Growth, Digital Tools and Simulation

Slime Mould

Allen Bell, Eda Sefa, Marlene Mautner

The Biology of Physarum Polycephalum - Slime Mould

Slime moulds, once classified as fungi in the class Myxomecetes, are now considered part of the kingdom Protista. There are two main types of slime moulds: cellular slime moulds, composed of multiple cells, and plasmodial slime moulds, consisting of a large multi-nucleated single cell. Physarum polycephalum, a plasmodial slime mould, is a single-celled amoeba-like organism. This organism demonstrates primitive intelligence during its plasmodium stage by forming a yellowish vascular network which expands up to tens of centimetres in response to chemo-attractants and repellents in search of nutrition.

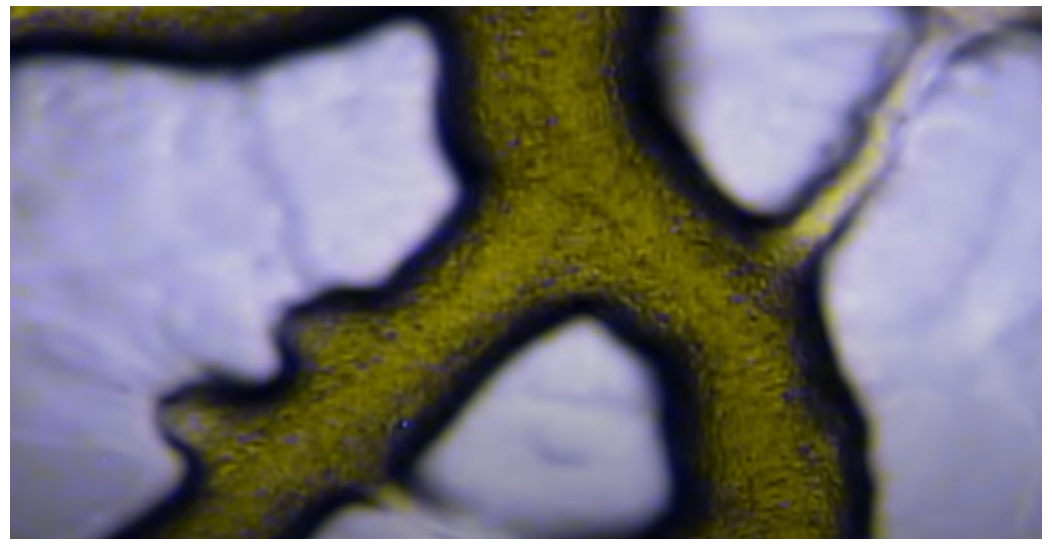
Physarum's behavior involves two self-organized processes:

- Expansion (exploration) and
- Shrinkage (exploitation)

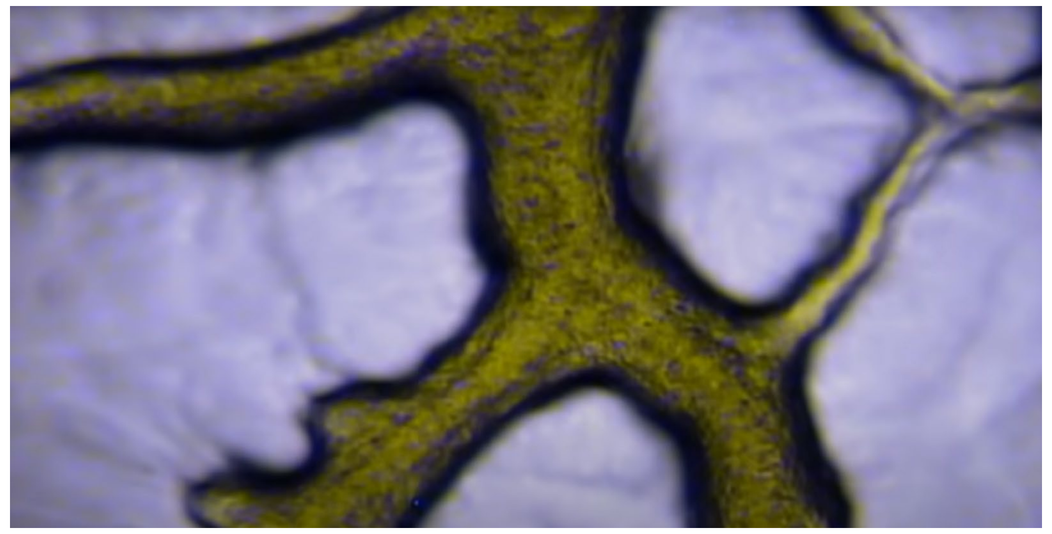
A SURVEY ON PHYSARUM POLYCEPHALUM INTELLIGENT FORAGING BEHAVIOUR AND BIO-INSPIRED APPLICATIONS
https://arxiv.org/pdf/2103.00172

The Biology of Physarum Polycephalum - Formation

Physarum polycephalum, is formed of a mycelial tubular network through which the chemical and physical signals, the nutrients, and the body mass are transported throughout the organism. The tubes of plasmodium Physarum are made of a gel-like outer membrane of actin–myosin cytoskeleton that generates periodic contractions of the tube walls. Inside this membrane, the cytoplasmic liquid is pumped back and forth in a rhythmically oscillating manner. The contraction amplitude and the frequency generally increase or decrease when encountering an attractant or repellent, respectively.



- Expansion (exploration)



- Shrinkage (exploitation)

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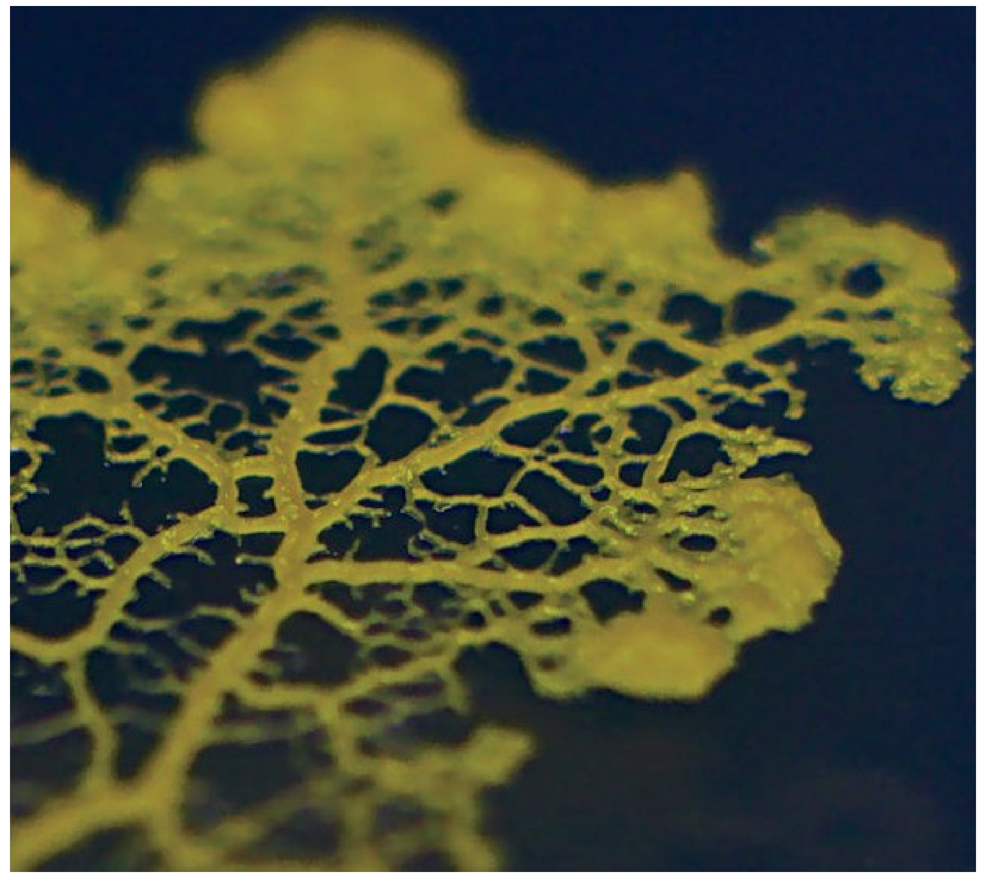
The Biology of Physarum Polycephalum - Sensory Capacities

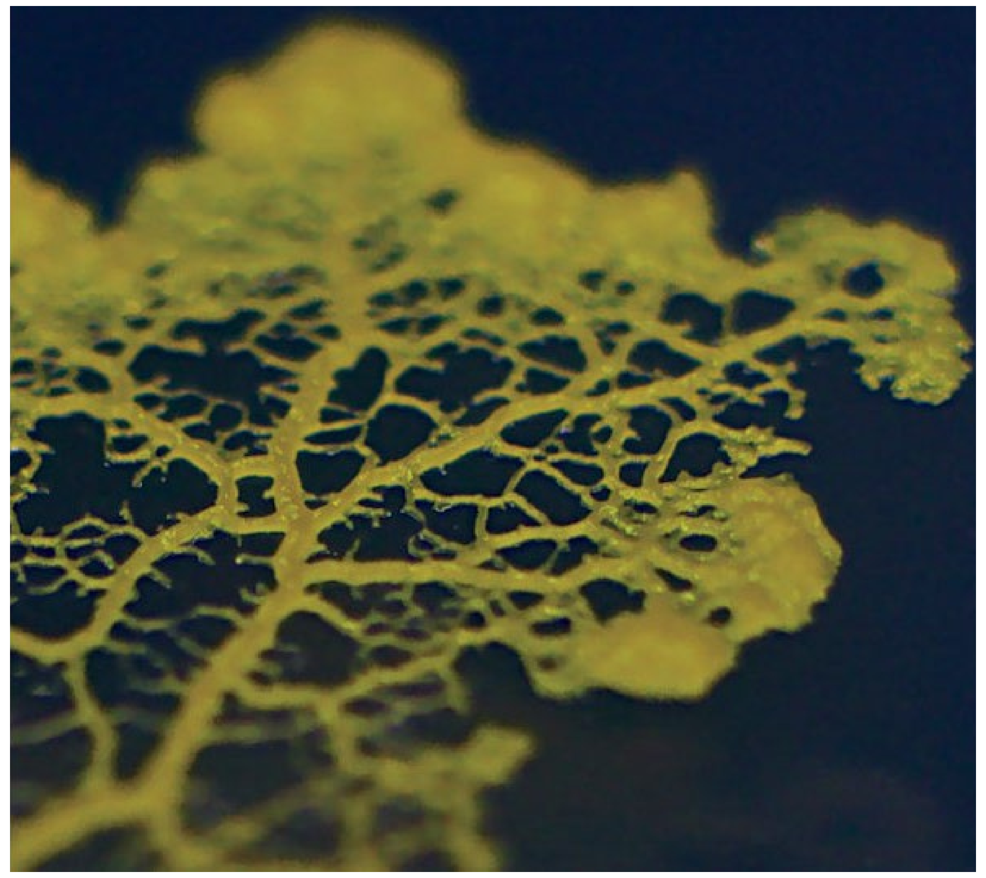
Physarum polycephalum reacts to stimuli by altering its electrical potential oscillations, which are driven by hundreds to thousands of biochemical oscillators. When a stimulus occurs, it triggers the release of the signaling molecule cyclic adenosine monophosphate (cAMP), initiating cytoplasmic streaming. This stimulus creates propagating waves, leading to increased cytoplasmic streaming through the vein, which in turn creates a positive feedback loop: the greater the rate of cytoplasmic streaming, the thicker the vein becomes.



https://cen.acs.org/biological-chemistry/chemical-communication/slime-mold-reorganizes-around-food/99/i7

The Biology of Physarum Polycephalum - Structure

The structure of Physarum exhibits two distinct geometric patterns: (a) thin branches that extend to search for food, and (b) bulging, droplet-like blobs that enlarge at the tips of these branches. During the initial exploration phase, the organism grows, with branches and their bulging tips lengthening through the foraging process. These branches further divide and connect like veins. In the subsequent exploitation phase, the nutrient-transporting tubes enlarge, while those that do not transport sufficient nutrients shrink and eventually disappear.



