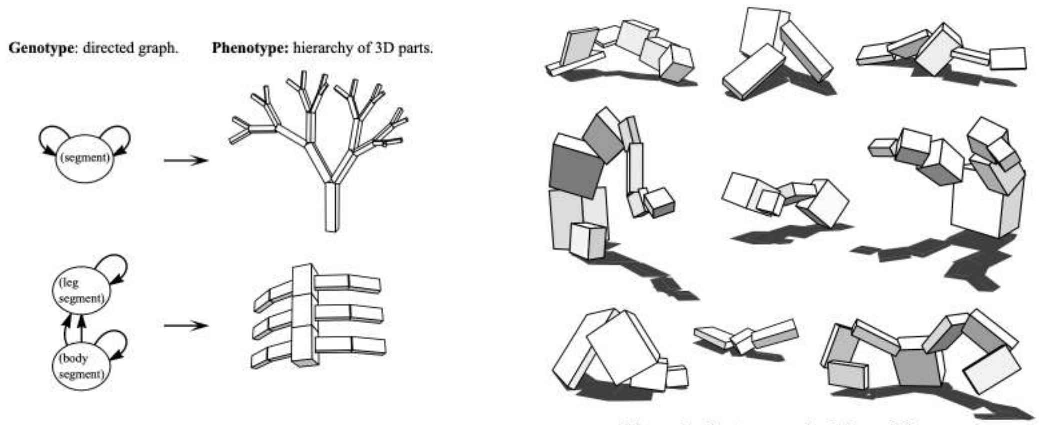

Figure 2 Left: How creature embodiments are represented as directed acyclic graphs in Sims's 1994 work. Right: Creatures evolved for walking. Source: Sims, "Evolving Virtual Creatures."

Karl Sims, a researcher who works between the arts and the sciences, is often considered a pioneer within EC. His 1994 seminal paper, "Evolving Virtual Creatures," is one of the foremost attempts to coevolve control systems alongside creature morphologies in silico. Though the original work was conducted within the space of computer graphics, it has gone on to inspire myriad derivative efforts in computational art, graphics and animation, evolutionary robotics, and ALife.[29] In his work, Sims leveraged a graph-based genotype to generate and evolve the physical traits and capabilities of populations of simulated block creatures. Organisms were tasked with achieving specific goals (e.g., swimming, crawling, following, competing) within various simulated environments. Those that scored well on task-specific fitness functions had their virtual genes copied, combined, and randomly mutated to spawn subsequent generations.[30] Over time, these "offspring" developed morphologies increasingly optimized to their assigned tasks, such as fins or jointed limbs. Echoing Charles Darwin's famous claim that "from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved,"[31] Sims posited that his experiment created a "world-space" wherein "autonomous three-dimensional virtual creatures" navigate "a genetic language" in "an unlimited hyperspace of possible creatures."[32] This digital ecosystem illustrates, in miniature, how morphological evolution can be uncoupled from strictly organic principles and driven by computational and engineering imperatives without excessive human involvement.

Further attempts to build on Sims's work span the sciences as well as the arts. Nick Cheney and colleagues extended this foray into morphological evolution by evolving soft robot morphologies composed of various simulated materials.[33] Dan Lessin and Sebastian Risi similarly investigated evolving creatures with simulated skeletons and soft-body muscles.[34] Notably, the authors describe their efforts as having the goals of achieving "bio-mimetic realism in virtual creatures" while also exploring "life-as-it-could-be in the virtual world."[35] This echoes the spectral nature between biomimicry and pure xenomorphia we identify in this paper. Rarely is a design (particularly EC-derived works) purely xenomorphic. Rather, most works occupy a space between biomorphism and xenomorphism. In the arts and related fields, researchers have also leveraged similar genetic-algorithm-based techniques to evolve line drawings,[36] devise interactive evolutionary approaches to create swarm-based animations,[37] and create "genetic music,"[38] among other things.

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29 Cheney et al., "Unshackling Evolution"; Corucci et al., "Novelty-Based Evolutionary Design."
30 Sims, "Evolving Virtual Creatures."
31 Darwin, On the Origin, 425.
32 Sims, "Evolving Virtual Creatures," 22.
33 Cheney et al., "Unshackling Evolution."
34 Lessin and Risi, "Soft-Body Muscles."
35 Lessin and Risi, "Soft-Body Muscles," 604.
36 Baker and Seltzer, *Evolving Line Drawings*.
37 Khemka et al., "Evolutionary Design."
38 Biles, "GenJam."

DOI 10.1162/ANTI.5CZL

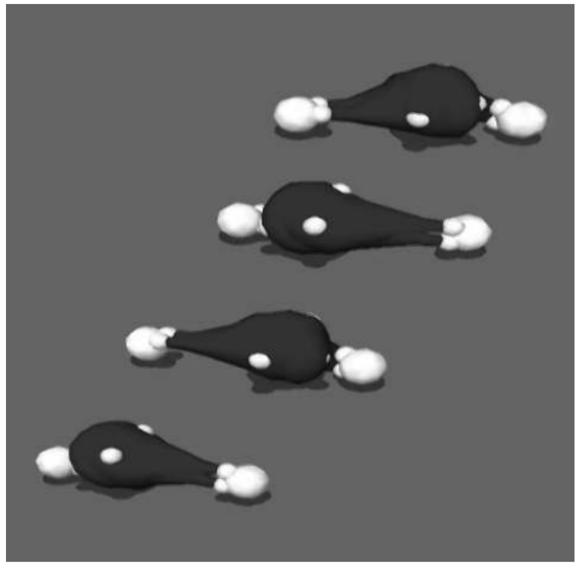

Figure 3 The locomotive technique of an evolved creature with both rigid/skeletal (white) and soft/muscle-like (red) body parts. Source: Lessin and Risi, "Soft-Body Muscles."

