Root-Inspired Generative Network

An Agent-Based Model for the Design of Context-Aware Architectural Structures

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Abstract. Natural root systems exemplify self-organizing networks that grow adaptively in response to complex environmental stimuli, revealing a bottom-up logic where efficient structures emerge from local interactions rather than centralized control. Building on this biological paradigm, this research investigates how the self-organizing principles of growth in natural root systems can be abstracted into an agent-based computational model to generate adaptive architectural forms, augmenting the architect's ability to create highly efficient, context-aware design. The model is developed by translating key biological mechanisms, including tropism, branching, and grafting, into geometrical operations that govern the iterative growth of agents in an algorithm written using Python within Rhino/Grasshopper. The model is subsequently applied in two conceptual design proposals in Hong Kong, demonstrating its capacity to generate proto-architectural systems for slope support and pedestrian circulation by adapting to specific site constraints. The outcome bridges the gap between biological principles and architectural synthesis by offering a generative conceptual framework for creating architectural forms with enhanced structural efficiency and ecological integration within complex environments at an early design stage.

Keywords. root systems, agent-based modelling, bio-inspired computation, generative design, context-aware structures

1. Introduction

The architectural discipline is confronted by escalating environmental issues, challenging conventional top-down design methods. These traditional approaches are inherently limited in their capacity to handle complex site conditions, often producing architectural forms asynchronous with their dynamic contexts. Already since the 1950s and the emergence of system theory and cybernetics, scientists have argued for a systemic approach, framing design as a "network of interrelated requirements" (Alexander, 1979), thereby establishing a foundation for bottom-up design thinking.

HUMANISTIC COMPUTATION AND INTELLIGENCE, Proceedings of the 31st International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2026, Volume 3, 665-674.
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This systemic logic finds a powerful analogue in biological systems that exhibit robust bottom-up intelligence developed over billions of years of evolution. D'Arcy Thompson described biological form as a "diagram of forces" (Thompson, 1992), a morphology emerging from context-aware growth. In particular, the root system of Banyan trees presents a highly efficient, decentralized structural network developed through local interactions with environmental stimuli like gravity and moisture (Fig. 1). This presents a potent model for an exploration of architectural methodology where form emerges as a system in direct dialogue with its context, rather than manually imposed.

Figure 1. Root system of Banyan trees adapting to its context for nutrient and support

Inspired by the context-awareness of root growth, this research develops an agent-based algorithm that translates the self-organizing principles in root systems into a generative tool for proto-architectural form-finding. Scripted in Python within the Rhino/Grasshopper environment, the algorithm does not aim for exact mimicry of roots but offers a conceptual interpretation that abstracts their growth logic to generate structural and circulatory organizational networks for architectural design.

The goal is to augment designers' capability to create complex, context-aware structures for circulation and support. This research bridges a critical gap between biological intelligence and architectural synthesis, demonstrating a bio-inspired systemic approach of architectural form-finding where structure emerges from direct dialogue with contextual constraints and opportunities.

2. Literature Review

This research is grounded in the shift towards a biological paradigm of architecture, which moves from object-making into the emergence of performative, adaptive systems. Hensel's "performance-oriented" approach frames performance as a dynamic outcome of interactions between subject, environment, and material organization (Hensel, 2013). Similarly, Weinstock's studies of morphological processes in nature provide a framework for understanding emergence and self-organization as generative principles (Weinstock, 2010) echoing Frei Otto's earlier research (Otto, 2011). This discourse establishes a crucial intellectual foundation but often remains conceptual, lacking practical methodologies for early-stage design.

Computational methods including L-Systems (Prusinkiewicz, 1991), Boids (Reynolds, 1987), and Conway's Game of Life (Berlekamp, 2003), demonstrate how complex order emerges from simple, local rules. These tools are powerful for simulation but often remain in representation or analysis, lacking a direct pathway to synthesize emergent patterns into architectural proposals that integrate spatial, programmatic, and tectonic requirements.

A dominant response is the material and fabrication-oriented approach pioneered at the ICD/ITKE, University of Stuttgart. Their research integrates computational form-finding and physical realization by making material properties and fabrication constraints primary design drivers (Menges, 2012). While crucial for materialization, its strength in articulating physical systems reveals a need for a complementary conceptual methodology to generate the underlying adaptive organizational logic.