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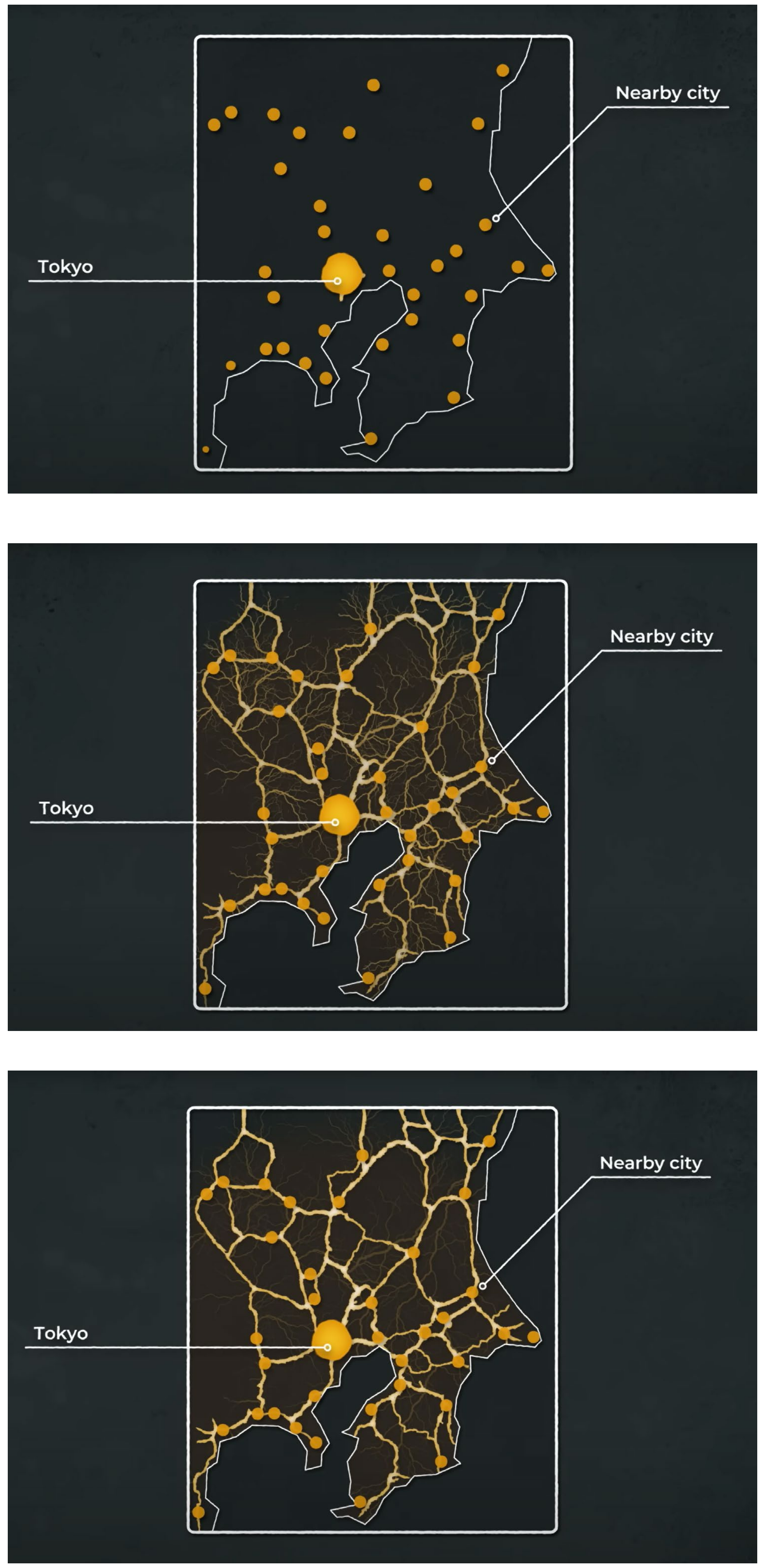
The Biology of Physarum Polycephalum - Behaviour

Physarum polycephalum demonstrates the ability to make complex foraging decisions by balancing risks, hunger levels, and food quality. This primitive intelligence is most evident during its plasmodium stage, where it functions as a large multi-nucleated single cell. The organism's intelligence and decision making are rooted in how it perceives its environment, integrates information, and makes choices. Inspired by these biological phenomena, researchers have developed novel, biologically inspired models for unconventional computational methods capable of solving real-world optimazation many problems.

https://www.youtube.com/watch?v=nPOQQp8CCls

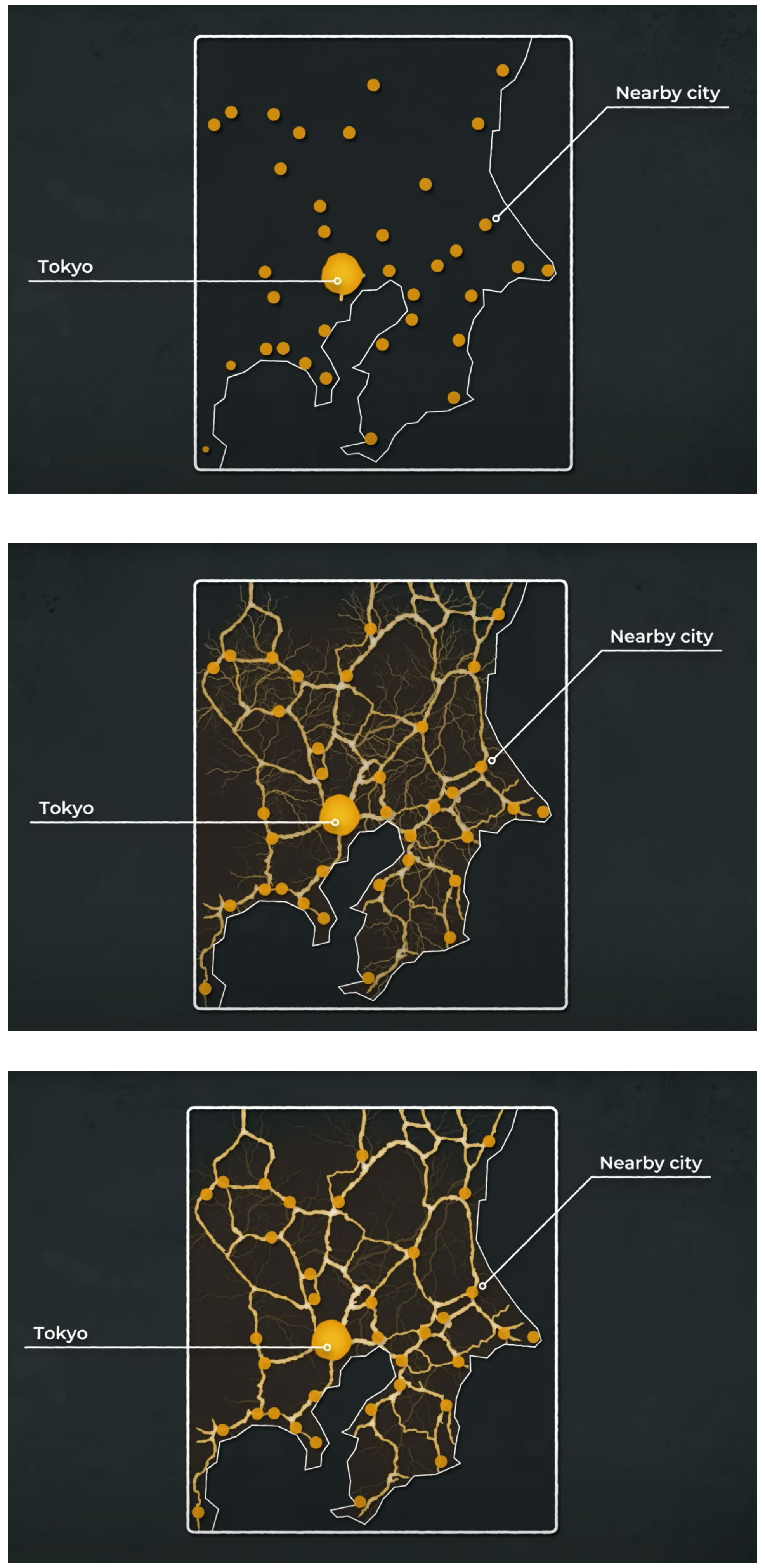
Kanto Region, Japan
Slime Mould Subway Experiment



The Biology of Physarum Polycephalum - Building High - Quality Networks

A notable experiment demonstrating Physarum's network design intelligence was its reconstruction of the Tokyo railway network. During the early exploration phase, the organism's branches grow, and the bulging blobs at their tips divide and link up like veins. In the subsequent exploitation phase, Physarum spans nutrient sources with a dynamic proximity graph (Voronoi pattern), where the links connect corresponding nodes. This network architecture is highly dynamic, allowing flexible rearrangement of junctions. As Physarum moves, the locations and sizes of the vertices and edges change, with some disappearing and new links and vertices forming. Since then, Physarum has been used to approximate other real-world transportation networks, including the Mexican highway, the Iberian highway, Route 20 in the USA, and the Autobahn 7 in Germany.

Kanto Region, Japan
Slime Mould Subway Experiment



The Biology of Physarum Polycephalum - Feedback Mechanism

Physarum protoplasm moves toward areas with the highest cAMP concentration while simultaneously secreting cAMP. This behavior creates a positive feedback loop, causing protoplasmic tubes with high cAMP levels to grow larger and those with low levels to gradually disappear due to lack of flow. Tubes that effectively transport nutrients will expand and offer less resistance, whereas those that do not transport enough nutrients will eventually vanish. This feedback mechanism enables Physarum to intelligently maximize nutrient sources and minimize transportation costs.