3.1.2 EC and Xenomorphic Traits

Moving beyond Sims, if we characterize xenomorphic forms and behaviors as those that diverge from existing biological pathways, then EC presents itself as a fruitful setting for investigation. In terms of moving beyond the constraints of the biological, EC practitioners have noted that evolution-inspired approaches are particularly notable for producing unconventional results that experts might have otherwise overlooked or disregarded. Joel Lehman and collaborators, in a 2020 paper titled "The Surprising Creativity of Digital Evolution," provide empirical evidence of "examples of how [researchers'] evolving algorithms and organisms have creatively subverted their expectations or intentions, exposed unrecognized bugs in their code, produced unexpectedly adaptations, or engaged in behaviors and outcomes, uncannily convergent with ones found in nature."[39]

Among these is a system that uses a "trial-and-error algorithm that enables robots to adapt to damage in less than two minutes in large search spaces without requiring self-diagnosis or pre-specified contingency plans."[40] In one scenario, a six-legged robot tasked with adapting to broken legs and motors was asked to evolve a gait in which none of its feet touched the ground—a task the researchers thought impossible to solve. The system, however, subverted the team's expectations by flipping the robot onto its back and having it walk on its elbows.[41] Such behavior is uncommon or, rather, often physically impossible for most organisms on Earth.

In a similar vein, Watson and colleagues' work evolving light-following steering behavior in physical robots resulted in locomotion that was both uniquely suited to their hardware setup and unintuitive for human designers.[42] Derived from Braitenberg's classic setup,[43] the robots employed two wheels, motors, and light sensors; steering behavior was dictated by how much a specific light-sensor reading was translated into driving speed for a specific wheel. Typically, engineers will drive the right wheel proportionally to the left light sensor, and vice versa, to direct such robots toward a goal. While attempting to evolve similar controls with digital evolution, however, Watson and colleagues found that the evolved robots drove toward the light source in surprising ways. "Some *backed up* into the light while facing the dark . . . Others found the source by light-sensitive eccentric spinning" (see Figure 4).[44] Interestingly enough, not only was the genetic search space related to spinning locomotion much larger than the traditional solution, but it was found that such spinning is actually better suited (with respect to the hardware) to driving at higher speeds, because trajectories can be easily adjusted on the fly.

[39] Lehman et al., "Surprising Creativity," 274.
[40] Cully et al., "Robots That Can Adapt," 503.
[41] See the demo video at Evolving AI Lab, "Behavior Performance."
[42] Watson et al., "Embodied Evolution."
[43] Braitenberg, Vehicles.
[44] Lehman et al., "Surprising Creativity," 289.

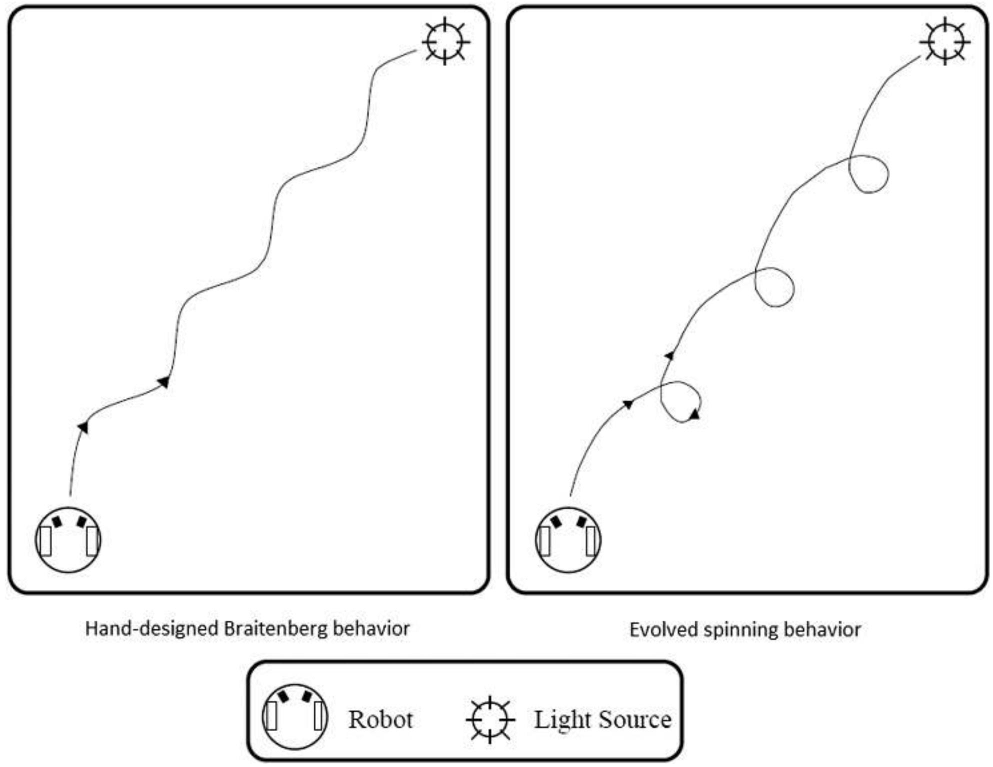

Figure 4 Steering behavior of Watson and colleagues' light-seeking robot. Left: The locomotion path of a robot employing the traditional Braitenberg approach of proportional left-right steering. Right: The path of a robot using evolved spinning locomotion. Source: Lehman et al., "Surprising Creativity."

These examples hint at the alternative path dependencies and capabilities evolutionary computational techniques are positioned to produce. Strictly speaking, neither Sims's creatures nor the unusual evolutionary results presented here were enacted with the explicit intention of creating strange, nonbiomorphic outcomes. However, Sims himself recognized a need for novel ways to architect and construct complex, intelligent systems, noting that "as computers become more powerful, the creation of virtual actors, whether animal, human, or completely unearthly, may be limited mainly by our ability to design them, rather than our ability to satisfy their computational requirements."[45] Given the serendipitous and divergent results observed, we suggest that such instances point to a potential space for intentional future exploration. EC has been leveraged as a vehicle for creating more efficient and optimal designs, recreating known designs, and searching through design spaces at paces faster than a human. Through the lens of the bio–xeno spectrum we propose in this work, why not also look to EC as a vehicle for producing fundamentally alien designs?