Positioned within these gaps, this research develops a root-inspired generative methodology. It aims to provide a framework for the conceptual design stage, translating the logic of biological growth into organizational networks. By focusing on the abstract generation of context-aware topologies, this work seeks to complement simulation-based analysis and material-oriented approaches, offering a missing link in a comprehensive bio-inspired design workflow.

3. Methodology

To create a computational algorithm by translating natural growth patterns in root systems into organizational networks for design applications, the methodology unfolds in three main sections: Geometrical Translations, Parametric Variations, and External Adaptations. It translates biological mechanisms of root growth into geometrical operators, building up a feedback loop that demonstrates emergent properties resulting from the interaction of its agents and their adaptation to external stimuli (Fig. 2a). The system as a network of flow is then applied to real-world design scenarios in the next stage to generate proto-architectural solutions for complex design conditions.

The algorithm operates under an iterative agent-based model where root growth is represented by a series of discrete movements of a point over time. In every iteration, a compound-vector with predefined magnitude directs the point to the next location. As this process repeats, a trajectory of movement in 3D is generated, simulating the growth of a continuous root in nature (Fig. 2b).

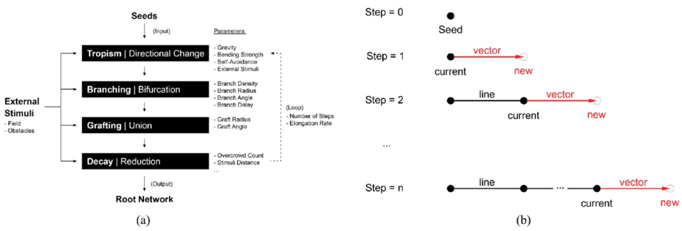


Figure 2. (a) Feedback loop composed of geometrical operators; (b) Iterative growth of roots

3.1. GEOMETRICAL TRANSLATIONS

The first stage focuses on translating three essential biological mechanisms: Tropism, Branching, and Grafting, into abstract geometrical operations. These mechanisms are responsible for directional growth, bifurcation, and union of root paths respectively, together they regulate the distribution of the system. Subsequently, the geometry-based rules translated are composed into an algorithm using Python in Grasshopper.

3.1.1. Tropism

The concept of tropism describes the directional growth response in plants to an external stimulus. The movement in response to environmental stimuli, such as gravitropism on gravity, hydrotropism on water, and thigmotropism on obstacles, demonstrates the crucial ability of root system to optimize resource uptake, avoiding collision with external objects, and offer structural support (Gilroy & Masson, 2008).

To translate the continual growth of natural roots into discrete movements over time in digital space, a compound-vector is calculated for each root tip in every iteration to determine its current growth direction. The resultant direction is the vector sum of forces exerted by multiple contextual elements and therefore subjected to constant deviation throughout its growth process (Fig. 3a).

While natural roots detect and avoid obstacles through direct physical contact, the algorithm implements an obstacle detection mechanism to respond to collisions with obstacles in digital space. To detect obstacle collisions, the algorithm checks whether the next growing point (root tip) lies inside any obstacle in each iteration. Upon collision, the growing point is moved to the closest point on its surface. Repeated operation allows the root system to walk along the surface of the obstacle when collision occurs and navigate across an artificial matrix (Fig. 3b).

Although the behaviour of self-avoidance between roots remains debated in plant physiology, this system emulates the self-avoidance between roots with each point within the system by exerting a repulsive force on all its neighbours within a certain radius, with a magnitude calculated using an inverse distance weighting method where the magnitude of repulsion is inversely proportional to the distance between points. This causes neighbouring roots to grow apart from each other and distribute themselves evenly in space for optimal flow of resource and forces (Fig. 3c).