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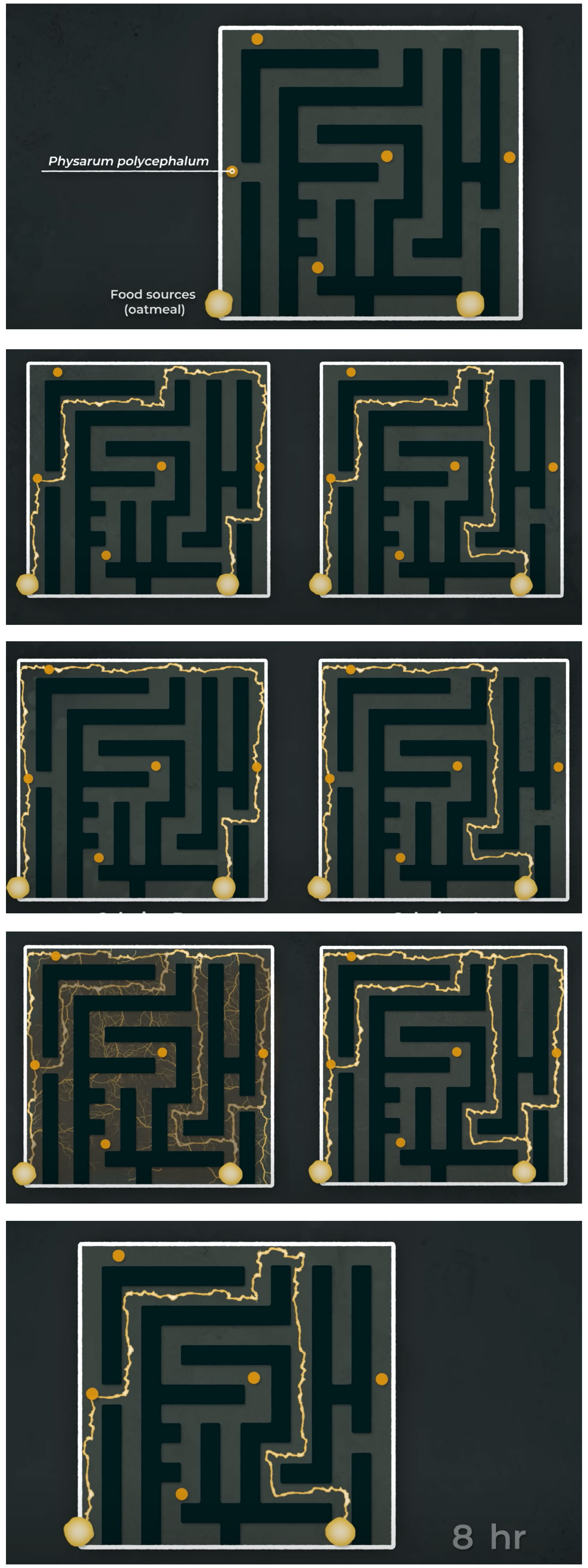
2000, Nakagaki
Japan/*Slime Mould Maze Experiment*



3h

4h

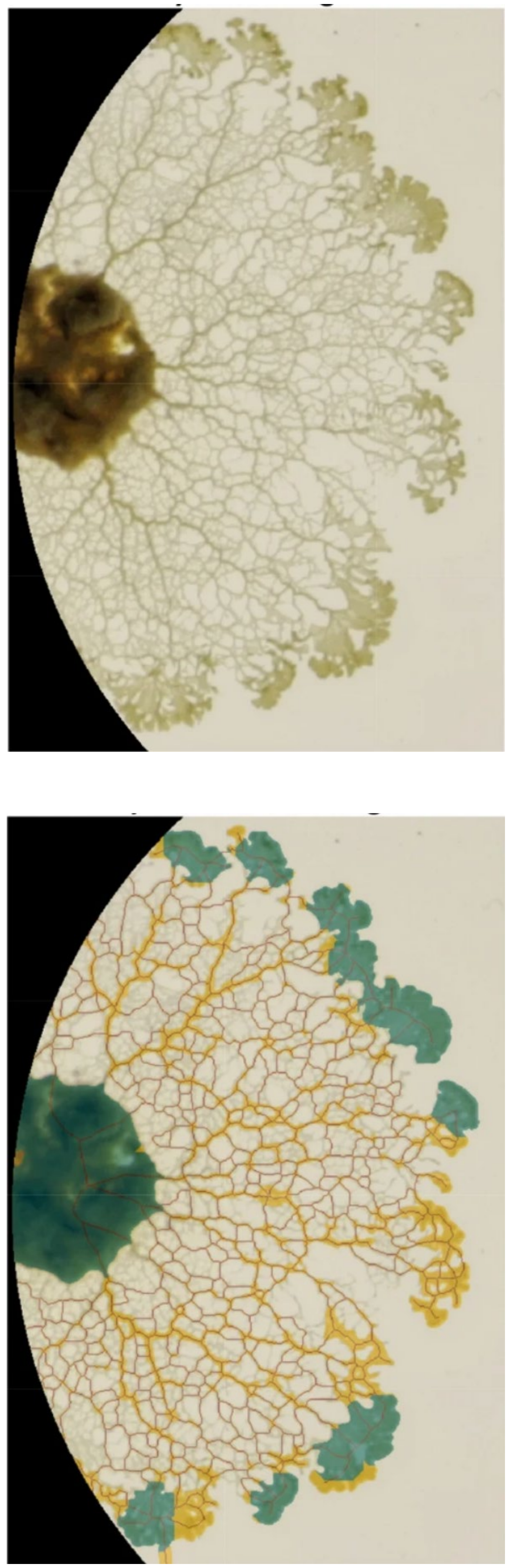
The Biology of Physarum Polycephalum - Memorising and Learning

Physarum can remember and anticipate repeated events, a behavior first identified by Saigusa et al. (2008) and further tested by Shirakawa et al. (2011) using associative learning experiments. Physarum secretes a slime trail during movement, serving as an extracellular spatial memory, which enhances foraging efficiency by avoiding previously explored areas. Physarum exhibits both short and long-term habituation, a simple form of learning. Information acquired during habituation, even to chemical repellents, is used as a "circulating memory" through constrained absorption of these chemicals.

https://www.nature.com/articles/s41598-020-80320-2

https://www.youtube.com/watch?v=nPOQQp8CCls

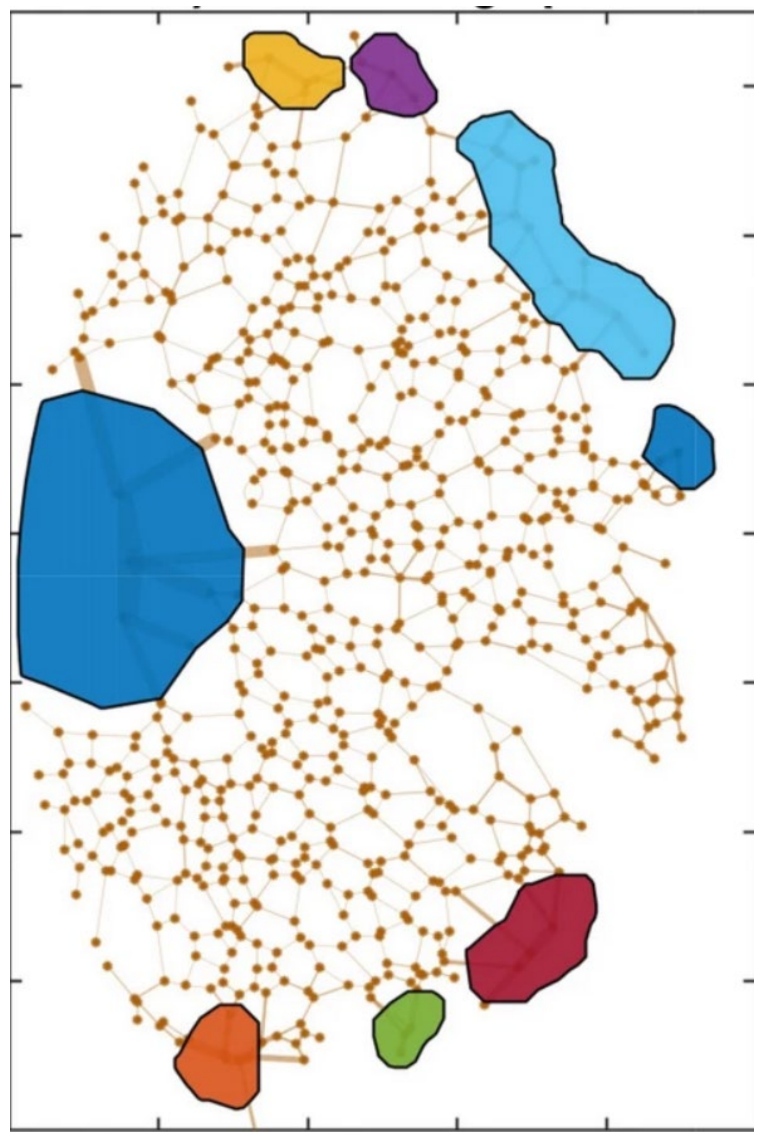
Slime Mould Network Dynamic



The Biology of Physarum Polycephalum - Feedback Mechanism

Studying the foraging behavior of Physarum Polycephalum, a plasmodial slime mould, and translating that behaviour into mathematical problems can inspire the development of bio-inspired algorithms to solve real-world problems. **Amoeba TSP** - an algorithm inspired by the plasmodium, found high-quality solutions that also increased linearly with the number of nodes. Scientists are exploring the possibility of using slime moulds as a physical computing medium. In a 2018 study, researchers created a slime mould computer chip which is made of a network of slime mould tubes coded with a conductive substance. It reacts to optimization problems just like a slime mould does and the conductor transmited the information quickly. The chip solves a wide range of computation tasks: optimization, computational geometry, robot control,.etc

Undirected graph: dots and segments correspond to nodes and edges respectively. Approximate location of clusters shown as colored polygons.



Physarum Polycephalum - Biological Experiments

Numerous experiments have demonstrated Physarum's intelligence, aiming to create mathematical models inspired by these biological experiments for solving real-world optimization problems. Such as:

Physarum Network Construction Experiment:

Tero et al. (2010) simulated the formation of the Tokyo railway network using Physarum. The experiment demonstrated that a single Physarum could form a minimum spanning tree connecting multiple food resources, representing various Japanese cities.

Physarum Solving Maze Experiment:

Nakagaki et al. (2000) showed that a single Physarum could solve a maze by finding the shortest path between two points, demonstrating its ability to solve the shortest path problem.

Shape Representation Experiment:

Jones and Adamatzky (2014) showed how environmental stimuli influence the growth parameter of Physarum, enabling transitions between convex and concave shapes. This highlights novel mechanisms of morphological computation and how Physarum can approximate shapes using chemo-attractants and light masking.

Living Cellular Automata Experiment:

Shirakawa et al. (2015) explored Physarum behavior in closed spaces, resembling a two-dimensional cellular automaton. They analyzed the movement of a single Physarum without attraction sources, proposing movement models based on statistical results.

Electrical Activity Experiment:

Whiting et al. and Traversa (2013, 2014) measured Physarum's electrical activity in response to stimuli, demonstrating how it adapts to attractants and repellents. Gale (2014) found that Physarum's protoplasmic tubes exhibit characteristics similar to memristor systems. Ntinas et al. (2017b) designed a maze-solving approach inspired by these electrical patterns.

Physarum Solving the Two-armed Bandit Problem Experiment:

In the experiment, Physarum chose the arm with higher-quality resources, showcasing its ability to make multi-objective foraging decisions by comparing relative qualities and integrating reward information. This experiment sheds light on the fundamental principles of Physarum decision-making and information processing.

Physarum Foraging Behaviour in Competition Settings Experiment

Stirrup and Lusseau (2019) conducted an experiment to observe Physarum behavior in competitive environments, placing two Physarum in a shared petri dish with one food source. Results showed that foraging time depended on hunger motivation, while initiation time depended on both motivation and competitor presence. Physarum initiated foraging quicker in the presence of competitors. In another experiment by Schumann et al. (2015), Physarum Polycephalum outgrew Badhamiautricularis, even overtaking its food resources. Physarum's success depended on its type, mass, and nearby food availability. Masui et al. (2018) studied Physarum allorecognition, finding that Physarum strictly identified allogeneic individuals and prioritized avoidance over fusion.