3.2 Xeno-Design via Machine Learning

If evolutionary approaches allow for forms unconstrained by biological path dependency, then the burgeoning field of GenAI, which combines EC with ML, offers to extend these capabilities even further. One recent example that echoes the spirit of this paper most closely is Tiwary and colleagues' research on generative visual intelligence (a field the authors dub "GenVI"). In their proposed road map, the authors outline a research agenda that leverages simulation and a combination of genetic and generative techniques to evolve sensing hardware and data-processing methods to craft a new breed of counterfactual visual intelligence. Such an approach, the authors posit, will help humans better understand the "environmental and biological factors that drive the emergence of specific aspects of an animal's morphology" and create "novel natural imaging systems and behaviors."[46] Echoing the sentiments in our framework, the authors reference the potential of GenAI to go beyond biological constraints: "While natural vision is a result of evolution and environmental constraints, we can use GenVI to *generate* new forms of vision."[47] Tiwary and colleagues also identify a set of high-potential directions for future investigation: leveraging LLMs to provide a design space (a list of symbols and rules for symbol recombination), searching through the design space via genetic algorithms, reinforcement learning, gradient-based methods, and GenAI-based latent space exploration (e.g., variational autoencoders, generative adversarial networks or GANs, and LLMs), and iterating on the results through simulation, learning, and selection.

[45] Sims, "Evolving Virtual Creatures."
[46] Tiwary et al., "Roadmap for Generative Design."
[47] Tiwary et al., "Roadmap for Generative Design," emphasis in original.

In a follow-up experiment, Kushagra Tiwary and colleagues also demonstrated the use of deep reinforcement learning in single-player games as a method for evolving vision systems in embodied agents. They showed that such simulation could deepen understanding of how environmental factors and specific tasks affect outcomes in eye morphology. In this instance, however, the goal was not to produce novel morphologies, but rather to "recreate the system-level process of vision evolution."[48]

On the whole, the combining of deep reinforcement learning with advancements in other avenues of ML has proven to be a rather popular approach to developing robotic controls.[49] However, many such works begin with bioinspired designs (e.g., anthropomorphic bipedal walking system, quadruped, hexapod, etc.) and often aim to optimize factors such as material cost, energy efficiency, or movement speed. As such, these explorations are somewhat tangential to the goals of generative exploration and counterfactual seeking that we emphasize here.

3.3 Xeno-Design via Material-Based Approaches

Finally, outside the realm of simulation, it is worth highlighting that recent work in modular and soft robotics also demonstrates traits that may be helpful in developing the paradigm of xenomorphology. Modular robotics, which concerns mechatronic systems composed of various cooperating units, has already demonstrated numerous creative examples of reconfigurable collectives working together to achieve a common goal—assemblages that we posit are xenomorphic in several aspects. As described by Alattas and colleagues in their review of the space, modular robotics promises to achieve "versatility, robustness, and low cost" by leveraging simple, reproducible modular components that can join together to form diverse assemblies. By applying evolutionary algorithms to this problem space, researchers are achieving configurations that are geared to "allow self-assembly from constituent modules, self-reconfiguration into different functional forms, self-repair to detect errors and recover from failures, and self-reproduce where one system can produce another autonomous functional system."[50] The resulting robots—reviewed extensively in works such as Alattas and colleagues and Yim and colleagues[51]—exhibit unconventional aesthetics, movement patterns, and affordances that, despite biomimetic origins, inherently diverge from biological norms because of the physical materials involved.

Chin and colleagues' AuxBots exemplify these characteristics through their use of the expansion and contraction of an auxetic shell to create shape-changing behavior and movement (see Figure 5).[52] In a similar vein, John Romanishin and colleagues' M-blocks are composed of self-reconfiguring cubic modules that bond through embedded magnets. Because the individual cubic modules can pivot on any one of twelve edges and contain internal actuators, the resulting observed behavior features various collective-driven obstacle traversal maneuvers, concave transitions, convex transitions, and translations.[53] Modules can also come together to form structures, as in Figure 6. While swarm behavior in nature might mirror some of this behavior, the particular manner in which such modular robots complete their tasks is unique in material, aesthetic, and overall locomotion. The wide range of human-designed morphological solutions exhibited by such works point to a vast design space unavailable to natural evolutionary pressures. Continued exploration with the help of, e.g., EC, might open up this space further. For these reasons, we look to work in modular robotics as sources of inspiration when considering the meaning of xenomorphia.

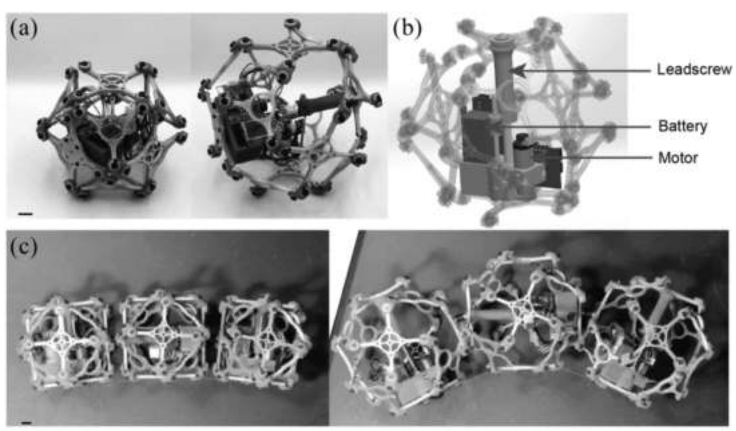

Figure 5 The AuxBots are composed of modules that expand and contract (a) to enable bending and forward motion when connected with wire constraints (c). Their individual make-up is shown in (b). Source: Chin et al., "Flipper-Style Locomotion Through Strong Expanding Modular Robots."

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[48] Tiwary et al. "What If Eye...," 3.
[49] Chen et al., "Deep Reinforcement Learning"; Kalimuthu et al., "Deep Reinforcement Learning"; Luck et al., "Data-Efficient Co-Adaptation."
[50] Alattas et al., "Evolutionary Modular Robotics," 818.
[51] Alattas et al., "Evolutionary Modular Robotics"; Yim et al., "Modular Self-Reconfigurable Robot."
[52] Chin et al., "Flipper-Style Locomotion Through Strong Expanding Modular Robots."
[53] Romanishin et al., "M-Blocks."

