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A critique of Physarum computing in architecture focusing on the role of digital and physical computation and the relationship between evolution and the built environment.

Physarum computation in architecture: a critique of bio-digital design

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Nature has always been a source of inspiration, solution, and creativity in architectural design. This relationship between nature and architecture has been influenced by developments in several disciplines, including but not limited to biology, chemistry, physics, mathematics, and philosophy. Undoubtedly, the introduction of evolution theory was one of the exceptional scientific developments that provided epistemological coherence to biology.[1] Before this, the general assumption was that there is a hierarchical, fixed, and non-transformable natural system in which every living creature shows a degree of perfection on the ladder of being.[2] With advancements in evolution theory that started with Charles Darwin, organisms were understood as evolving and changing systems under the influences of natural mechanisms.[3] In time, evolutionary processes in nature began to be conceptualised and evaluated at different scales from gene to organism and environment.[4] Subsequently, thanks to developments in computer science techniques, natural systems have increasingly been represented by computational evolution models.[5] From the early 1990s, architects started to propose design methodologies that utilise simulations of evolutionary processes as a design logic. Since the mid-2000s, they have also started to directly integrate physical evolutionary processes into design procedures and prototypes.[6]

Historically, there have been two main computational approaches for applying evolutionary processes within architectural design methods. The first approach utilises digital computation to represent computational models of evolutionary processes from micro to macro scales for form-finding experiments.[7] In these design experiments, digital computation provides an indirect and abstract connection to physical evolutionary processes because everything must be defined as an algorithm – a simplified representation of a biological system. The second approach proposes to go beyond simulating evolution to directly integrating physical evolutionary processes into the architectural design process itself, thereby creating reciprocal feedback between synthetic and biological systems within the built environment.[8] Digital computation is also sometimes used to simulate the behaviour of organisms to anticipate their growth and change over time. However, the novelty in these design experiments is embedding physical evolution processes into architectural design through material interaction, which takes place through a direct interaction of living organisms or non-living materials with their environment. This development has led architects to contemplate the vision of a complete and straightforward association between physical evolution, computation, and architectural design.

One of the living organisms that has started to be observed and integrated into architectural design processes is Physarum polycephalum, a single-celled and multi-headed slime mould. If foods are distributed spatially within an environment, Physarum polycephalum creates an optimised network of protoplasmic tubes that grow and evolve to connect food sources. After millions of years of evolution, Physarum polycephalum has gained distinctive features to continuously optimise metabolic efficiency regarding the balance between energy consumption and its growing network structures. In the last fifteen years, architects have begun to experiment with the physical computation capacity of living Physarum polycephalum and its digital simulation as a co-designer for road network optimisation, urban design, 3D form-finding, and the development of building components. Various bio-digital design concepts for integrating living Physarum polycephalum and its algorithmic representation into architectural design have emerged that point the way to a paradigm shift in how designers can exploit biological processes.

Evolution is a process that takes place within various timeframes and scales in nature. Biological evolution is commonly understood as the change of species populations over generations, mainly led by natural selection.[9] The change of individual organisms within their lifetime has generally not been considered an essential part of the evolutionary process. However, more recent research in evolutionary biology demonstrates the fact that inherited traits during an individual organism's lifetime can heavily affect variation and natural selection processes.[10] For this reason, the developmental processes of organisms have an essential impact on the direction of evolution in populations.[11] Evolution processes are not just about how populations change over long periods of time but how organisms themselves change and adapt to various exogenic factors within their lifetime, which include morphogenesis and developmental processes.

This broader understanding of evolution is critical to realise that the growth of Physarum polycephalum, as well as its change and response to environmental conditions, is an evolutionary process. Physarum polycephalum imbues physical computation characteristics that are quite different from digital computation because these take place through direct interaction with physical matter and the environment it inhabits. For this reason, exploiting Physarum polycephalum's computational processes within the design process may provide new perspectives regarding the relationship between biological evolution, computation, and architecture. Although many design theories and models have been proposed for the utilisation of Physarum polycephalum in architectural design, there is still little research evaluating its critical design limitations and how digital and physical computation can act as a bridge between evolutionary processes and architectural design. Current bio-digital design theories concerning the application of Physarum polycephalum and its potential future as a co-design tool for the built environment have been barely challenged to date.

This article discusses the significance and future potential of Physarum polycephalum, foregrounding and evaluating various bio-digital design approaches that have been recently proposed by architects and designers working with the organism to expand the boundaries of architectural design. The article focuses on the limits, potentials, and differences between physical and digital computation. It critically reviews bio-digital design possibilities, proposing various ways in which Physarum polycephalum can enable alternative approaches to communication between evolution, computation, and the built environment. The idea of integrating the intelligence and cognitive processes of Physarum polycephalum into architectural design is challenged by referring to the characteristics of both digital and physical computation procedures. Moreover, the challenges arising from the scale and context differences between Physarum polycephalum and design project sites are discussed. The original contribution of this work is in establishing a first comparative review of Physarum polycephalum's applications in architectural design processes through a critical methodology founded upon the theory of digital and physical computation.