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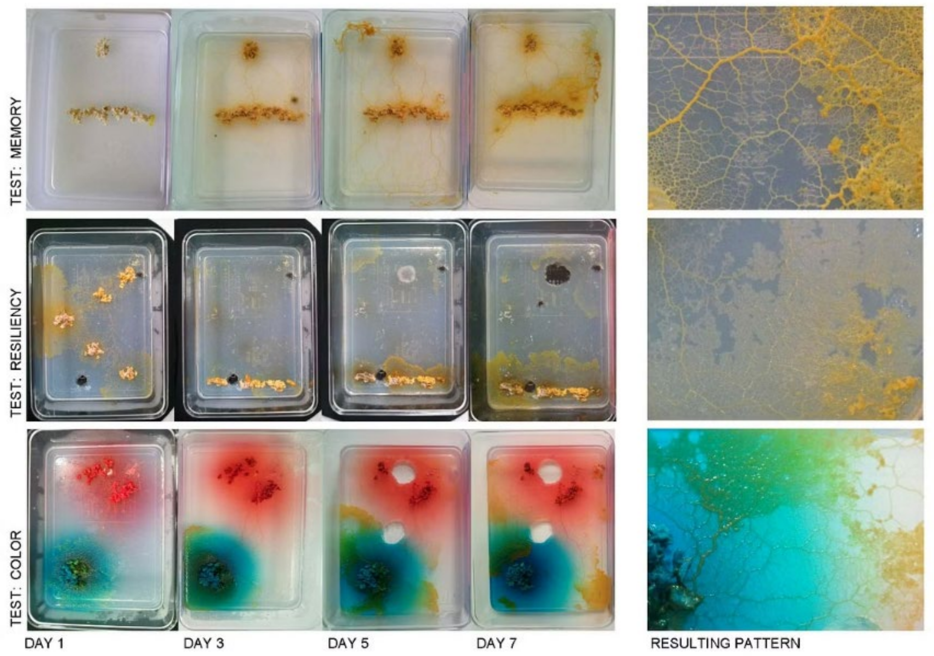
Physarum Polycephalum - Architectural Application

By drawing inspiration from Physarum Polycephalum's natural behaviors and properties, architects and designers can explore innovative and sustainable architectural solutions that are adaptive, efficient, and environmentally friendly. Physarum Polycephalum's unique characteristics and behaviors could be leveraged for architectural applications in several ways such as in:

- Network Design
- Adaptive Design
- Biological Computing
- Living Architecture

Physarum Polycephalum - Architectural Application Facade Example:

The research aims to utilize the biological properties of slime to create a structural bio-machine that enhances the cognitive relationship between users and space. It is divided into two main parts: the first involves analyzing the natural properties of slime, while the second focuses on applying these properties in an architectural context through computer-aided prototyping.



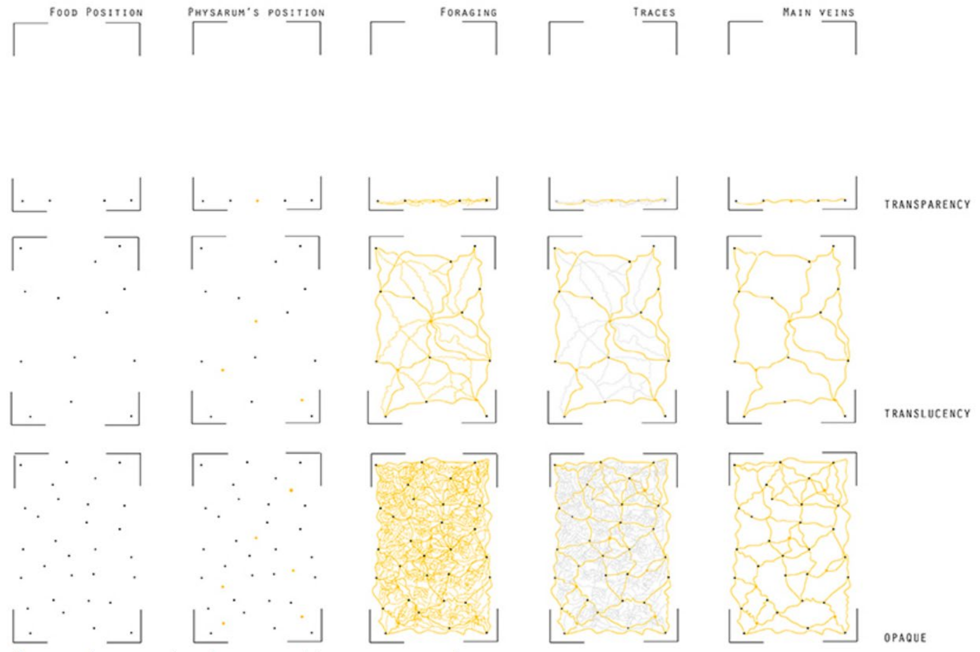


diagram of opaque, translucency and transparency performance

https://www.designboom.com/design/living-screens-slime-mould-iaac-11-01-2017/
https://archinect.com/allyn/project/slime-mold-bio-facade

The Biology of Physarum Polycephalum: Design Intention

The pathfinding quality of Physarum Polycephalum is the primary utility designers have harnessed in designing with this slime mold, as it is renowned for its incredibly efficient way to solve puzzles between point A and point B. With this in mind, our design intention is to utilize the simulation tools available to us to create a column capital design reminiscent of the structure of the Greek Corinthian column order. By using the slime mold's growth pattern, we aim to revise the aesthetic hierarchy of the column order into a digitally-augmented ornament, blending ancient architectural beauty with modern computational biology. This approach not only highlights the innovative potential of combining biological patterns with classical design but also explores new aesthetic possibilities through the lens of digital augmentation.

Simulating the Growth of Physarum Polycephalum

English computer scientist Jeff Jones have research into the formation of this fascanating creature. Recently, he published From Pattern Formation to Material Computation. In this book he adopted a synthesis approach and a mobile multi-agent system with very simple individual behaviors employed. The presented model reproduces the biological behavior of Physarum; the formation, growth and minimization of transport networks.

Rhino + Grasshopper
Physarealm Plugin

3D Growth of Slime Mould as an Architectural Application as an Ornament

By limiting the slime mould to the 3D grid, we are curious to examine how the mould will bridge the gaps between the elements. The slime mould's ability to grow in multiple directions suggests its capacity to form intricate three-dimensional structures, making it relevant to architectural considerations. Consequently, this single-celled organism can actively contribute as a co-designer in such endeavors.

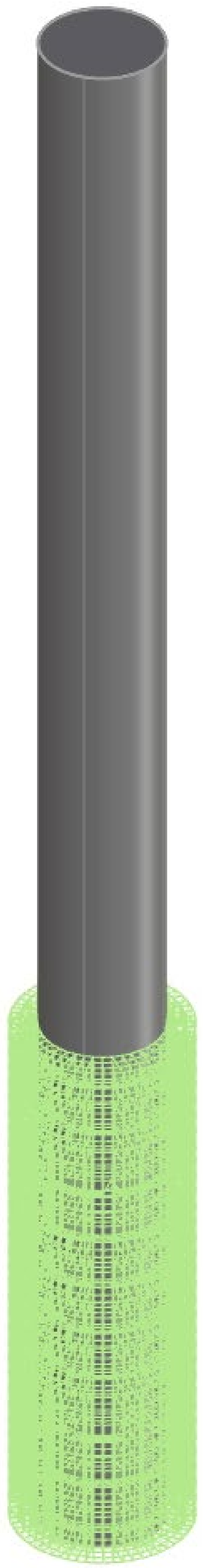
https://www.food4rhino.com/en/app/physarealm

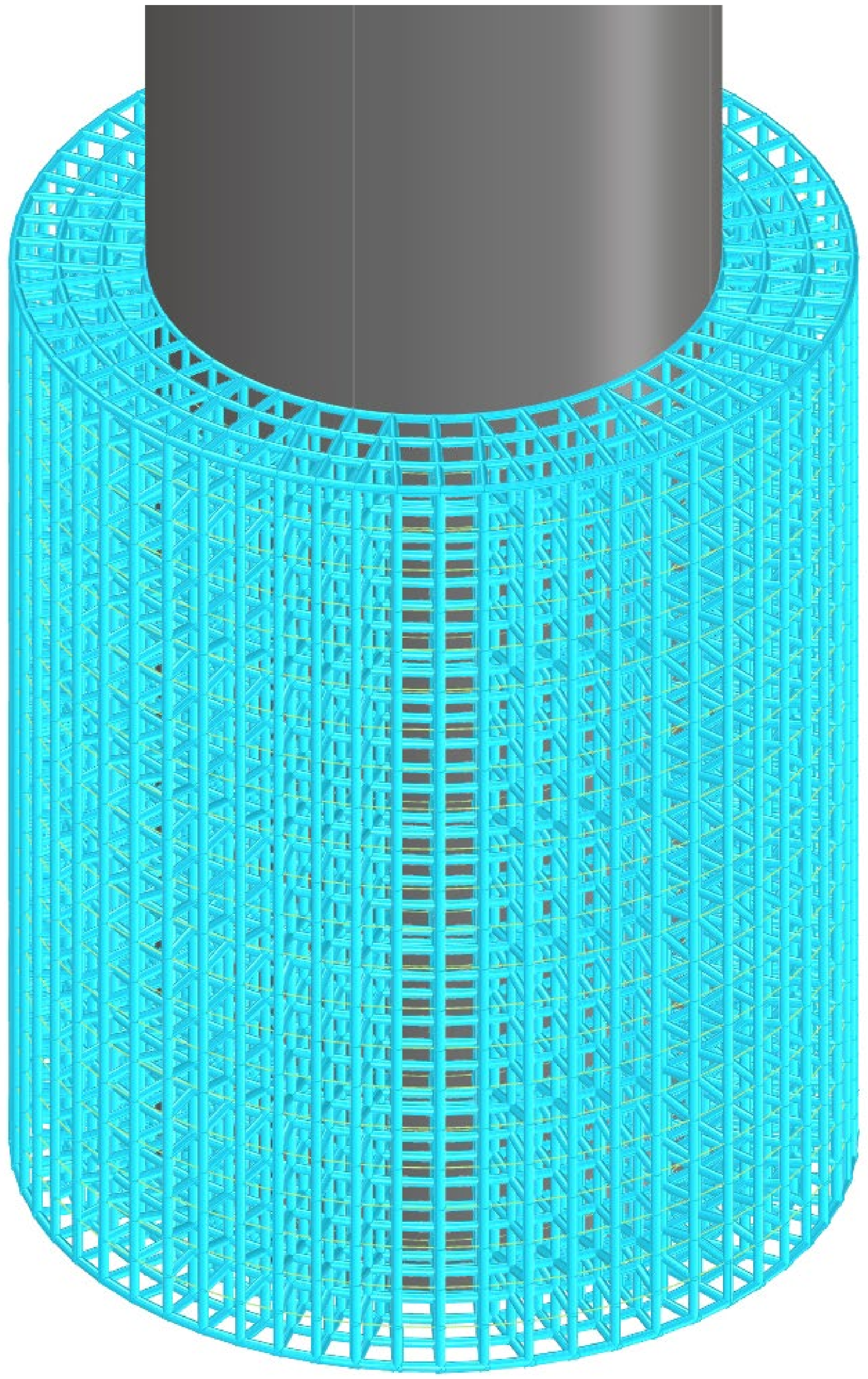
https://www.youtube.com/watch?v=WxvQmzvGQEo