DOI 10.1162/ANTI.5CZL

Figure 6 A modeled progression of M-block modules traversing an obstacle (indicated by a black box). Source: Romanishin et al., "M-Blocks."

Beyond traditional rigid materials, researchers have also begun to investigate the potential of soft, flexible, and biobased materials to enable conformable, shape-changing mechanisms. This results in mechanisms that demonstrate dynamic behaviors and assemblies once considered the exclusive domain of organic tissues. One among many examples is Wani and colleagues' bionic flytrap, an autonomous liquid-crystal elastomer device that uses optical feedback to trigger a photomechanical, Venus-flytrap-like snapping action (Figure 7).[54] The device is completely self-contained and does not require electricity or compute or external power, sans natural light. Another soft robot with a rather alien-like gait is Haojian Lu and colleagues' multilegged millirobot, whose profusion of tapered feet and unassuming appearance seems to occupy a space between that of a caterpillar, starfish, and sentient carpet.[55] Fabricated out of polydimethylsiloxane (PDMS), hexane, and magnetic particles, the robot's motion is regulated by the force of an external magnetic field. Figure 8 shows how the movement of a magnetic bar enables the authors to create two distinct gaits. Such work shows how artifacts from soft robotics tend to be recognizable yet alien at the same time.

Yet another bioinspired engineering endeavor, Ren and collaborators' jellyfish-inspired, soft millirobot[56] references the fluidic control abilities of *scyphomedusae* ephyra (a type of jellyfish) to craft a soft robot made of magnetic composite elastomer (Figure 9). The final configuration relies on an external oscillating magnetic field to move through space. It can selectively trap and transport objects (see Figure 10), burrow, enhance the mixing of different chemicals in a solution, and generate a concentrated chemical path. Notably, the millibot exhibits the capability to execute five different swimming modes—some more xenomorphic than others: (1) one that attempts to mimic the natural motion of *scyphomedusae* as closely as possible, (2) one characterized by a shorter contraction phase, (3) one with a shorter recovery phase, (4) one with an extra glide phase after contraction, and (5) one with a smaller beating amplitude (see Figure 11). These modes show that nature-inspired design can—through being put in conversation with synthetic and novel materials, and modifications across even a handful of parameters—create something that builds on simple biomimicry to produce something cyborgian. Indeed, in their review of soft robotics for space exploration, Zhang and colleagues identified these jellyfish-inspired devices as potentially useful for exploring "planetary surfaces and even Titan-like planets with lakes."[57]

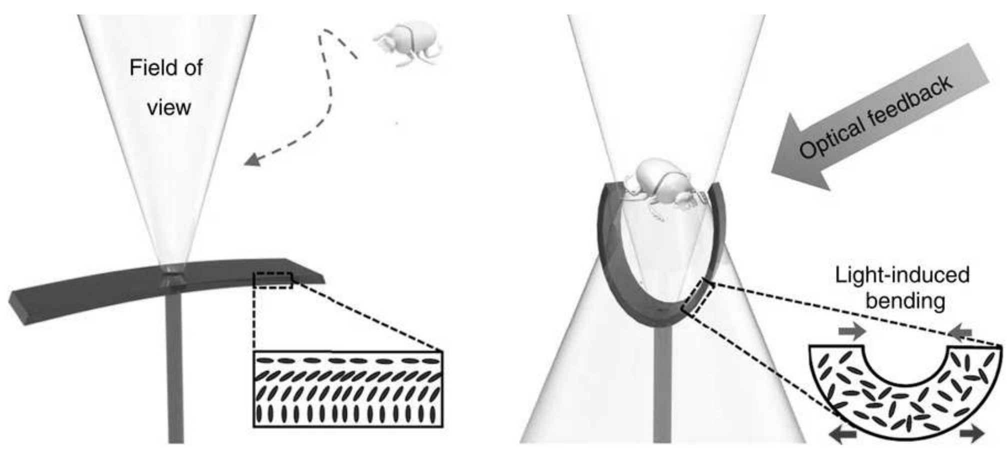

Figure 7 Left: Modeled after the Venus flytrap, the light-triggered artificial flytrap is depicted in its default state. No light is back-reflected to the LCE actuator, shown in red. Right: When an object enters the flytrap's field of view, it triggers optical feedback to the LCE actuator, which causes the material to bend, the trap to close, and the object to be captured. Source: Wani et al., "Light-Driven Artificial Flytrap."

[54] Wani et al., "Light-Driven Artificial Flytrap."
[55] Lu et al., "Bioinspired Multilegged Soft Millirobot."
[56] Ren et al., "Multi-Functional Soft-Bodied."
[57] Zhang et al., "Progress, Challenges, and Prospects," 11.

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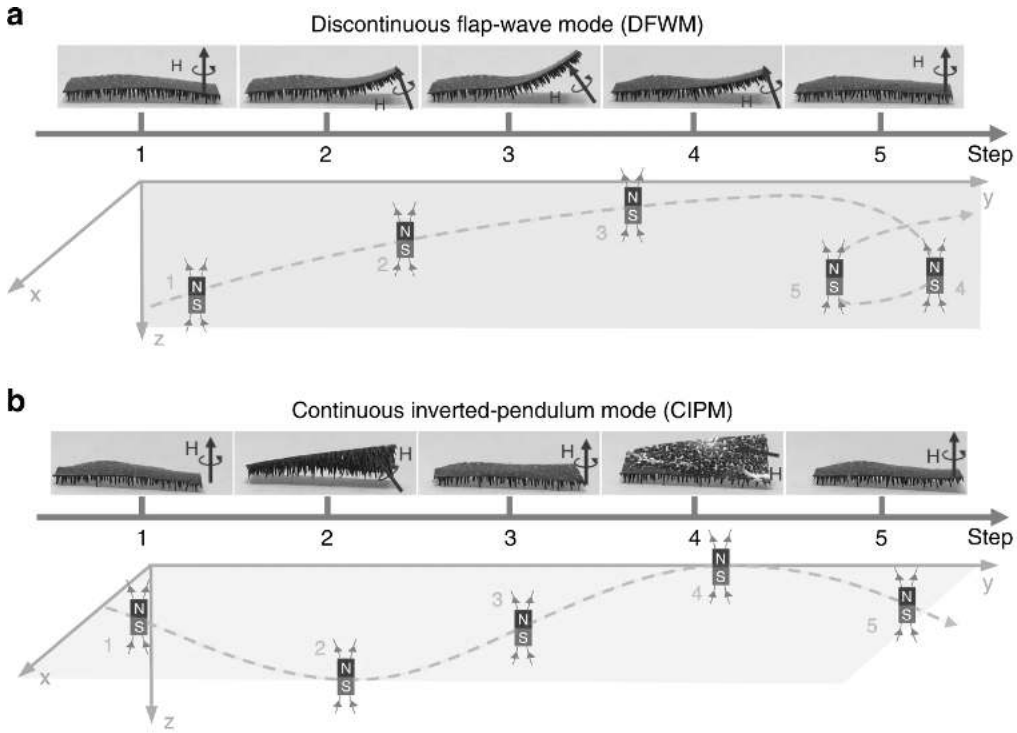