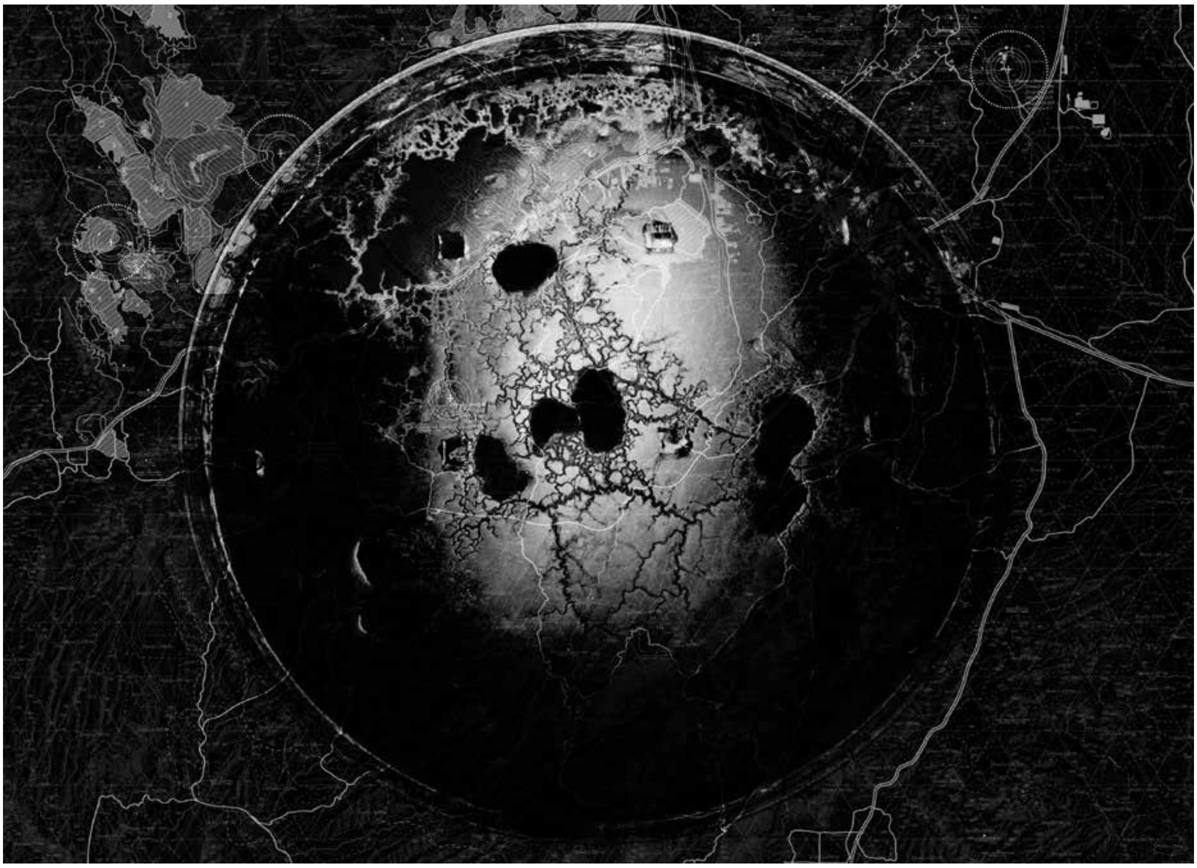
In the first part of the article, Physarum polycephalum is introduced, and the characteristics of its physical computation capacity are discussed in relation to the theory of computation. The main differences between the physical (unconventional) computation of Physarum polycephalum and its simulation through digital computation are evaluated, and the reason why these differences are important for bio-digital design arguments are explained. The second part reviews the utilisation of Physarum polycephalum at urban design and building scales, focusing on the nature of employed computational procedures. In conclusion, the importance of utilising Physarum polycephalum in the history of digital architecture is expressed regarding its potential relationships between evolution, computation, and architectural design.

Physarum polycephalum and computation

Physarum polycephalum was initially discovered in 1822 by mycologist Lewis David von Schweinitz. The organism has subsequently been studied as a classical model organism in cell and developmental biology research to understand the evolution of cognition.[12] In its plasmodium stage, the organism starts foraging behaviour and creates an efficient tubular network connecting food sources. It can also perceive external attractants or repellents and anticipate the timings of periodic events.[13] The organism's behaviour comprises a simple feedback mechanism between signalling molecules and fluid flows.[14] Therefore, without centralised control (a central brain), it can form the shortest route between foods in a maze and build an optimal network in terms of cost, transport efficiency, and fault tolerance compared to existing rail networks.[15] Such behaviour demonstrates Physarum polycephalum's physical computation capacity through primitive evolutionary intelligence, which has attracted computer scientists to consider exploiting its computation properties as part of a bio-computer.[16]

The act of computing can be defined in several ways. Different kinds of computation processes reveal various interpretations of computers since computation is embedded in the quality of any computer.[17] A typical characterisation is that a computer as a device or machine, takes data, processes it according to a set of instructions, and then creates results.[18] In a general sense, the accepted data as input and produced as output can either be in discrete or continuous form. Digital computation processes data in discontinuous form through 0 (off) and 1 (on) syntax functions. On the other hand, analogue computation employs continuous linear quantities to represent physical magnitudes, such as differential analysers designed to solve differential equations.[19] Various systems of communication can have both digital and analogue computation working together.

In this context, Physarum polycephalum's physical computation characteristics are quite similar to analogue computation as the organism's action emerges from continuous material interaction within a physical environment. Evidently, digital computation can be used to simulate the behaviour of Physarum polycephalum



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1 Living Physarum polycephalum's computing and growth directed by light fields and nutrient sources on a 3D-printed substratum morphology of the copper mining zone in Arizona.

as algorithmic codes. However, it is essential to understand that logical description of any physical process through digital computation can be achieved in countless ways. It is impossible to completely describe physical processes using digital computation as any computational representation includes abstraction and simplification due to the ontological difference between digital simulation and the physical world.[20] One needs to be mindful when thinking about the potential of digital simulation as it is a reductive process and is therefore insufficient for fully encoding all the physical processes related to a given living organism.[21] As biological processes do not synchronise with logic and symbol-based digital computation, exploring new kinds of computation is essential to reveal the very fabric of evolutionary processes.