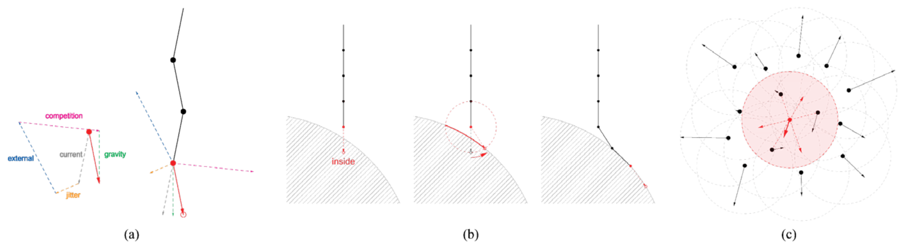


Figure 3. (a) Compound-vector as the sum of environmental forces; (b) Geometrical operation of obstacle detection and avoidance; (c) Self-avoidance mechanism between growing roots

3.1.2. Branching

As a fundamental process in root development secondary to elongation, branching involves the formation of lateral roots from meristems located in the pericycle. This mechanism allows root systems to maximize its area of contact in the most nutrient-rich region of the soil matrix for efficient resource capture (Atkinson et al., 2014).

While the branching frequency of natural roots is regulated by nutrient and hormonal signals in response to contextual conditions (Smit et al., 2000), the translated mechanism uses a local sparsity evaluation that counts the points in its neighbourhood with fixed frequency, branching off only when no point is close by (Fig. 4a). This mechanism emulates the branching behaviour that avoids overcrowding in certain area of the soil matrix to ensure optimal spatial distribution and resource capture.

Although the branch angle is often fixed in natural roots, the branching azimuth around the axial direction of the root is often determined at random (Smit et al., 2000). The system instead takes the compound-vector of influence on its location to determine the branch azimuth and branch point towards a desirable area in the soil matrix (Fig. 4b). This adds further context-awareness to the system, not only directional changes, but also branch pattern influenced by contextual conditions.

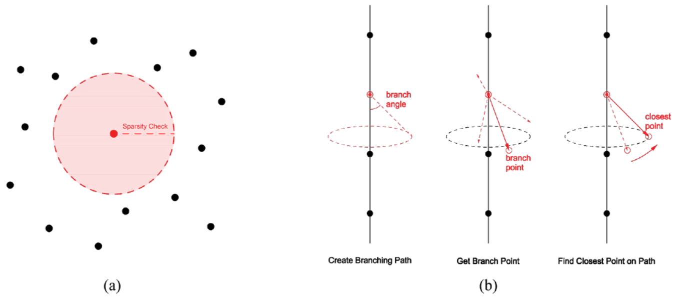


Figure 4. (a) Local sparsity evaluation; (b) Geometrical operation of branching

3.1.3. Grafting

In addition to the directional growth of tropism and bifurcation of branching, grafting is the morphological union resulting from two or more distinct roots in pressured contact with each other during the growth process (Graham & Bormann, 1966). It contributes to added mechanical support and efficiency to nutrient flow within the plant by interconnecting different distinct flow paths in the system (Loehle & Jones, 1990).

While natural grafting happens under physical pressure of roots colliding with each other (Graham & Bormann, 1966), the union of roots in the system is triggered by a proximity evaluation between root tips, followed by the redirection of their growing paths. If the distance between two growing points falls below the distance threshold and the angle between their direction of growth is smaller than a predefined angle, the two growing paths will be redirected into an average point, continuing their growth as a united path in the coming iterations (Fig. 5). This process allows the root system to self-regulate its proliferation by reducing the number of growing branches when the population density of branches exceeds the limit of its environment.

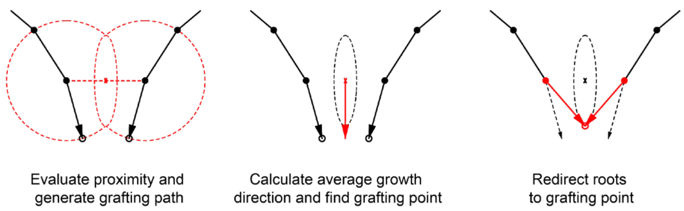


Figure 5. Geometrical operation of grafting

3.2. PARAMETRIC VARIATIONS

This part investigates the emergent properties, such as spatial dispersion, structural hierarchy, and interconnection, derived from the interaction of agents under geometrical rules by varying the growth parameters in the algorithm. The first variation modulates the spatial dispersion of the system by adjusting the parameters of self-avoidance (Fig. 6a). Increasing either the avoidance strength or the detection radius causes individual root points to experience stronger repulsive forces from their neighbours. This forces the system to grow and branch away from densely populated zones, resulting in higher degree of spatial dispersion. The next variation controls the structural hierarchy by changing the parameters of branching (Fig. 6b). The branch radius defines the sparsity required for a point branch, while branch density sets the frequency of this sparsity evaluation. Reducing either parameter causes more frequent lateral root initiation and a higher density of branches. This produces a more densely hierarchical system with higher number of branching orders. In contrast to the expansive tendencies of the previous variations, the last variation enhances the interconnection of the system through grafting (Fig. 6c). The key parameters are the grafting radius (the maximum distance between points for grafting) and the allowable angular difference between their growth directions. By increasing these thresholds, more roots are allowed to fuse, resulting in a more interconnected spatial network.