Figure 8 This figure shows the two ways the multilegged millibot can move through space. Below the frames of each locomotive mode is a graph showing along which axes a bar magnet is being manipulated to generate the resulting movement. (a) In the DFWM, the millibot moves according to an "O"-shaped magnetic field on the "y–z" plane. (b) In CIPM, the millibot moves according to an "S"-shaped magnetic field on the "x–y" plane. Source: Lu et al., "Bioinspired Multilegged Soft Millirobot."

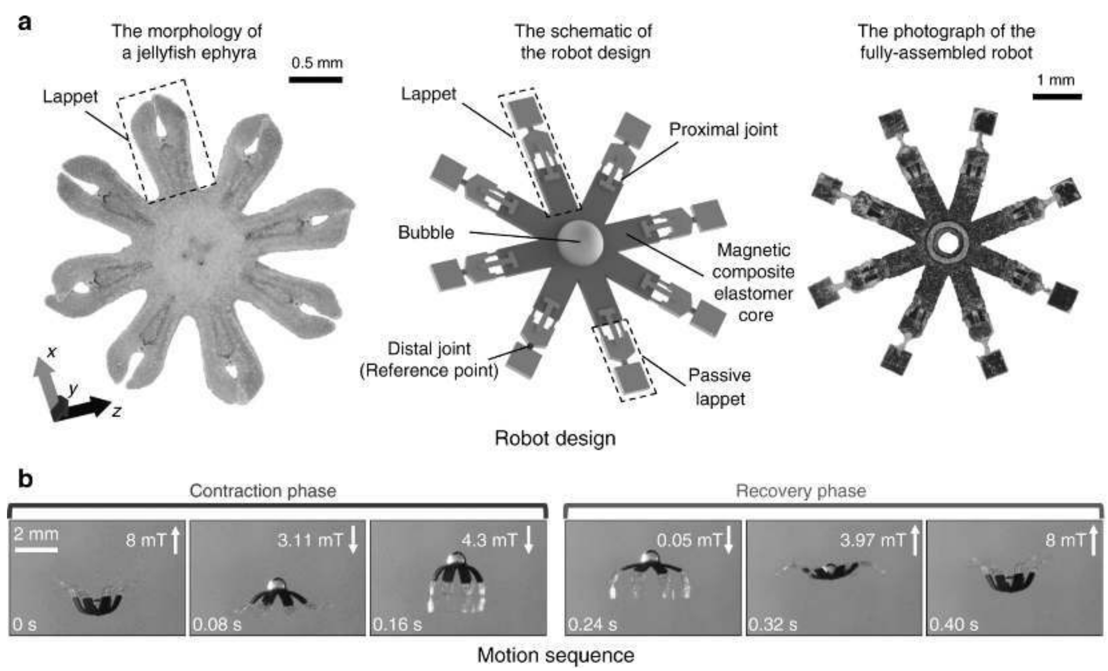

Figure 9 (a) The morphology of scyphomedusae ephyra side by side with the schematic and fabricated millirobot. (b) A motion sequence depicting the millirobot in action, capturing a buoyant bead using the fluid flow around its lappets. Source: Ren et al., "Multi-Functional Soft-Bodied."

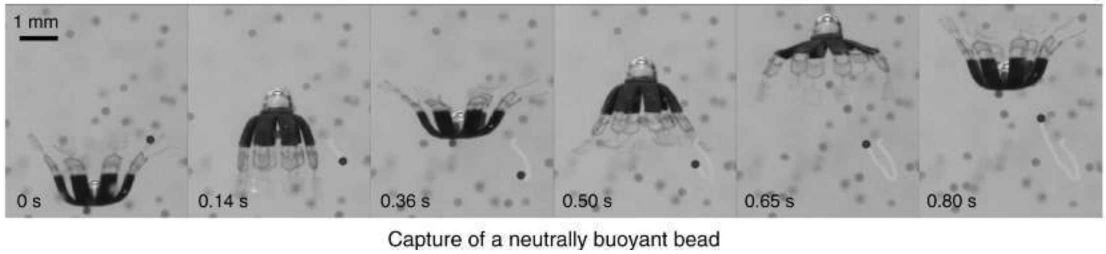

Figure 10 A motion sequence depicting the millirobot in action, capturing a buoyant bead using the fluid flow around its lappets. The red and green annotations indicate the flow of fluid around the millibot. Source: Ren et al., "Multi-Functional Soft-Bodied."