The desire to move beyond the restrictions of digital computation can be found in unconventional computing research. The computation capacity of Physarum polycephalum (i.e., Physarum computation) has been considered part of this unconventional computing approach since the organism's behaviour does not follow the digital computation rationale. Unconventional computation uses natural features and processes of non-living or living materials to develop non-standard algorithms and computation procedures.[22] The main interest is to take advantage of emergent behaviour, self-organisation, fault tolerance,[23] and efficiency in natural systems, contributing to their capacity to survive and adapt to various environmental conditions. Nevertheless, unconventional computation has disadvantages, including the challenge of sufficiently and accurately representing some computational problems suitable to the physical computing format, which takes place through material interaction. Also, there is no complete stop function when a problem is solved since physical computation in nature is a continuous process.[24] These challenges are also valid for Physarum computation as it does not necessarily try to solve a computational problem that can be predefined by humans. Instead, the organism struggles to survive by finding the food sources in the environment to support its own evolution.

Physarum computation has been considered a reaction-diffusion computer embedded in a growing living material. As a class of unconventional computing, reaction-diffusion systems perform computation through growing patterns and interaction of waves and can solve combinatorial problems in finite systems with parallel processing.[25] In some ways, Physarum computation differs from other unconventional computing procedures such as DNA, protein-based, or amorphous computing since their computation does not take place through the decision-making of a living organism.[26] In the plasmodium state, Physarum polycephalum demonstrates a growth behaviour, creating graph geometries in which nodes and edges responsively change depending on the interaction of the organism with external environmental conditions. Therefore, Physarum computation can solve some problems that reaction-diffusion computers cannot solve, such as the shortest path or spanning tree. However, Physarum polycephalum also has limitations, including slow computation speeds, strict environmental regulations, unpredictability, and the necessity to represent all problems as spatial configurations.

Some restrictions of Physarum computation can be overcome by simulating the organism's behaviour through digital computation. Several modelling techniques like cellular automata, agent-based systems, and differential equations have been used to simulate its behaviour by focusing on the organism's morphology, taxis, and feedback dynamics. However, generated computational models are only abstract and simplified representations of the organism and its dependent environmental conditions. Computer scientist Andrew Adamatzky claims that Physarum polycephalum is capable of *universal computation*.[27] Even though Physarum computation achieves some basic logic operations, the model's reliability is low because its behaviour can change depending on several factors.[28] Physarum polycephalum can only be partially controlled due to its living agency. This realisation highlights the main differences between digital computation and physical computation. Although digital computation works depending on descriptive logic and mathematics to represent evolutionary processes in nature,[29] the physical computation agency of Physarum polycephalum is about its continuous material growth and change which occurs in real time within the physical environment. This complex relationship between synthetic and biological systems cannot be completely modelled through digital computation.

Understanding the differences between the physical computation characteristics of living Physarum polycephalum and its representation through digital computation procedures is extremely important in developing a critical approach to fully understand its potential in the built environment. It is essential to realise that utilising both living Physarum polycephalum and its simulation have distinctive implications for bio-digital design in terms of incorporating its intelligence/cognition in the built environment and addressing scale challenges. These will be revealed by discussing how architects have begun experimenting with living Physarum polycephalum and its computational representation in design processes from building to urban scales. The interpretation of digital and physical computation will be used as a critical instrument for reviewing the bio-digital design theories in terms of the relationship between evolutionary processes, computation, and the built environment.

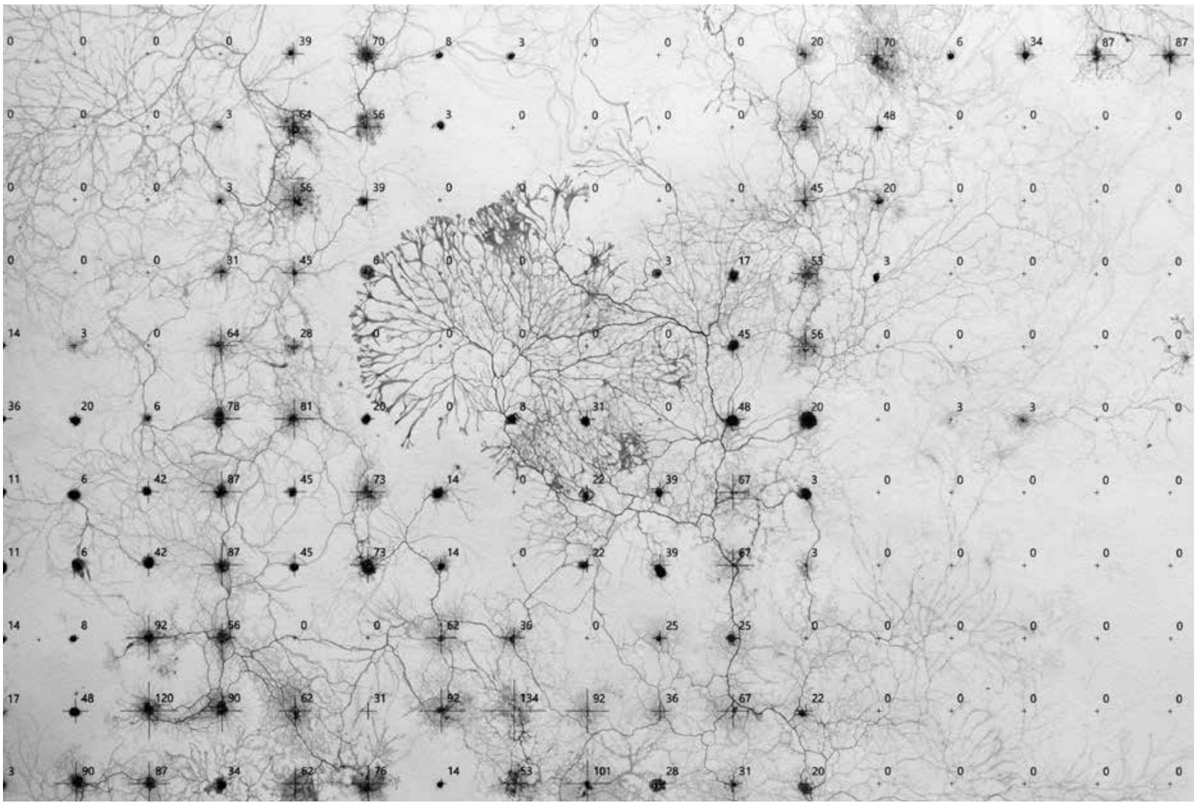
Physarum computation in architectural design