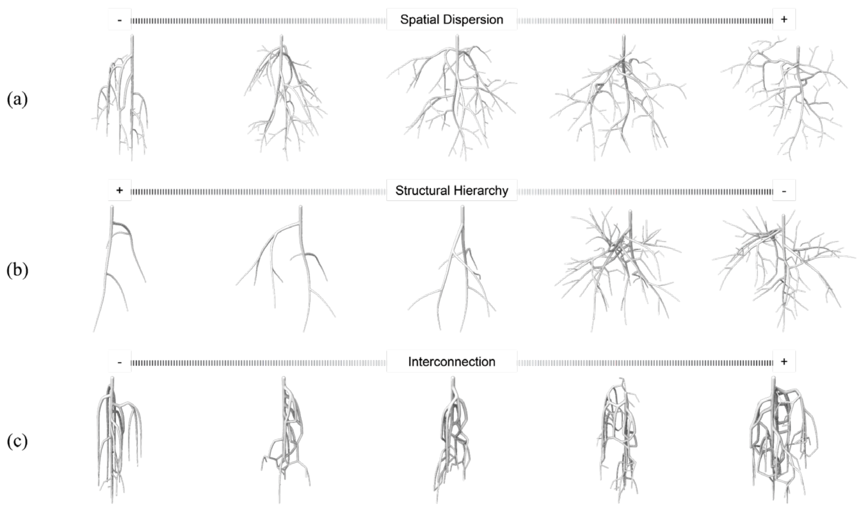


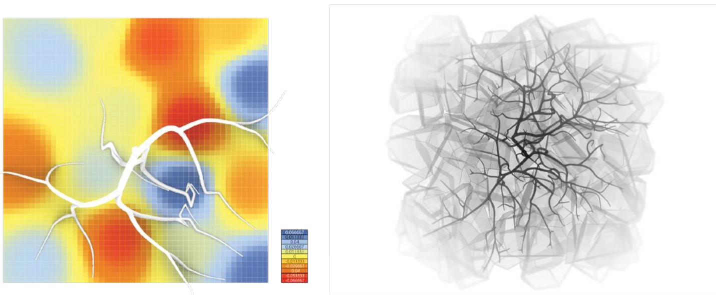
Figure 6. (a) Spatial dispersion; (b) Structural hierarchy; (c) Interconnection

3.3. EXTERNAL ADAPTATIONS

In a natural setting, roots grow adaptively in response to gradients of environmental stimuli and navigates through the obstacles it encounters when seeking nutrient and anchorage. To simulate these adaptations, two types of external stimuli, force fields and obstacles, are introduced to test how the system adapts to its context.

The first adaptation introduces a computational force field constructed from attraction and repulsion points (Fig. 7a). As a root grows, each point in the force field exerts an influence vector upon the growing tip with magnitude calculated via inverse distance weighting. These vectors influence the root's growth direction, allowing it to navigate towards favourable conditions and away from unfavourable ones, demonstrating a direct translation of environmental gradients into growth paths.

The second test introduces external obstacles such as surfaces, solids, and matrices into the system, analogous to ground, rocks, and soil in nature (Fig. 7b). Guided by the object avoidance mechanism defined in the geometrical translation, the growth direction and branching pattern of the root system is redirected according to the shape of obstacles it encountered and are distributed evenly across the surface.



(a) (b)

Figure 7. (a) Adaptation to force field; (b) Adaptation to obstacles

4. Design Applications

Drawing from the conceptual parallel between root systems and architecture, the following two proto-architectural proposals apply the context-awareness of root systems into structural and circulatory organization strategies in design.