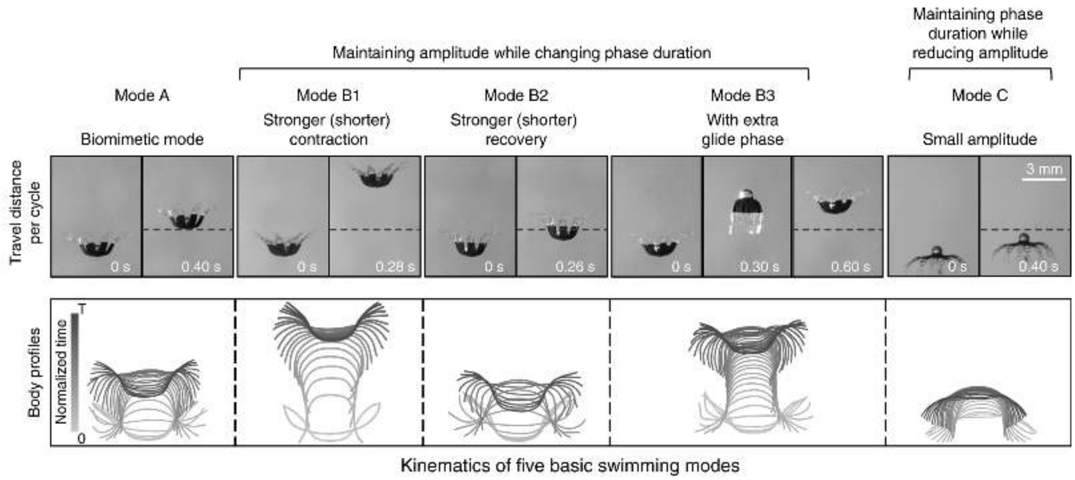

Figure 11 The kinematics of each swimming mode, with the start and end frames of one swimming cycle displayed side by side for each. The dashed red line denotes the final position of the robot when in Mode A to facilitate cross-mode comparison. Source: Ren et al., "Multi-Functional Soft-Bodied."

3.4 Assembly not Assemblage

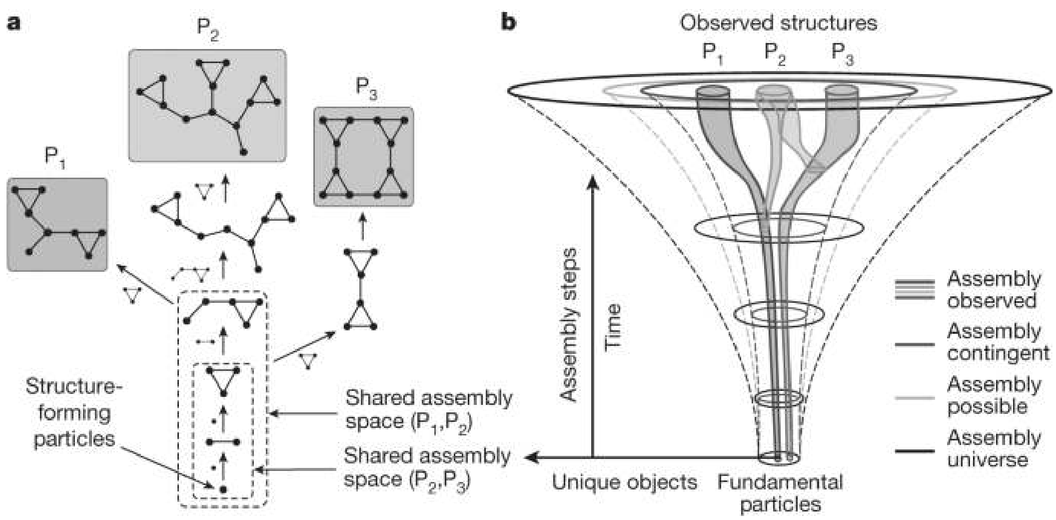

Figure 12 As explained by Sharma et al. in "Assembly Theory Explains: "a, Assembly observed of the three objects shown as graphs (P1, P2 and P3) with their shared minimal construction process called their 'joint assembly space'. b, Illustration of the expansion of the assembly universe, assembly possible, assembly contingent and assembly observed (see text for details). Assembly universe has no dynamics and is displayed with assembly steps as the time axis. Note that the figure illustrates their nested structure only, not the relative size of the spaces where each set is typically exponentially larger than the subset." Source: Sharma et al., "Assembly Theory Explains," 325.

DOI 10.1162/ANTI.5CZL

Where natural evolution produced, among other things, tetrapodal body plans suited to Earth's conditions, techniques incorporating ML, synthetic evolution, and unusual physical materials can explore an almost limitless morphospace. We can imagine assembling entirely new lineages of modular entities—what we call *xenomorphological components*—recombined and reconfigured to produce behaviors and structures devoid of biological precedent. Indeed, it is not uncommon for researchers to tread a middle ground, combining evolutionary algorithms with more traditional algorithmic approaches. As Agoston Eiben and Jim Smith write: "Such hybrid algorithms can often find good (or better) solutions faster than a pure evolutionary algorithm when the additional method searches systematically in the vicinity of good solutions, rather than relying on the more randomized search carried out by mutation."[58] Recent advances in machine learning and generative AI are well positioned to accelerate this embracing of that gray area between the nature-inspired and the uniquely machinic.

While such combinatorial experimentation might be loosely described by concepts of "assemblage," as conceived by contemporary post-Deleuzian readings,[59] we can gain more precise causal insight by turning to AT. Pioneered by Michael Levin, Lee Cronin, Sara Walker, and collaborators, AT provides a quantitative framework for measuring how many "assembly steps" are needed to form a given object.[60] Borrowing from molecular assembly theory, AT treats complex biological assemblies as if they were molecular bonds, establishing a minimal path count—an *assembly index*—that captures the structural prerequisites for producing a given entity. Whether an artifact is natural or synthetic, AT tracks the evolutionary (or design) complexity embedded in its form.

Levin's additional work with collaborator McMillen underscores how multiscale architectures define adaptive functionality in biological systems. From cells and tissues up to organs, bodies, and entire swarms, organisms exhibit nested layers of collective intelligence. During embryogenesis, for instance, a blastoderm's cells "agree" on an anatomical fate—say, forming a head versus a tail—through processes of *cellular alignment*. Rather than being a singular vital force, biological unity emerges through compositional engineering across these varied organizational levels.[61] For AT, such coordination can be measured in terms of the assembly steps needed to produce functional outcomes, illuminating how life's remarkable complexity often results from the alignment of subsystems working in concert.