In the last fifteen years, architectural designers and computer scientists have used the physical computation capacity of living Physarum polycephalum and its simulation through various digital computation procedures. The scales and the contexts of the projects range from urban design, the three-dimensional form-finding of building surfaces, or forms to the design of building components. Architects have proposed diverse bio-digital design concepts in all these projects, claiming various connections between the physical world and the digital domain. The main interest has been in exploring the non-human agency of Physarum polycephalum as a computational tool within design. Architects attributed many abilities to living Physarum polycephalum and its simulation to introduce its intelligence and cognitive aspects to urban and building design contexts. They have faced the challenge of scaling up, while integrating and validating the application of Physarum polycephalum's growth processes in the context of real-world design projects.

Urban scale

The initial prompt for the introduction of Physarum polycephalum in urban design was the realisation of the organism's capacity to produce scalable patterns for network design. It was demonstrated that without centralised control, living Physarum polycephalum created dynamic adaptive networks that exhibited inherent efficiencies, fault tolerance, and cost optimisation compared to existing networks employed in the Tokyo rail system. In subsequent studies, simplified and scaled-down physical models of several real-world topographies have been inoculated with living Physarum polycephalum to generate growing dynamic networks connecting food sources, which represent geographical locations of cities or urban areas.[30] Thanks to its optimisation capacity, Physarum polycephalum created similar growth networks comparing actual roadways or highways under suitable environmental conditions.[31] However, in some cases, the networks created by Physarum deviated from the original network and did not generate certain parts of these due to several reasons, including the autonomy of the organism, undesirable environmental conditions, and overly simplified models of the physical topography.

Nevertheless, realising the strong correlation between real-world networks and the growth of living Physarum polycephalum has led scientists and designers to find ways to simulate the organism's behaviour and explore its design potential further; including using cellular automation, agent-based systems, and differential equations for network planning purposes.[32] While cellular automation-based models working on grid cells failed to simulate Physarum's thickened protoplasm, agent-based models are always attracted to food-rich locations, simulating only the contraction behaviour and failing to capture its inherent searching and retraction

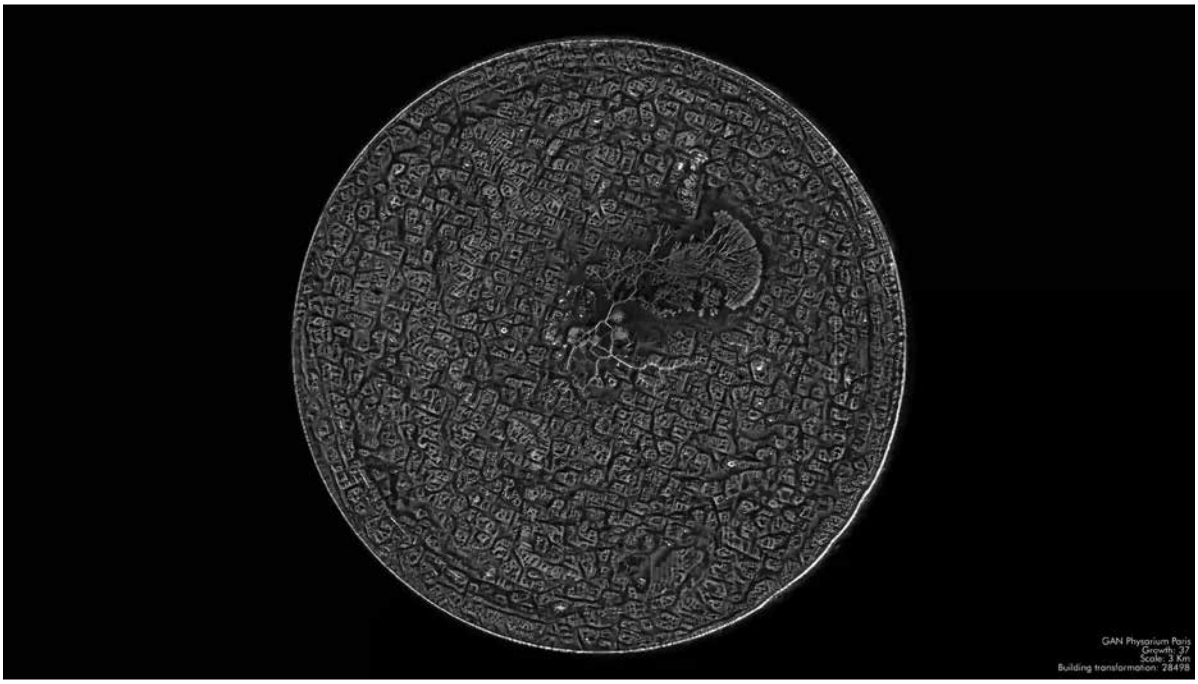


2 **Living Physarum polycephalum's growth on the canvas, connecting food resources that represent the distribution and density of biotic layers of Paris.**

mechanisms.[33] More recently, another approach proposed separating two stages of Physarum polycephalum's growth to provide stepwise design control for a bio-inspired urban design network.[34] It focused on attractor-based information to simulate Physarum's behaviour, ignoring the impacts of repellents in the environment. Due to the limits of digital computation for representing physical evolutionary processes, any proposed simulation models are destined to be incomplete, reflecting some aspects of the organism's behaviour while neglecting other qualities.