4.1. FORCE FLOW

The first design application is a supporting system for a building on a natural slope in Hong Kong. It uses the root system to dynamically distribute supporting structures, interfacing between the irregular landscape and the building mass above. Instead of imposing a rigid grid system onto the natural landscape, the goal is to design an alternative structural system that distribute loads adaptively to minimize on-site alteration, therefore preserving and coexisting with the natural ecosystem.

To adapt to the site, key contextual elements such as transportation networks, pedestrian paths, and hydrological features, are abstracted into a computational repulsion field. These elements are translated as line-based repellents, each assigned a strength value based on its significance (Fig. 8a). Using inverse distance weighting, this field influences root growth, directing the structural network away from sensitive areas. Combined with the 3D model of the terrain, it creates a comprehensive boundary condition that guides the generative process toward a structure that adapts to its context.

The generative process starts with defining a building mass and "seeds" between the building and the landscape. The seeds grow under the contextual field and terrain geometry, dynamically redirect, branch, and graft, resulting in a spatial structure emerged from the continuous interaction between its internal growth principles and the external site constraints (Fig. 8b). A subsequent Finite Element Method (FEM) analysis using Karamba3D revealed that the root system distributes structural stresses more evenly, avoiding the stress concentrations typical of column-and-beam grids.

The outcome is a context-aware structural support system that distributes its members spatially to efficiently transfer forces to the ground, while intelligently avoiding intersection with critical site features. The resulting morphology demonstrates a rich blend of structure and habitat, creating a covered space that is both functionally robust and ecologically integrated (Fig. 8c, 8d).

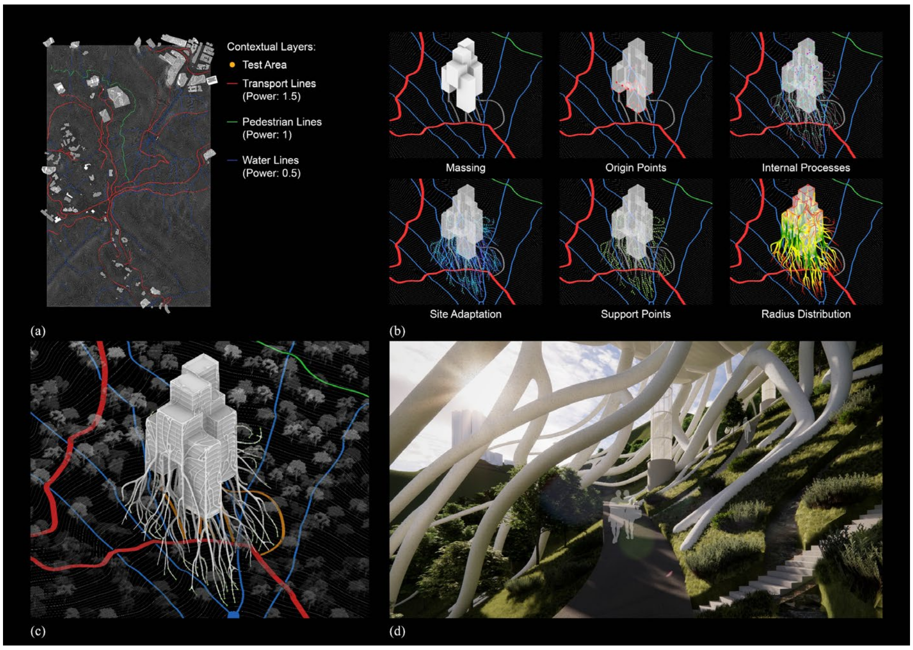


Figure 8. (a) Contextualization of site elements; (b) Generative process of support system; (c) Isometric view of support system; (d) Blend of structure and natural habitat in the covered space

4.2. HUMAN FLOW

The second design application is an elevated pedestrian network in Wan Chai, a densely populated district in Hong Kong. Here, the root system is interpreted as a circulatory network for directing human flow in an urban context. Compared to conventional top-down planning, this application treats the urban fabric as a soil matrix, under which a network of elevated circulation paths grows adaptively to distribute human flow across the area and reconnect different parts of the city.

To computationally contextualize the design, key urban elements are abstracted into a data field. Obstacles such as vehicle roads are defined as repulsion elements, while key destinations, including the harbourfront, historic alleys, and public transportation nodes, are mapped as attraction points (Fig. 9a). The goal is to generate a network that connects the harbourfront and historic alleys via the transport nodes, creating an elevated pathway through the city while avoiding ground-level traffic.