Bringing these threads together suggests a way to design lifelike behaviors or even "new phyla" without relying on genetic inheritance. In doing so, the diagnostic cosmology of AT is extended as a design strategy. By modularizing xenomorphological components and systematically exploring their recombination, researchers could engineer unprecedented forms in silico (or eventually in the physical world), manifesting capacities that surpass biomimetic imitation.

In moving beyond biomimesis, we open a broader morphospace for discovery—one that frames evolution itself as an iterative design process. If the first Cambrian explosion was shaped by environmental conditions and genetic variation, the forthcoming synthetic explosion may be driven by the directed experimentation of AI systems, robotic platforms, and human creativity. Conceiving of evolution as a programmable process—rather than a strictly natural one—promises expansions in both complexity and functionality. In this sense, xenomorphology does more than suggest alien forms: it offers a blueprint for engineering those forms into being, heralding a new era of synthetic morphogenesis on a planetary (and perhaps interplanetary) scale.

4 Xenomorphology as a New Paradigm

The paradigm of generalized biomimesis has thus far exerted considerable influence on experimental thinking in design. While biomimetic approaches aim to replicate the outcomes of terrestrial biology, we propose that a different paradigm is increasingly appropriate. Inspired by AT and Karl Sims's virtual experiments, xenomorphology—and by extension, xenomorphic design—charts a departure from strictly biomorphic principles. Instead of seeking analogies within biological systems, xenomorphology explores forms that evoke true foreignness (*xenos* or ξένος refers to the "strange" or "alien"). By focusing on morphogenetic innovations that do not merely imitate life's evolutionary logic, xenomorphic design envisions shapes and behaviors arising either from the *xenos* of in silico experimentation (as with Sims's work) or, quite literally, from the *xenos* of extraterrestrial environments. To understand this pivot, it is helpful to note that biomorphic design—whether in architecture, robotics, or synthetic biology—relies on the established structures and functions of living organisms. Even when these designs depart from exact replicas (e.g., bipedal robots modeled loosely on human gait), they remain tethered to existing biological archetypes. Xenomorphology, by contrast, proposes forms that, in some way, shape, or form, eschew known biological constraints or evolutionary precedents. Etymologically, "xenomorphic" suggests intrinsically alien morphologies. Popular culture—Ridley Scott's *Alien* foremost among such references—associates "xenomorphs" with disturbing otherness that defies terrestrial norms.

Yet this dichotomy between biomorphism and xenomorphism is not always absolute. In geology, for instance, the terms biomorphic and xenomorphic describe minerals based on their crystallization timeline relative to surrounding structures. Xenomorphic minerals crystallize later,

[58] Eiben and Smith, 479.
[59] DeLanda, Assemblage Theory; Hayles, "Cognitive Assemblages."
[60] Cronin et al., "Assembly Theory."
[61] McMillen and Levin, *Distributed Intelligence*.

DOI 10.1162/ANTI.5CZL

resulting in shapes unconstrained by neighboring formations. This highlights a continuum rather than a strict opposition: biological and nonbiological features often overlap or merge, with each informing the other in unexpected ways.[62] For design research, acknowledging this fluid interplay can open paths to novel architectures that fuse or move beyond purely organic reference points.[63] NASA's TESSERAE (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments) project exemplifies how xenomorphic principles can be applied in literal alien environments.[64] Developed for reconfigurable space architectures, TESSERAE modules are designed to float in microgravity, *quasi-stochastically self-assembling* into desired geometries. Inspired by Roman mosaic tesserae, these tiles can interlock and form larger bases—or be deconfigured and recombined—thus adapting to the vacuum-based constraints of orbit. Crucially, the modules' behavior is not *biologically* derived; they transcend the rigidity of biomorphic forms through their flexible, reconfigurable morphology.

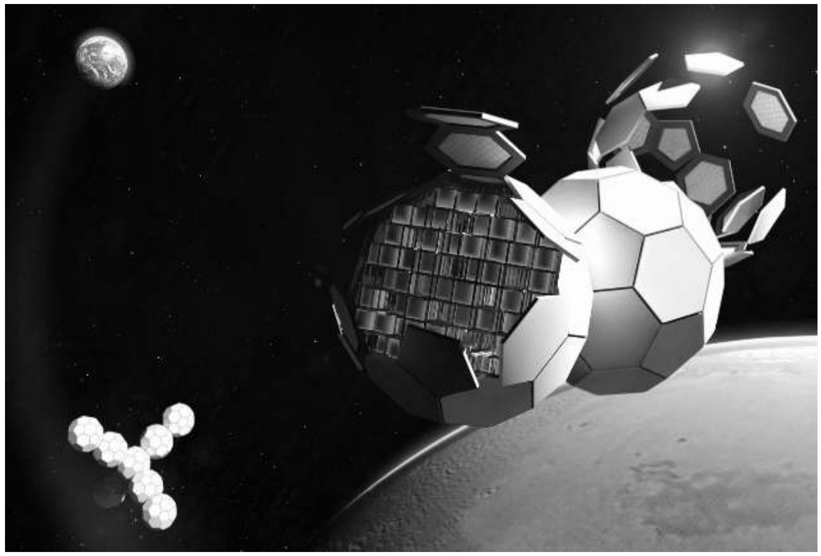

Figure 13 The modular and self-assembly structure of TESSERAE. Source: Artist Rendering of TESSERAE by TU Dortmund – MIT Media Lab.

In virtual contexts, xenomorphological design bypasses biological and physical constraints entirely. Morphologies develop outside of Earthly selection pressures, enabling a catalog of design elements that account for emergent behaviors unrelated to human physiology. Forms might range from enhanced sensory receptors to chemical harvesters or detectors of differential electromagnetism—capabilities that surpass human senses and address digital or off-world requirements. By suspending fitness conditions tied to Earth-based evolution, xenomorphs in silico can evolve traits defying organic intuitions, producing forms and functions that truly challenge our usual design heuristics. Xenomorphological design often involves iterative testing and population-scale experimentation, drawing on combinatorial logics akin to those employed in AlphaFold or reinforcement-learning environments such as Imbue's Avalon.[65] Instead of a rigid blueprint, an adaptable scaffold supports randomized or algorithmic recombination, allowing xenomorphic responses to emerge on their own terms. This iterative approach could eventually move beyond virtual space—for instance, into a modern "Biosphere 2" setting, where newly designed morphologies adapt in physical but still controlled, semiartificial conditions.