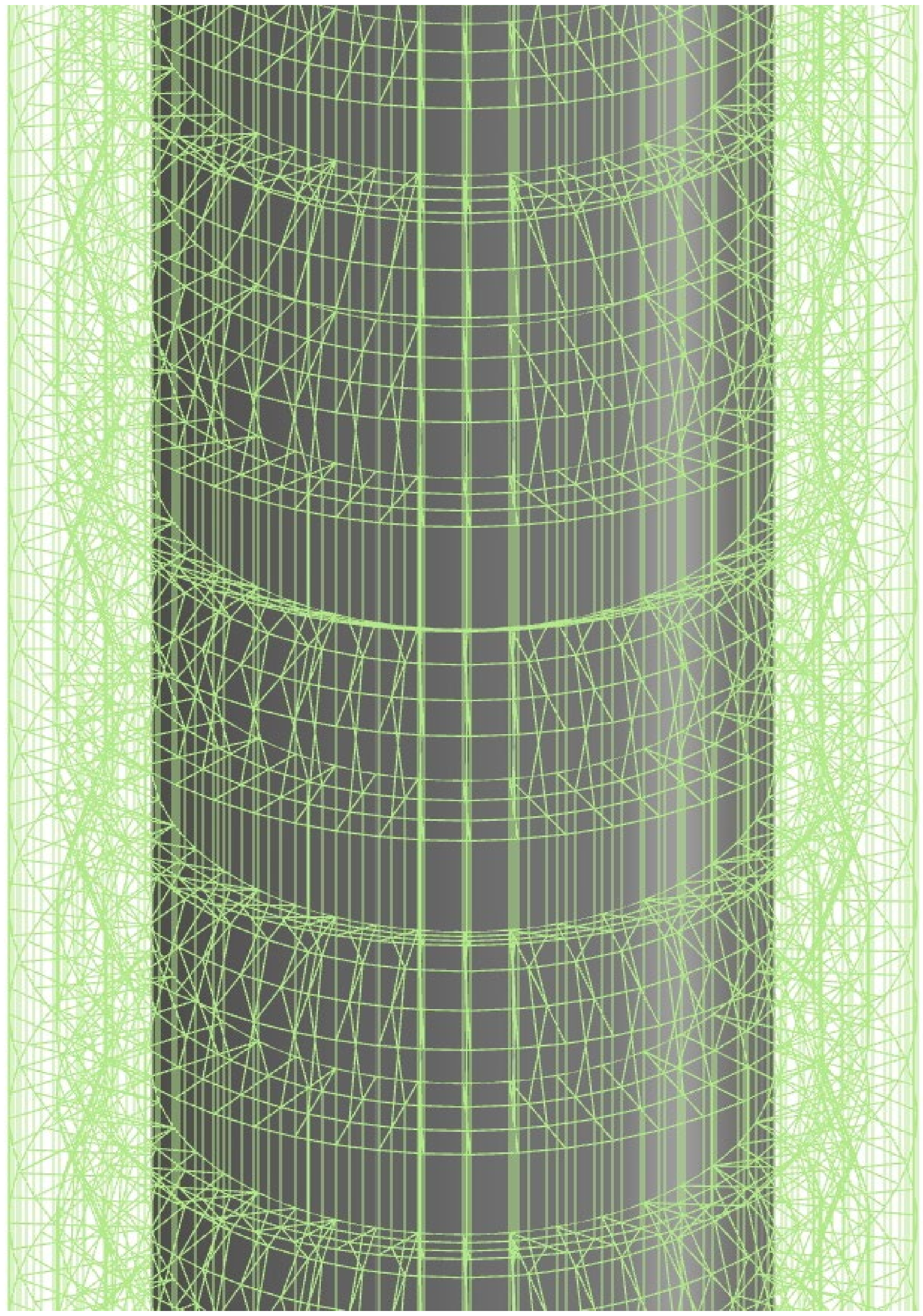
Designing with our Simulation Tools

In revisiting the lattice structure and fitting the Physarealm simulation tools into the lattice, the relationship between the column capial and the light parameters from Louis Kahn's precedent must be accounted for as well as the rectalinear framing of the lattice cells. In our early tests, we have found success in fitting the sim ulation tools into our structure and accounting for gravity, but we still need to examine how the placement of the food particles can trully affect the outcome of the simulation. Furthermore, we need to coopt a geometric language to inform with the movement of the particle growths that will inform the capital design. By cross-referencing withour planned slime mold growths, we will try to hone the results to peak accuracy.

Initial Tests
Simulation Results





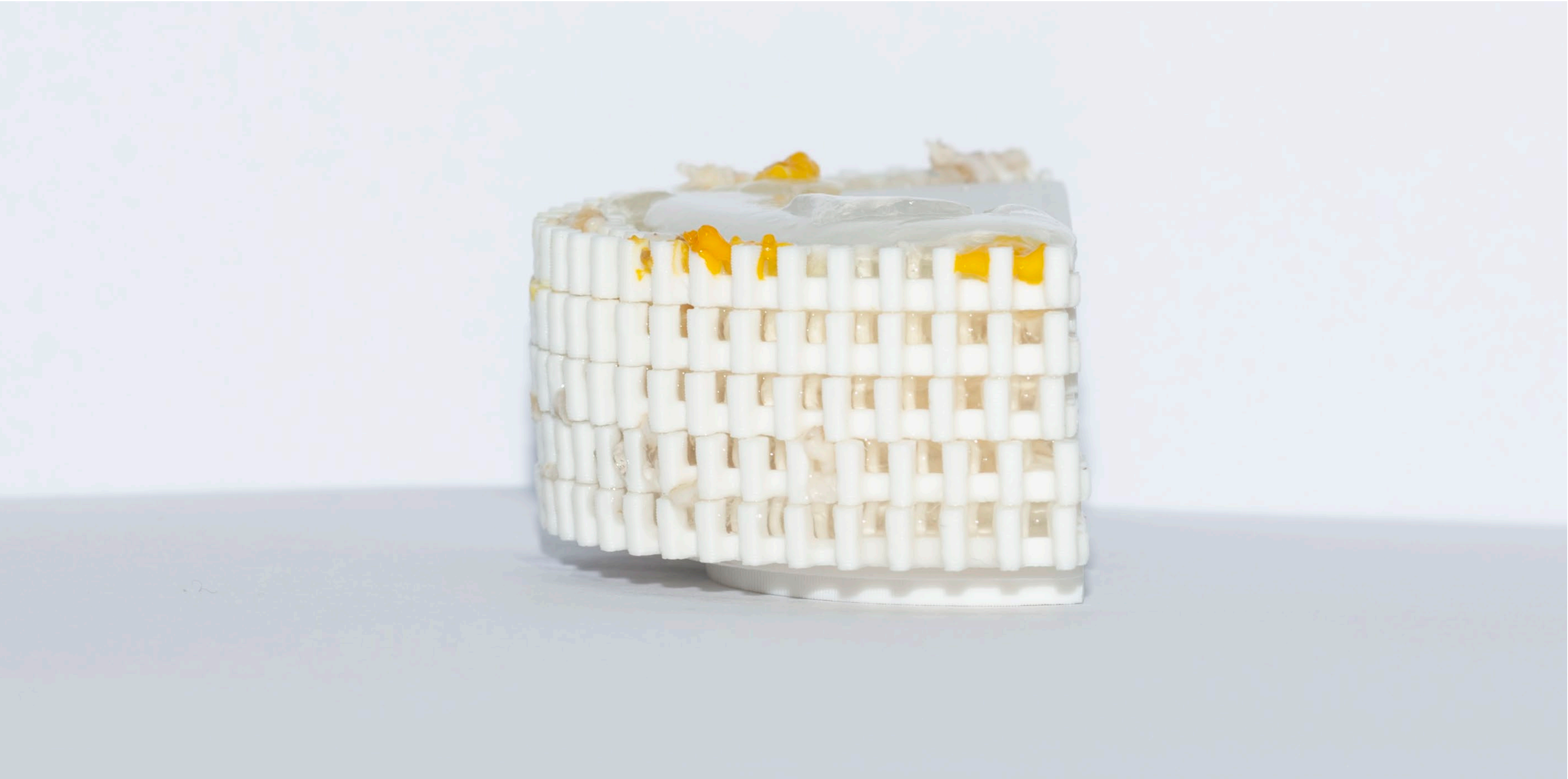
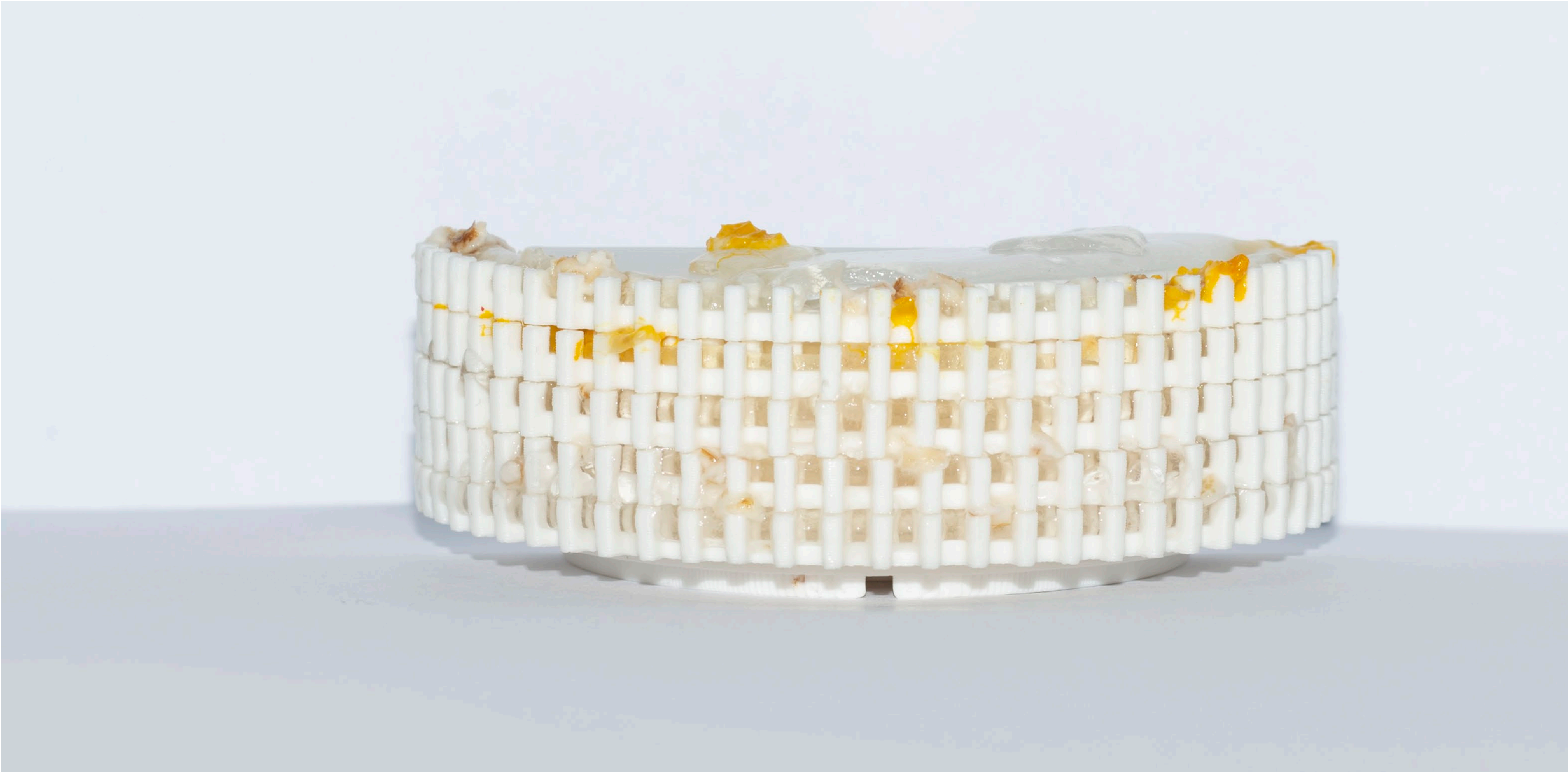