The generative process initiates from “seeds” placed along an existing central footbridge. These points navigate the volumetric massing of surrounding towers, branching and grafting in response to spatial conditions while extending tendrils into the urban fabric. Global attraction forces pull the growth towards the harbour and old alleys, while local attraction points pull it towards transportation nodes to create access points (Fig. 89b). Vertical level changes are introduced only at branching or grafting points, otherwise kept planar to ensure walkability. The thickness of the path is determined by its simulated "age," transitioning from the densely populated central area into the remote peripheral connections.

The outcome is a speculative design for an elevated, root-inspired pedestrian network that appears to grow through the city (Fig. 9c, 9d). It reinterprets the urban fabric as a living soil matrix to be navigated, not a blank slate to be drawn upon. This model proposes an alternative to top-down master planning, suggesting a methodology for human flow to emerge from the organic, adaptive interactions of a bio-inspired computational system with its context.

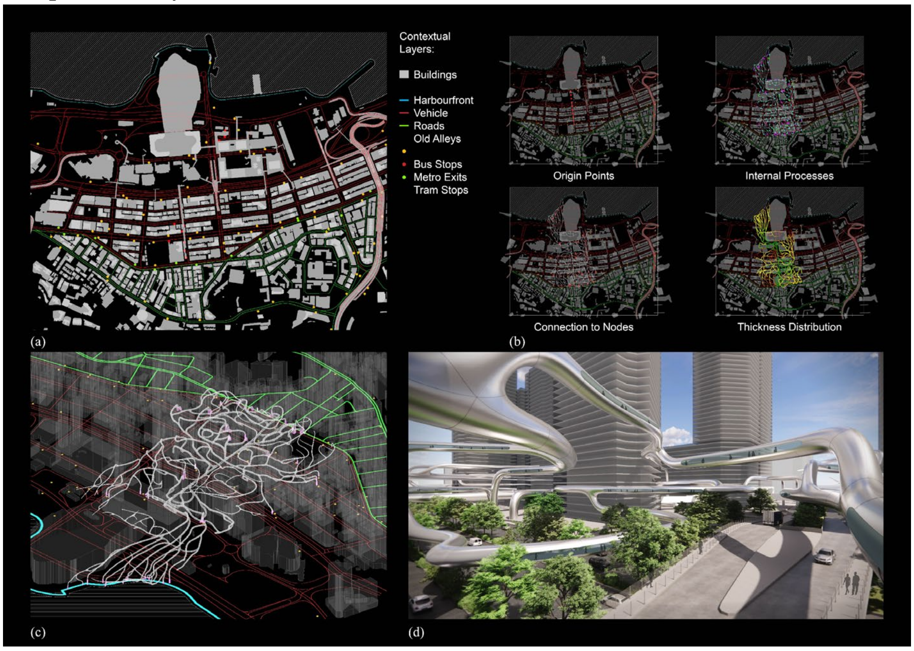


Figure 9. (a) Contextual elements mapped in colour; (b) Generative process of path system; (c) Isometric view of path system; (d) Render of elevated walkway over ground level traffic

5. Conclusion

This research demonstrates the translation of abstracted growth mechanisms of root systems into geometrical operations, enabling the generation of viable proto-architectural solutions for context-aware structural and circulatory organization networks. In response to the top-down design approach, this research provides an alternative methodology for augmenting the designer's capability to handle complex design problems, exploring a solution space where form is defined by system-level parameters and boundary conditions that adapt to the site condition. The results address the research gaps by providing an operational method for translating biological principles into an architectural context, advancing beyond pure simulation into architectural design proposals, and acting as a conceptual framework for material-oriented approaches.

The proposed proto-architectural methodology has several limitations. The algorithm abstracts the geometrical aspect of biological root growth and focuses primarily on speculative and conceptual potential rather than on detailed tectonic resolution. Therefore, the materialization of these organizational networks as buildable structures remains a critical area for future investigation. Future work will focus on integrating material and structural feedback directly into the growth algorithm, developing real-time interactive models for design exploration, and physically testing the structural strength of the generated networks. This research serves as a conceptual starting point for further development towards materialization, learning from the bottom-up intelligence of nature to develop more responsive, efficient, and ecologically integrated architectural designs.

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