Downstream of xenomorphology lies what we might call *xenobehaviorism*: a lens for analyzing the unique behaviors that alien morphologies engender. Here, AT's concept of an assembly index becomes critical. By tracking the minimal set of "steps" or structural components needed to bring a form into existence, we can interpret how that form might inhabit an alien morphospace and generate novel behaviors unrestricted by Earth's evolutionary lineage. Indeed, xenomorphic forms in silico need not be judged by their potential translation into real-world systems but by the unprecedented behaviors they manifest in virtual or extraterrestrial domains. Fundamentally, true xenomorphology maintains an incommensurability with terrestrial forms. Some influences may, of course, be traced to Earth-based biology, but the foundational structure of xenomorphs should not simply be relabeled biomimicry. This shift compels a reevaluation of how such entities might coexist with humans and with each other—as distinct layers of intelligence and agency that can cooperate or coevolve without collapsing into anthropocentrism. These are alien intelligences, echoing the multiscale "collective intelligence" work of Levin and others, extended to realms beyond the biosphere's known repertoire.

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[62] Kauffman, *Investigations*.
[63] Cronin, "Assembly Theory."
[64] Ekblaw and Paradiso, ""TESSERAE."
[65] Albrecht et al., "Avalon."

DOI 10.1162/ANTI.5CZL

In short, where generalized biomimesis anchors design in the familiar terrain of life's historical templates, xenomorphology relinquishes those anchors in pursuit of genuinely novel morphospaces. Whether operating in microgravity, virtual simulation, or any domain unbound by Earthly evolutionary constraints, xenomorphological design invites us to explore—and ultimately, engineer—the truly alien.

5 Conclusion: Speculative Visions for a New Antifragile Xenophylum

For xenomorphological design to fulfill its potential, it must embrace a rigorous scientific and architectural framework. AT offers precisely this: a quantitative approach for charting the structural pathways and "assembly sequences" that lead to novel forms. Coupled with what we might call *xenoarchitectural theory*, researchers can actively anticipate previously unimaginable morphogenetic outcomes. Rather than reproducing life's known forms, this paradigm propels us to explore the radical otherness of xenomorphospace. In doing so, we might cultivate entire environments in which alien intelligences proliferate, challenging established boundaries of morphology, behavior, and human–machine interaction.

The convergence of ideas from Karl Sims, Michael Levin, Lee Cronin, and Sara Walker underscores the unifying role of morphology across the domains of evolution, technology, and intelligence. By quantizing how complex forms come into being—whether through cellular alignment in embryogenesis or modular recombination in virtual simulations—morphology transcends the binary of the organic versus the synthetic. In this sense, xenomorphology emerges not simply as a design novelty but as a structural alternative to biomimesis, realigning the focus of design thinking toward unknown pathways of form.

This perspective resonates with the advent of generative AI, which encourages morphological exploration in its architectures. The most speculative instances of xenomorphological experimentation may initially unfold in silico, but their impact extends to physical infrastructures and cultural imaginaries. Over time, these virtual experiments filter into how we perceive and construct our environments, subtly redefining our relationship to both the biosphere and a nascent xenosphere.

Crucially, it may take adversarial events or stressors to catalyze the emergence of progressively antifragile xenomorphic forms. Because these forms are engineered with artificial responsiveness and flexibility, they adapt more quickly than their biological counterparts. By deploying large-scale simulations and iterative testing—akin to Sims's evolutionary software or Imbue's Avalon environment—designers can accelerate the discovery of xenomorphic responses. When promising new behaviors surface, they can be refined and scaled further, eventually migrating into physical test beds reminiscent of Biosphere 2.

This antifragile imperative—where morphology itself becomes the wellspring for evolving behaviors—reflects a design philosophy attuned to a complex, rapidly shifting world. In reframing evolution as a synthetic and modular process, we glimpse the birth of a new xenophylum of forms adapted to alien intelligences and nonbiological morphospaces. Pushing beyond the constraints of terrestrial body plans, xenomorphology embraces the alien in all its unsettling potential. By prioritizing antifragility and dynamic adaptation, we can seed resilient, exploratory, and provocative designs that transcend the boundaries of the biosphere—marking a transformative milestone in both the theory and practice of design.

Sometimes, an adversarial event can induce an unexpected, xenomorphic response. In this case, acquired xenomorphic behaviors might lead to greater resilience and increased proliferation in various contexts. This insight underscores the need to rethink design frameworks through the lens of a new xenomorphic paradigm, which emphasizes adaptability and innovative responses to challenges. By adopting this paradigm, designers can cultivate more resilient systems that are better equipped to navigate complexity and engineer this new Cambrian explosion.

In this framework, the antifragile response mediates between the morphology (which begets the morphospace of new behaviors) and the emergence of the xenobehavior itself. Without some adversarial stimulus, in other words, a potential xenobehavior may never emerge. Thus, as with Levin's argument for problem-solving capabilities being distributed beyond the bounds of the individual agent, the possibilities of xenomorphology either can be left to chance, to emerge within adversarial encounters, or else such antifragile stimuli can be experimented with. The stimuli that might solicit such a response may be adversarial but are inherently unpredictable and difficult to predetermine. Thus, as with Sims's virtual evolved creatures, experimenting with such emergence benefits from a scaling of experimental frequency.

A small number of xenomorphological components might be recombined either randomly or according to a specific algorithmic logic based on the "multi-sequence alignments" of projects such as AlphaFold.[66] To establish their postcombinatorial morphospace for potentially novel behaviors, these assembled xenomorphs must be tested in potentially adversarial environments. Promising novel behaviors might be iterated upon.

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[66] Jumper *et al.*, "Highly Accurate Protein Structure," 583.

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