The researchers that have used living Physarum polycephalum or its simulation for road network design have not claimed that intelligence and cognitive behaviour of the organism are embedded in the design projects. However, they are aware that when Physarum polycephalum's behaviour is translated into a growth algorithm, it is a simplified representation. Also, if they use living Physarum polycephalum's growth on physical topography models, they must scale down the urban topography and eliminate the details of actual physical conditions. Nevertheless, both the living Physarum polycephalum and its simulation through digital computation are quite helpful when the design problem can be outlined as a shortest path and network optimisation problem. The main aim of these design experiments is not to entirely model the organism's physical growth behaviour but to transcribe its optimisation characteristics and mechanisms into an algorithmic simulation. For network design queries, the simplification and abstraction of living Physarum polycephalum are not necessarily troublesome because the objective is to create a growth algorithm that helps to optimise road network connections. The precision of digital and physical models can be improved by developing datasets containing the organism's behaviour or setting up a more detailed physical model incorporating finer-grained properties of the natural topography.

Beyond its problem-solving and optimisation capacity, London-based ecoLogicStudio has proposed using Physarum polycephalum's physical computation as a cybernetic communication between architecture and nature, blurring the conceptual boundaries between the artificial and biological world.[35] In their Physa-City project, they experimented with living Physarum polycephalum growing on a 3D-printed physical model of the copper mining zone in Arizona, United States. The team used three input parameters in this physical topography model: substratum morphology, light fields, and food resources. While the substratum morphology was used as a three-dimensional scaled-down model of the natural topography, light fields were used as repellents indicating obstacles within the environment. The food points were used as attractants to stimulate the organism to grow and change its morphology accordingly. Using a high-resolution camera, they were able to capture the organism's behaviour in real time, resulting in an



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3 **A video frame demonstrating the growth of the GAN algorithm of Physarum polycephalum on the morphology of Paris within the scale of 3x3 km.**

emergent landscape pattern *[1]*. In another project named Bio.Tallinn, a similar methodology was followed, this time for the urban morphology of Tallinn, Estonia.[36]

In another project by ecoLogicStudio: GAN-Physarum: La Dérive Numérique, a machine learning algorithm was trained to perform like a living Physarum polycephalum to reinterpret the urban morphology of Paris, France.[37] GAN (Generative Adversarial Networks) are a class of machine learning consisting of two competitive neural networks; one is trained to generate fake data, and the other to separate the fake data from real examples.[38] In this project, the data concerning the biotic layers was initially extracted from satellite images of Paris and diagrammed into a grid order on a physical canvas where each point demonstrated the distributions and densities of nutrients within the environment. Then, living Physarum polycephalum was introduced to start its physical computation process on the surface of the canvas connecting food resources *[2]*. The GAN algorithm was trained by images of growing Physarum polycephalum and satellite images, allowing the algorithm to learn how to illustrate the organism's behaviour in relation to the urban morphology of Paris in different scales *[3]*. According to ecoLogicStudio, when the trained algorithm is applied to the urban fabric of Paris, the emerging network represents the possible future of the city, introducing the cognitive capacity of the organism into urban design.[39] In other words, decision making mechanisms of Physarum polycephalum are used to co-design the relationship between the built environment and nature in Paris.

The main idea in these projects from ecoLogicStudio is to move beyond the descriptive power of digital computation by embracing the physical computation capacity of living organisms to generate a closer connection between architecture and nature. The emergent patterns of the organism were considered to have the potential for envisioning co-evolution of both artificial and natural systems within the built environment. They inferred a new bio-digital design paradigm by attributing a cognitive value to the Physarum polycephalum's growth as those patterns emerged as a result of real-time material interactions with the environment.[40] Physarum computation allows direct interaction with physical matter compared to abstract simulation of evolutionary processes through digital computation. Also, the organism's emergent patterns can provide insights into the morphological formation of urban design projects. However, using Physarum polycephalum's growing patterns in urban design carries many challenges in terms of incorporating the cognitive traits of the organism and its contribution to the co-evolution of the built environment with the biological processes.

These design experiments started with the growth of living Physarum polycephalum on a scaled-down physical topography model. In the next stage, architects either directly exploited emerging patterns or developed algorithms to simulate the physical growth behaviour of the organism by utilising digital computation techniques to co-design cities' landscapes. In both scenarios, the physical computation of the organism was terminated first so that architects could contemplate how the emerging patterns could be used for transforming urban morphologies. It is important to recognise that the material interaction of the organism with the physical environment only takes place on a simplified physical model representing the urban topography that is supported with elements (food, light, etc.) inhibiting or facilitating the organism's growth. This approach simplifies complex properties of real-world conditions and fails to integrate the dynamic and changing characteristics of environmental conditions at larger urban scales. Also, if the design experiment includes training algorithms to imitate the organism's behaviour, the resulting model is inevitably a simplified representation of its agency. In this sense, the use of digital computation tools inevitably prevents reciprocal material interaction between the slime mould and urban-scale design interventions.

It is critical to expand on this scaling challenge in exploiting both living Physarum and its digital simulation in urban design experiments. The organism's physical computation occurs only on an abstracted small-scale topographical model which is used as the substrate to support the organism's growth and its emergent patterns. When considered as propositions for real-world urban contexts, the resultant patterns will be quite different to the scale and environmental context of the *physical model* used to support the organism's physical computation. Because of the scale and environmental differences, there is no direct feedback and interaction between the organism's physical computation and real-world urban design contexts. Thus, questions remain as to the validity of using Physarum polycephalum's growth behaviour to envision the co-evolution of nature and the built environment, which seems out-of-reach at the present time.