Slime Mold growth throughout the lattice structure

The Biology of Physarum Polycephalum - Feedback Mechanism

The slime mold's progress is carefully documented, with a focus on which food sources are reached at each layer and depth. Visual comparisons between the digital and physical models help identify any discrepancies and refine our understanding of slime mold navigation.The structured design allows for detailed observation of how slime mold navigates complex environments. This can lead to discoveries about its problem-solving abilities and decision-making processes. Food sources are placed at varying depths within each layer, adding a three-dimensional aspect to the feeding pattern. This placement simulates the complexity and depth of Corinthian column carvings, requiring the slime mold to explore different vertical levels to reach the food.

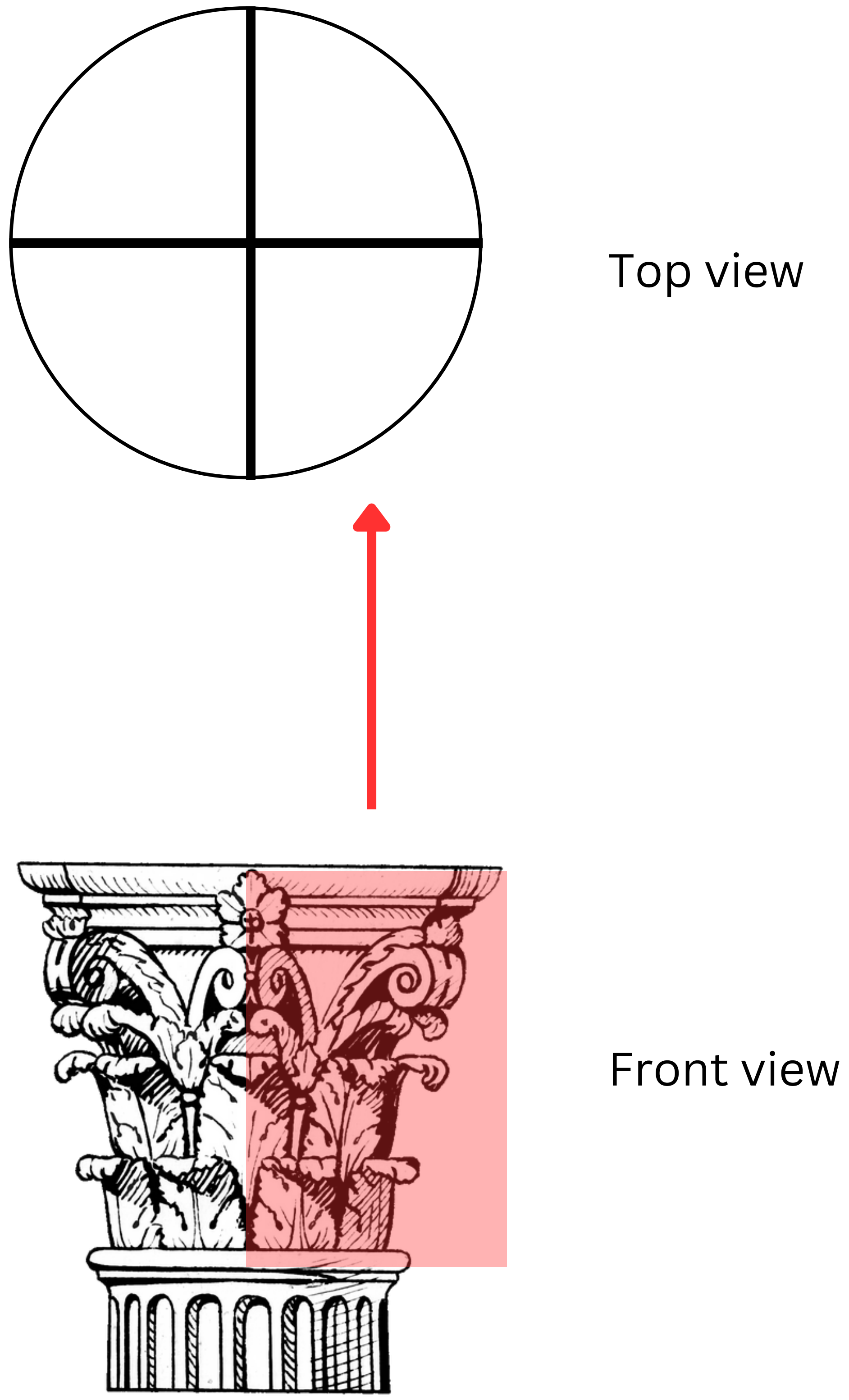
Food Source Placement:


Predictive Models and Practical Application

Our design uses the classical elegance of Corinthian columns to guide slime mold's exploration and feeding patterns. The intricate structure and layers of these columns provide a systematic approach to studying slime mold behavior in a controlled environment. By combining the architectural beauty of ancient columns with modern scientific inquiry, we create a visually appealing and scientifically rigorous framework for our experiments.

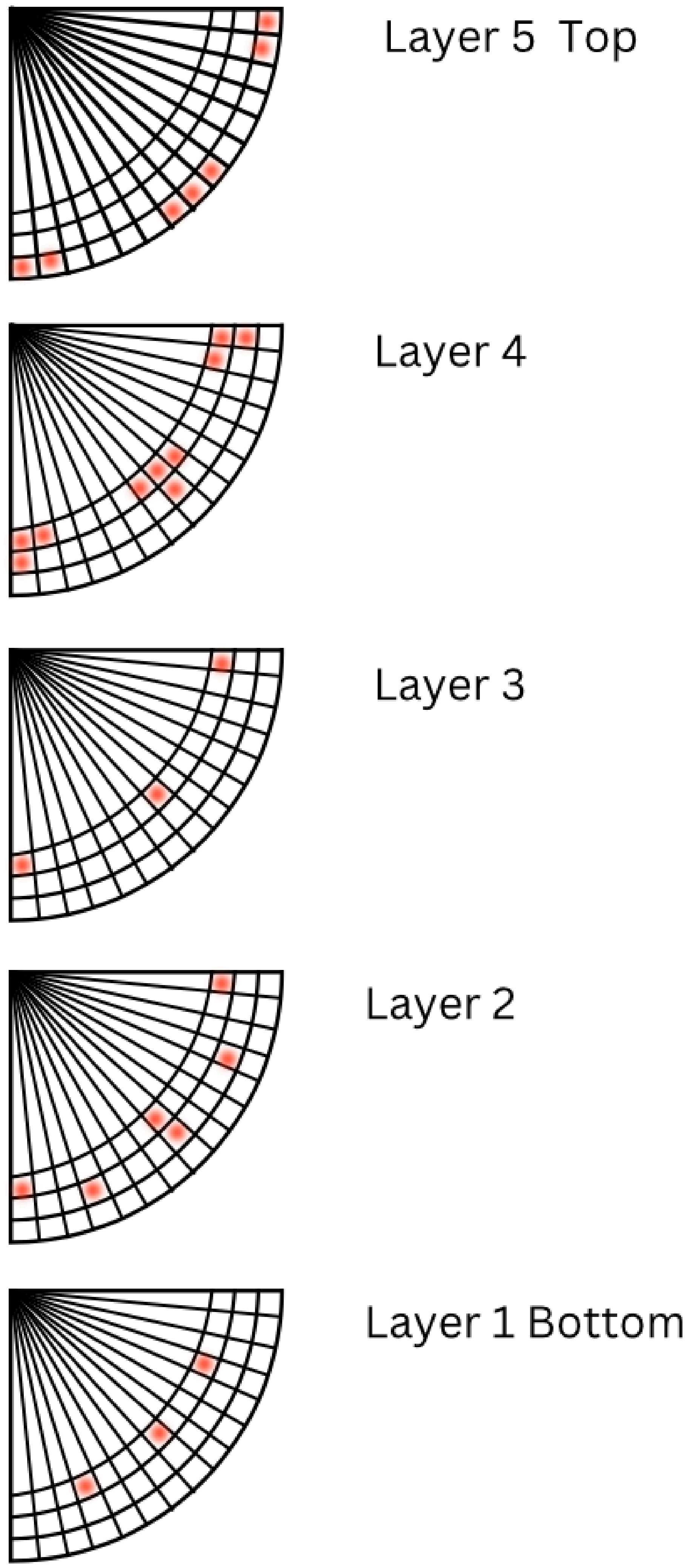
5 Layers:
The food sources are arranged in patterns inspired by the decorative motifs of Corinthian columns, such as acanthus leaves and scrolls. The design incorporates five distinct layers, each inspired by the different levels of a Corinthian column. These layers provide a structured framework that mimics the vertical progression and complexity of the column design.



Predictive Models and Practical Application

Each of these layers represents a distinct environment or set of conditions under which the slime mold operates. The red dots in these layers are strategically placed to act as food sources, enticing the slime mold to grow towards them. In the digital simulations, we have modeled these columns and the placement of food sources, mirroring the physical setup as closely as possible. The goal is to observe how the slime mold navigates through the digital environment to reach these food sources. By doing so, we can predict the slime mold's growth patterns and compare them with actual growth in the physical columns.

Depth and Intricacy:
Each layer varies in depth and intricacy, reflecting the ornate and detailed carvings typical of Corinthian columns. This variation introduces different environmental conditions for the slime mold to navigate.