It is obvious that the emerging patterns of living Physarum polycephalum are the result of its cognitive qualities, including decision-making and bias, which shape the behaviour of the organism in different environmental conditions. The physical computation of Physarum polycephalum has a more direct connection to the materiality of evolutionary processes because it is not descriptive and representative in the way that digital computation is. For this reason, there is a more direct relationship between the emerging patterns of living Physarum polycephalum and its cognitive traits. However, it would be a reductive approach to equate the organism's cognitive traits to its emergent patterns, whether the result of physical computation of living Physarum polycephalum or its digital simulation. For these reasons, the degree to which the growth patterns of Physarum polycephalum can reflect a cognitive value on urban design is questionable.

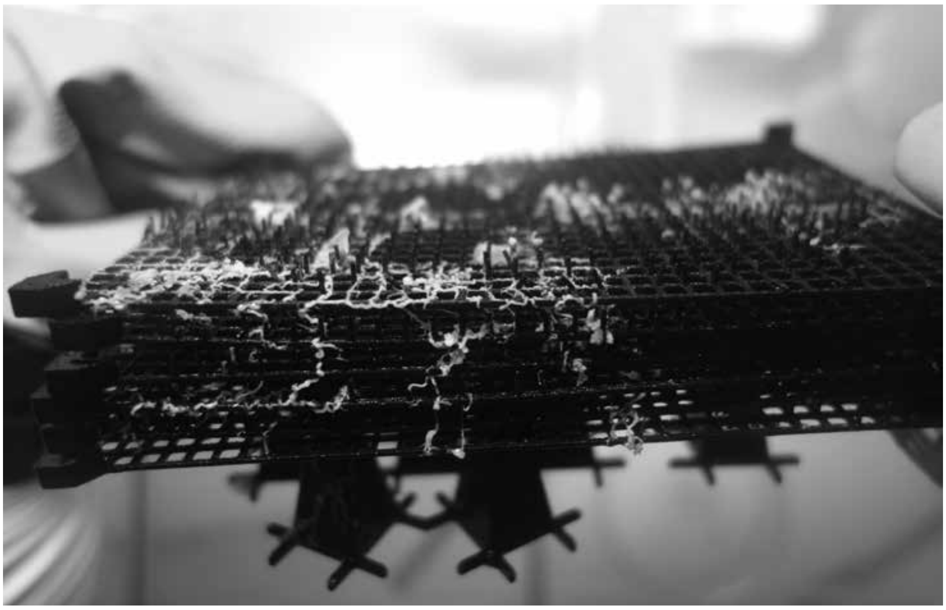
In summary, no direct feedback route exists between the organism's physical computation and urban design due to scale constraints. Physarum polycephalum does not make decisions based on urban design scale and context. The organism strives to survive by connecting food resources in scaled-down physical models of the urban topography. However, it is not concerned about how its emerging patterns can be evaluated as part of the master plan of the city. The organism's cognitive behaviour cannot comprehend macro-scale design dynamics that can't be translated into network optimisation problems. For these reasons, it might be useful to observe the emerging patterns of the organism for the network design problems or to take inspiration from the aesthetical appearance of its growth behaviour. However, it is still early to attribute a genuine cognitive value to these applications for the co-evolution of the built environment with the biological processes on an urban design scale.

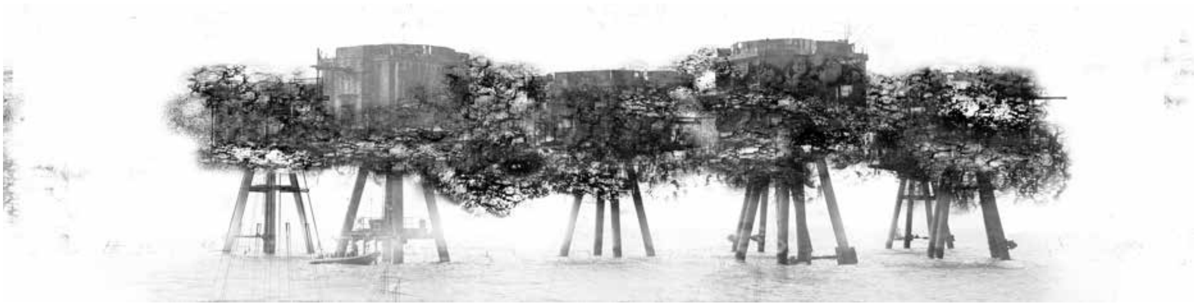
Building scale

Beyond its utilisation in network design and experiments in growth patterns on topological surfaces, living Physarum polycephalum has also been tested in relation to exploiting its vertical and three-dimensional growth capacity in form-finding experiments on a building scale. As part of the GrAB (Growing as Building) project by Barbara Imhof and Petra Gruber, researchers initially investigated the ability of the organism to grow vertically. Initially, they added agar mixture into a jar and installed a scaffold composed of a plexiglass sheet wound in cotton string. Then, they located food resources on both the bottom and top of the cotton string, which was vertically arranged. After sterilisation of the jar and scaffold, Physarum polycephalum was located at the bottom of the jar. The organism successfully reached the top of the string and demonstrated that Physarum polycephalum could grow against gravity.[41]

Following this, the researchers focused on utilising Physarum polycephalum's three-dimensional network optimisation capacity by letting it grow on three-dimensional grid structures, expanding its potential from growing on planar or topographical surfaces. Initially, different experiments were conducted by changing the location of Physarum polycephalum and food sources distributed within the three-dimensional grid to evaluate how various arrangements affected its growth behaviour. Positive observations then encouraged the researchers to test its growth behaviour for co-designing architectural spaces and forms. For this purpose, the team utilised four layered and 3D-printed floor plans of one of the Maunsell Fort towers as a scaffold. When the organism was successfully grown on the scaffold *[4]*, its emergent form was digitally extracted and overlaid on the three-dimensional model of the fort *[5]*. In the final step, Physarum polycephalum was also used to design an optimised connection between the towers and their landscape.[42]

The researchers were quite aware of the distinctive working logic of living Physarum polycephalum, which makes it challenging to adapt the agency of the organism into an architectural design project through human reasoning. Designers genuinely accepted the challenges of information transfer between disciplines when addressing the emergent patterns of living Physarum polycephalum in architectural design procedures. Their argument was mainly related to utilising the organism's growth





4 Growth of Physarum polycephalum throughout the 3D-printed grid floor plans of Maunsell Fort towers.

5 Side view of the Maunsell Fort towers redesigned by Physarum polycephalum.

behaviour for 3D form-finding experiments and network optimisation inside and between Maunsell Fort towers. Not all parts of the emerging patterns of Physarum polycephalum are about the shortest path or network optimisation. Accordingly, the researchers were also interested in the aesthetics of growth patterns, which they then interpreted at various scales of architectural design interventions within the Fort.

The researchers did not hesitate to change and adapt Physarum polycephalum's emergent form according to the needs of the design project. The idea was not to precisely utilise the emerging geometries of the organism but take advantage of it alongside the designers' intentions and reasoning. This means that the non-human agency of the organism was not proposed as the single author for design processes. Instead, a collective design action shaped by the decision-making mechanisms of the slime mould and designer was proposed. The interpretation of the organism in this design project can be considered coherent as it takes into account the characteristics of Physarum's physical computation and the challenges of incorporating its growth patterns into building scale proposals. In this context, the project demonstrates another preliminary experiment of the multi-scalar potential of Physarum polycephalum in architectural design in terms of three-dimensional form-finding informed by its physical computation.

Another building scale design experiment was The Convergent Ambiguities project undertaken by Andrea Rossi and Lila Panahi Kazemi, which was part of 'Codes in the Clouds' studio led by Liss C. Werner.[43] In this project, designers used a digital simulation of Physarum polycephalum to propose a conceptual, self-growing architectural intervention that forms physical connections and communication between various abandoned buildings. The project focused on simulating the organism's self-organisation behaviour, not utilising physical computation of living Physarum polycephalum. In this context, various digital computation procedures such as multi-agent systems, diffused-limited aggregation, and cellular automata are useful for recognising Physarum polycephalum's decision-making logic and applying the emerging growth patterns as an architectural design methodology. Werner claims that, in addition to the organism's ability for network optimisation at various design scales, Physarum can potentially introduce cybernetic characteristics of learning and feedback into digital architecture. This approach inherently visions more direct ways of communication between architecture and the materiality of nature.[44]

As previously discussed, utilising cognitive traits of living Physarum polycephalum in architectural design through its simulation by digital computation procedures has various challenges. In the case of the Convergent Ambiguities Project, the simulation of Physarum Polycephalum can provide insights to architects about using its emergent behaviour for network optimisation or utilising the formal aesthetics of its growing patterns. However, the critical point is that the simulation of the organism's behaviour through multi-agent modelling cannot wholly reflect its cognitive agency due to its reductive logic, simplifying and approximating its behaviour. Also, digital simulation of environmental conditions cannot genuinely represent shifting ecological conditions as only specific characteristics can be described in the computational system. This fact opens the multi-scalar contribution of algorithmic representations of Physarum polycephalum in architectural design to the discussion beyond its capacity for dynamic network optimisation and the aesthetic emergence of its growing patterns.

In the Convergent Ambiguities Project, all self-organisation and self-growth processes of the built environment are limited to the boundaries of digital simulation. As all proposed interaction takes place in the virtual domain, it is impossible to talk about direct feedback between the physical computation of the living organism and the architectural design proposition. Digital simulation of Physarum polycephalum can give insights into its behaviour under certain conditions. In this context, it can introduce compelling aesthetical qualities into a three-dimensional arrangement of the architectural space on various scales through its emerging dynamic morphology. Nevertheless, the agency of the living organism regarding its decision-making, learning, and feedback should not be equated with its digital simulation and growth patterns.

The living Physarum polycephalum has also been utilised to develop building materials. The 'Living Screens' research project was developed by Catalina Puello, Fabio Rivera, and Johana Monroy at the Institute for Advanced Architecture of Catalonia (IAAC) in 2017. The fundamental aim was to create cognitive connection between the slime mould, users, and spatial organisation by letting the organism grow inside a panel wall. For this purpose, the growth of Physarum polycephalum was planned to be used as a filter of the light, continuously changing the atmosphere of interior space *[6]*. A screen was developed that comprised a panel of transparent layers containing a food distributor to an array of nutrients across various locations and a humidifier to control humidity levels *[7]*, which led the Physarum to grow and form optimised networks in various densities.[45] The food distributor followed the working logic of the two-dimensional axis of the CNC milling machine, spreading nutrients depending on user inputs received in the form of geometric code (G-code). In this sense, humans had a direct impact on the growth behaviour of the slime mould as they controlled the food distribution.