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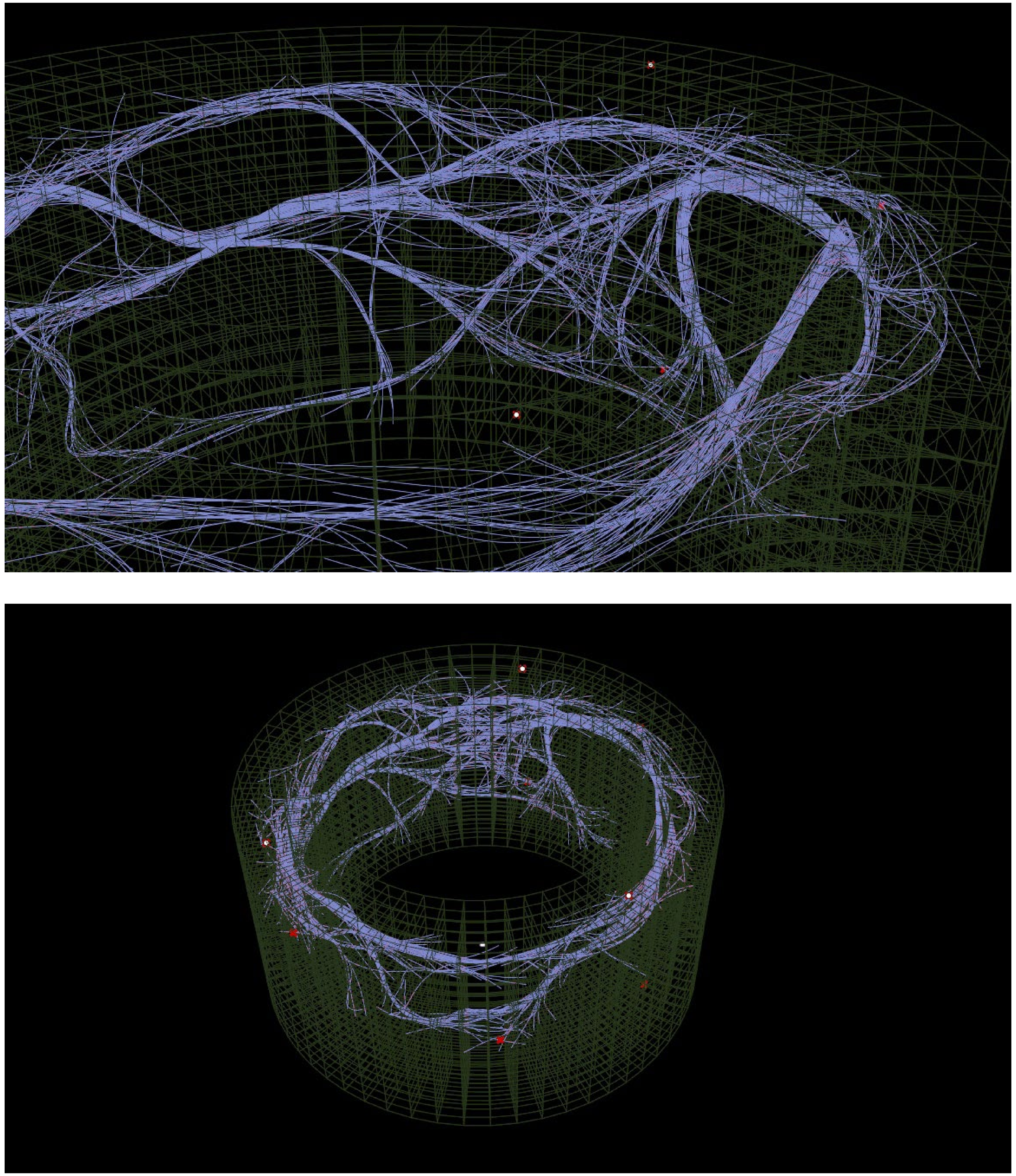
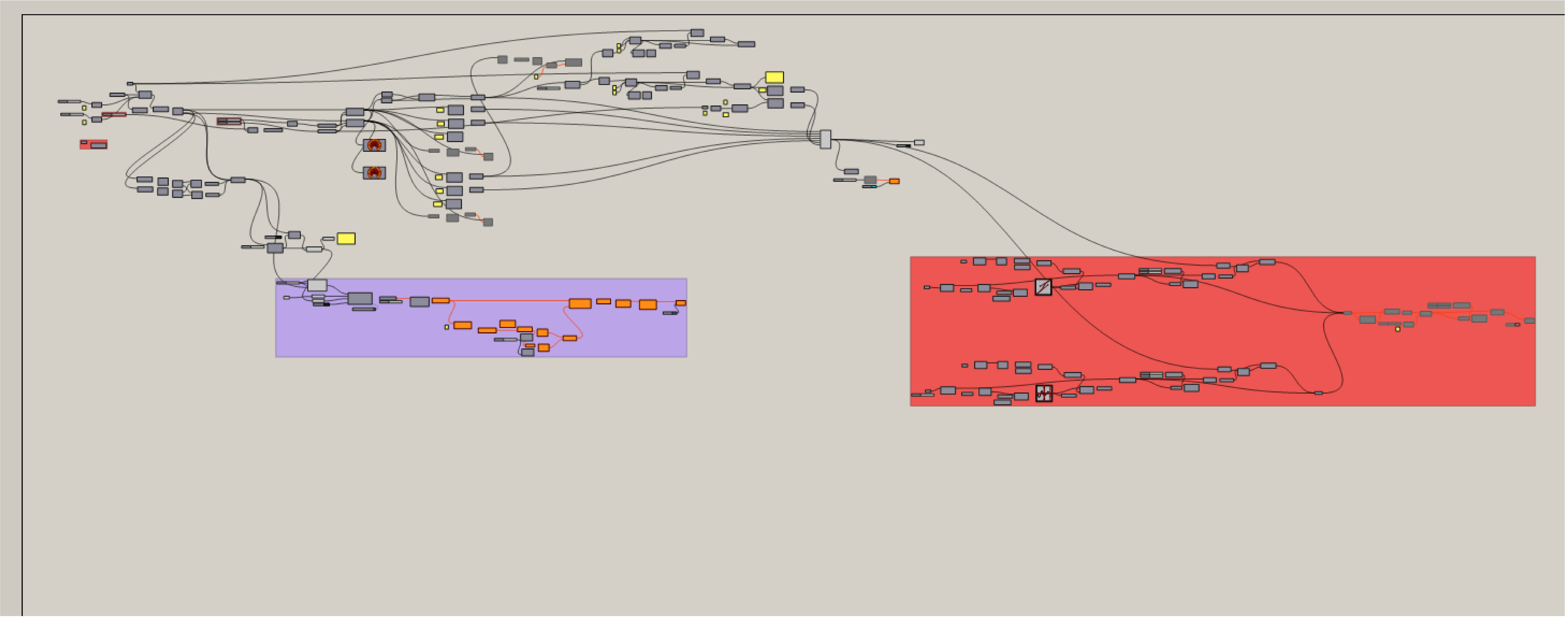


Slime Mold growth throughout the lattice structure

Initial Tests

Simulation Code



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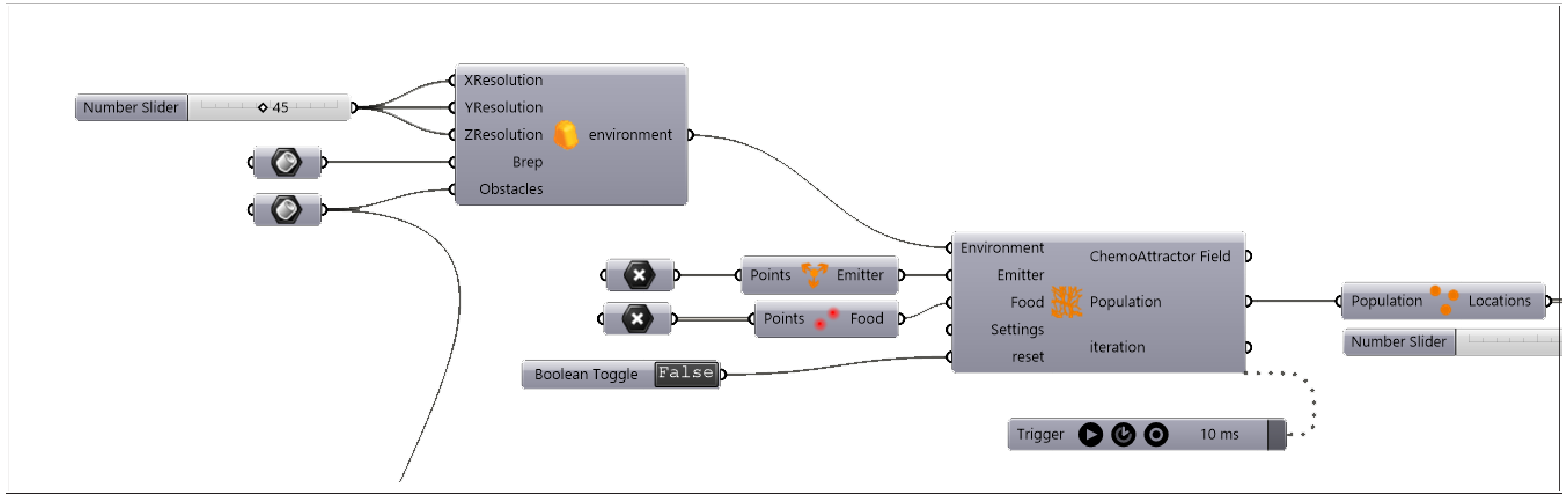
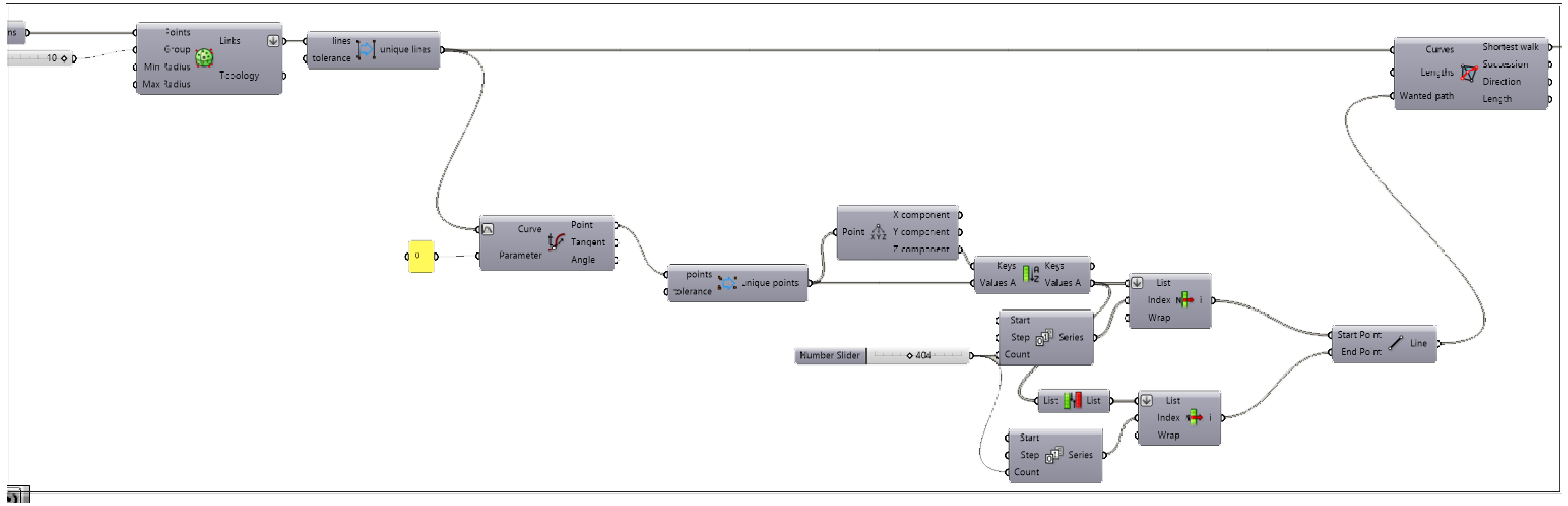
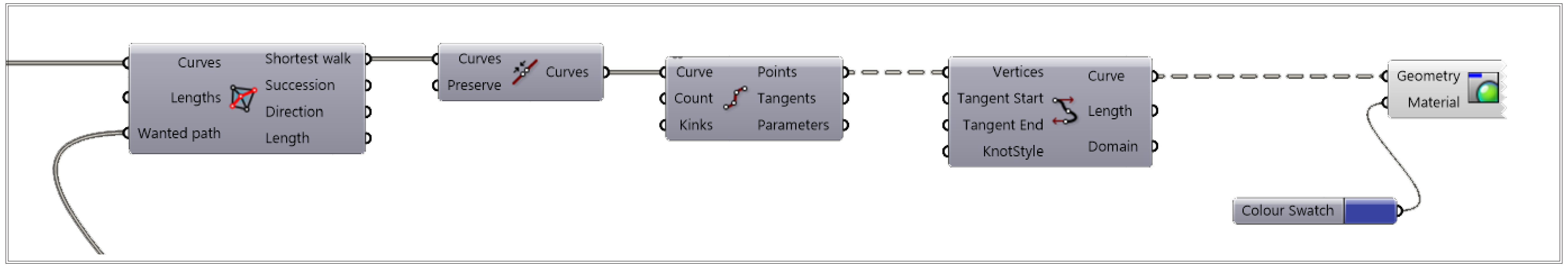