According to the researchers, the proposed prototype had the potential to build an evolving dynamic communication between the organism and humans by filtering light transmittance through the wall panel. This vision was beyond the idea of using Physarum polycephalum as a shape and form generator for architectural design. Their concern was not using Physarum polycephalum's network optimisation or form-finding capacity for the

6 **The final prototype vision demonstrating the perceptual human-organism-environment interaction through the interplay of light and shadows.**

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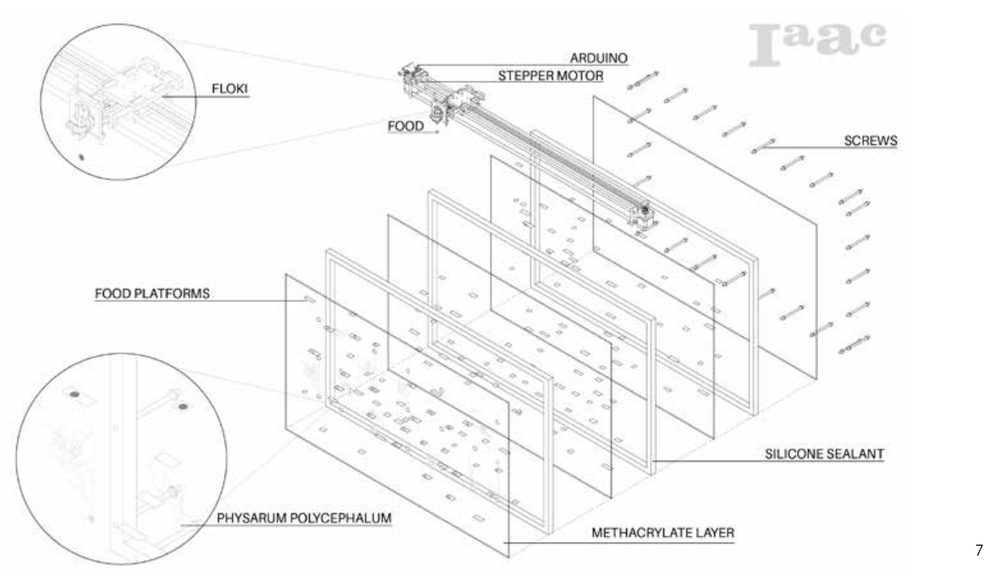

7 **The assembly diagram of the final prototype demonstrates how a food distributor provides Physarum polycephalum with nutrient resources.**

geometrical articulation of building forms or urban morphologies. Instead, the organism was physically integrated into the building components themselves. Such a function can be considered more reasonable as the challenges of changing scale and environmental dynamics in other projects do not apply. Humans are still dominant in this design scenario by providing food and arranging suitable environmental conditions for the organism. While humans maintain vital living conditions, Physarum polycephalum changes the atmospheric impact of the interior space by growing inside the screen while searching for food sources. This approach proposes a vision for constantly evolving perceptual human-organism-environment interactions.

The argument of cognitive connection between humans and Physarum polycephalum in the project is partly limited as the association of the organism with humans only takes place through the interaction of light and growth patterns. The creative contribution of Physarum's physical computation capacity for generating these atmospheric impacts in indoor spaces can become vague if similar experiments can be conducted without any living organism by triggering the change of density and pattern inside the screen with artificial materials. The project genuinely reflects the possibility of physically integrating the slime mould into building interfaces. However, its vision for the co-evolution of the built environment with living organisms is also restricted, as building components only provide a niche for the organism to grow and survive. There is no strong proposition for dynamic and mutual feedback between the building component and the slime mould that will take shape in time. In other words, Physarum polycephalum and building components are not planned to physically evolve together through their physical and material interaction.

Computing with nature

This article reviewed the bio-digital design theories and experiments of architects using living Physarum polycephalum and its digital simulation for urban and architectural design projects and has focused on the critical limits of digital and physical computation processes and the challenges of scale differences. The article discussed how the physical computation of living Physarum polycephalum and its simulation through digital computation creates various opportunities and limitations when considered in architectural design from urban to building scales. When the organism's behaviour is simulated through digital computation procedures, the generated algorithm is an idealised and simplified representation of cognitive traits of Physarum polycephalum, reducing its decision-making and learning capacity into emergent patterns. Still, these growth patterns can inform architectural design processes in various scales for network optimisation problems or form-finding experiments. However, attributing cognitive value to these emerging idealised patterns regarding the geometrical arrangement of design projects is a reductive approach because of the abstract nature of digital computation techniques.

On the other hand, there are other specific challenges in using living Physarum polycephalum within the design process. The value of Physarum computation lies in its ability to compute through material interaction with the environment but this becomes mostly irrelevant in terms of introducing its cognitive traits into design processes to co-evolve the built environment with the living world. The fundamental reason is that designers need to scale up the growth patterns of the Physarum from small-scale physical models and then apply these emergent geometries into larger scale building forms and urban morphologies. The utilisation of scaled-down physical models of real-world topographies and conditions that are used to support the growth of the organism only represent simplified and reductive scaffolds that can never imbue the complexity of the physical world. For this reason, it is essential to be cautious when thinking about the cognitive value and direct transferability of the organism's emerging patterns for the co-evolving the built environment and natural world due to changing scales and contexts.

In the history of digital architecture, Physarum polycephalum should be understood as an important milestone for employing the capacities of physical computation of living organisms in architectural design. Beyond applying idealised and simplified models of evolutionary processes through digital computation, Physarum polycephalum provides an opportunity to compute with nature. The organism's computation characteristics change the focus from the population-level understanding of evolutionary processes to the organism and material scale. Nevertheless, it is necessary to understand that when the organism's behaviour is represented as an algorithm, or its living and dynamic morphology is adapted into a complex design context as a form generator, its contribution does not go beyond network optimisation and three-dimensional form finding. The physical computation of the organism terminates when the digital computation starts or when architects begin to interpret emergent patterns. For this reason, Physarum computation cannot yet propose a complete synthesis of the bio and digital in architectural design, which aims at the co-evolution of architecture with nature. Beyond this ambitious objective, Physarum computation allows architects to utilise the non-human intelligence of the primordial organism, which has been so far limited to harnessing network-optimisation capacity and the aesthetical emergence of Physarum polycephalum for design proposals across various scales.

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Competing interests

The author declares none.

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