Predictive Models and Practical Application

When examining the code used to simulate this type of growth pattern, the tools are quite user-friendly. An input of "food" points and "emitter" points act as the point A and point B the pathfinding algorithm is to solve between and an environment of "Brep" geometry acts as the basis for collision. After the solver produces the clouds of points for each iteration over time, the code generates a cluster of lines which are then approximated, averaged, and interpolated are grenerated and act as the basis for which the hierarchy of the column capital is formed. The curves are then flattened and forced into a shortest walk algorithm, interpolated again, and then visualized for examination. Each moment in time during the itertive process of the script can be valid as an assessment of the column structure by the code, so the process is as ephemeral as the organism itself.

Structural Investigation:

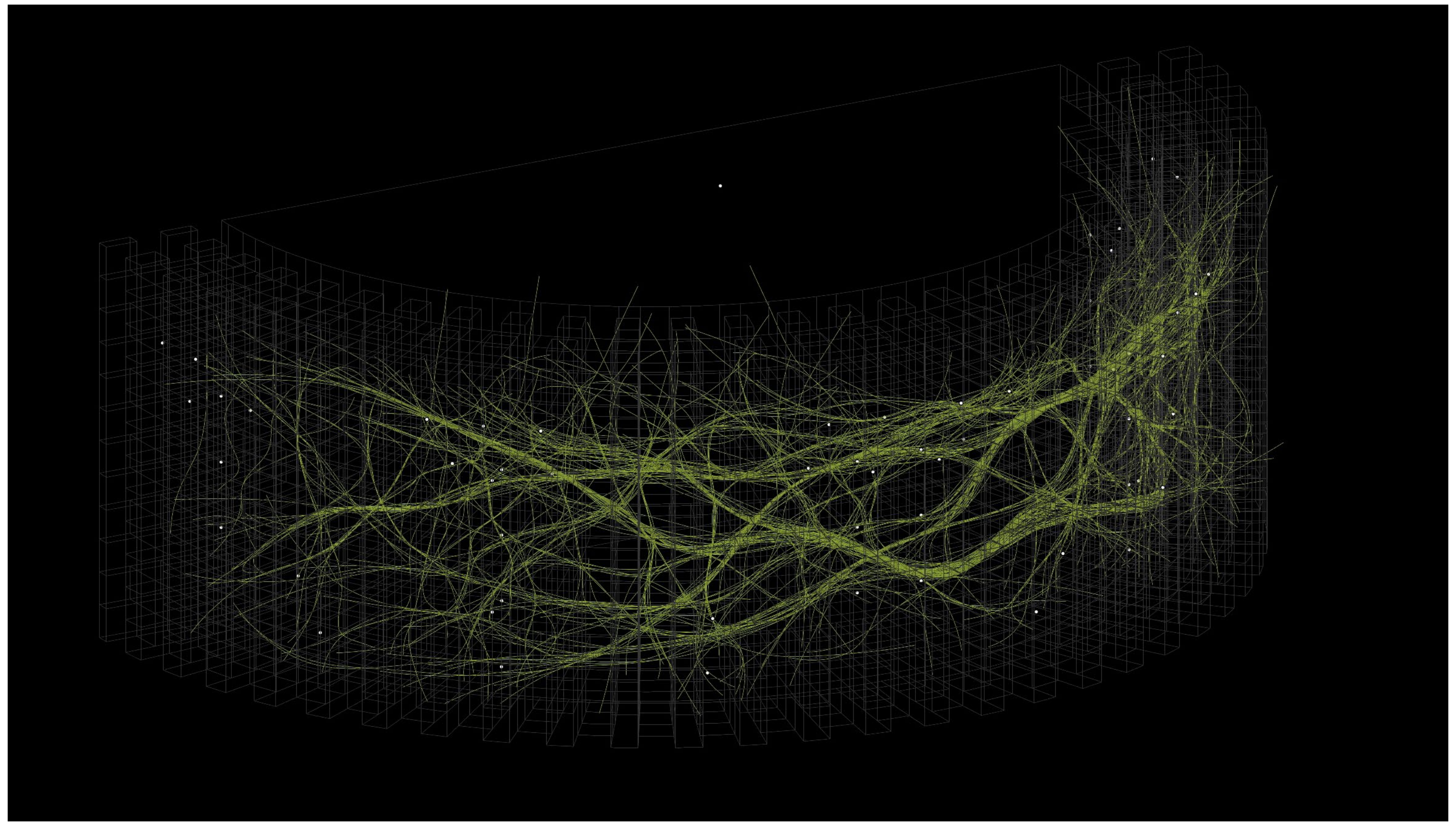
The simulation excels in analyzing the broader structural patterns and characteristics of slime mold growth. It helps us understand the general rules and principles that govern the organism's behavior, such as its network formation, efficiency in finding food sources, and adaptation to environmental changes. By examining these structural qualities, the tool provides insights into the underlying mechanisms of growth and development, which can be valuable for theoretical and conceptual studies.

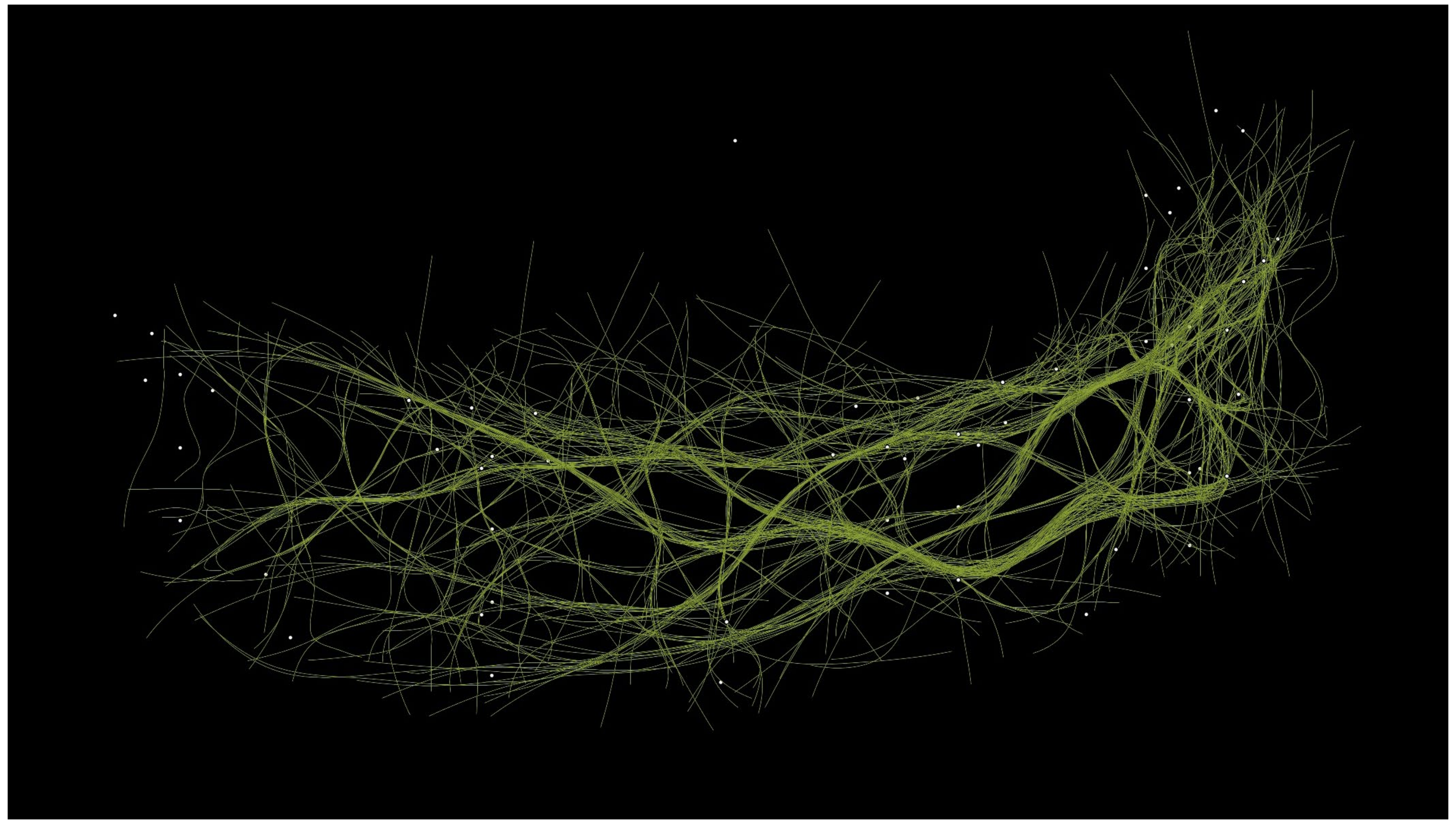
When used to fit mathematical models to the observed behavior of Physarum Polycephalum, the simulation tool is quite effective. It allows to test hypotheses and refine models that describe the organism's growth dynamics. This form-fitting process helps validate and improve mathematical representations of the slime mold's behavior, contributing to a better theoretical understanding of its growth patterns.

Predicting Growth Patterns:

The tool falls short in predicting the exact growth trajectory of a single organism in real-world conditions. The complexity and variability of individual slime mold growth, influenced by numerous environmental factors, make precise predictions challenging. Each slime mold organism may exhibit unique behaviors and responses that are difficult to replicate accurately in a simulation, leading to discrepancies between predicted and actual growth patterns.

Real-world experiments provide critical data that capture the nuances of slime mold behavior, which simulations alone cannot fully replicate. Thus, physical trials remain indispensable for validating and refining our understanding of the organism's growth.





Predictive Models and Practical Application

As we have discovered, the simulation tool we had access to is much less of a tool that should be used to predict the individual growth of one organism of Physarum Polychephalum and more of a tool to investigate the structural characteristics inherint to the quality of growth of the organism. If using it for the purpose of form-fitting with the mathematical breakdwon of the organism, it is successful. However, fot the purpose of cross-referencing with an existing trial to evaluate accuracy, the simulation tool is decidedly not a replacement for a real-world test.

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