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14

Disruptive Material Intelligence of Physarum: Liquid Architecture of a Biological Geometry Computer

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Physarum polycephalum, also called slime mold or *myxamoeba*, has started attracting the attention of those architects, urban designers and scholars, who work in experimental trans- and flexi-disciplines between architecture, computer sciences, biology, art, cognitive sciences or soft matter; in short, disciplines that build on cybernetic principles. Slime mold is regarded as a bio-computer with intelligence embedded in its physical mechanisms (Adamatzky, 2013; Jones, 2016). In its plasmodium stage, the single cell organism shows geometric, morphological and cognitive principles potentially relevant for future complexity in human–machine networks (HMN) within architecture and urban design. The parametric bio-blob presents itself as a geometrically beautiful[1] graph structure–morphologically adaptive, logistically smart. It indicates cognitive goal driven navigation and the ability to externally memorize, similarly to ants (Johnson, 2001). *Physarum* communicates with its environment. The chapter introduces the 'creature' in the context of 'digital architecture'[2]: (a) in an overview of the current state of architectural and urban projects based on slime mold, (b) in digital

[1]The emotional and subjective term 'beautiful' may generally be inappropriate for a scientific publication; here it refers to the three qualities of architecture coined by the Roman architect and engineer Vitruvius (80–70 BC–15 BC). The Vitruvian Triad, firmitas, utilitas, venustas, describes the quality of architecture as scientific means of measure.

[2]'Digital architecture' here refers to the 'first digital turn' in the 1990s (Novak, 1991).

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theory with a glimpse into *Physarum*'s parallels to our digitally networked multi(cyber)space, (c) I will consider *Physarum* as liquid geometry computer – a cybernetic disruptive bio-architectural device. A discussion on its algorithmic and parametric design strategies for architectural optimization and computational urban planning for a lean networked (un)conscious city is envisaged at a next stage.

14.1 Introduction

Physarum structure reveals two distinct geometric patterns: (a) on the edges *Physarum polycephalum* develops thin branches, searching their environment for food (Figure 14.1(a), (b)), (b) at a 1:10 enlargement the tips of the branches reveal a double-curved surface geometry of bulging droplet-like blobs[3], which occasionally turn into elongated three-dimensional oval shapes. Those clusters of blobs have an intricate topography at their edges demonstrating a landscape of regularly shaped and rounded hills (Figure 14.2(a), (b)). They can be seen as the edges where foraging growth is happening through the actuation the protein actin enabling the construction process of the contracting filament membrane, ectoplasm as outer layer and endoplasm, the liquid found within. Actin is partly responsible for the built up of contractile filaments of muscle cells (D'Haese, 1978). Once the organism grows and the branches with the bulging blobs at their tips become longer through foraging, they divide into further branches and link up like veins. Self-organizing growth is triggered through cytoplasmic liquid pumped back and forth in a rhythmically oscillating manner inside the membrane (Kishimoto, 1958; Zonia, 2007). Eventually, the organism grows a regular – slightly noisy – Voronoi pattern. The links (the edges surrounding the Voronoi cells) connect corresponding nodes (vertices). Once the slime mould moves, location and size of vertices and edges change, disappear or merge; new links and vertices (nodes) develop (Figure 14.3(a)–(c)). They traverse according to the geometrical and structural change of the blob, steered by external and internal parameters. The large membrane acts as transport network for

[3]The term *blob* stands for binary large object. In architecture, the *blob* was introduced by the architect Greg Lynn in the 1990s, the era of the first digital turn in architecture. It describes an amoeba-like architectural forms. See 'Folds, Bodies and Blobs', (Lynn, 1995; Lynn, 1998). Since then blob-itecture or blob-architecture has been established as a formal typology of architectural round forms modelled or generated using digital tools and became part of digital theory in architecture – especially in the discussion around *bio-digital and genetic architecture* (Sykes, 2010; Werner, 2015).

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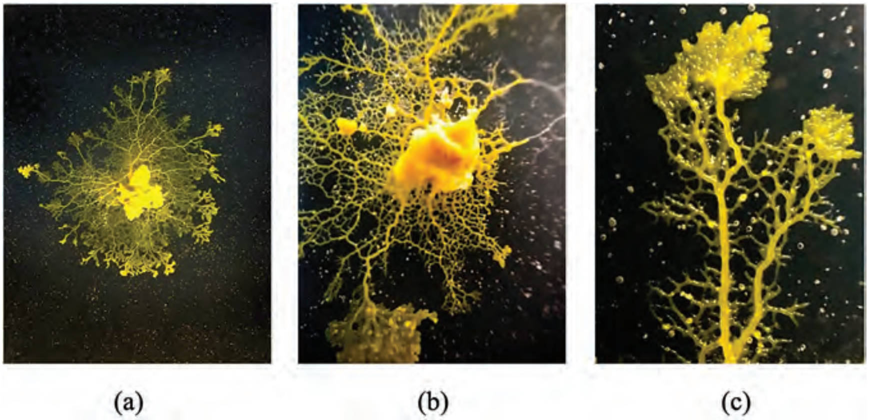

Figure 14.1 1(a), 1(b) (left, centre). Branches departing from food source (oat), searching for nutrition, Voronoi pattern partly formed. (c) (right). blob-like *physa* bubble at end of searching branch.

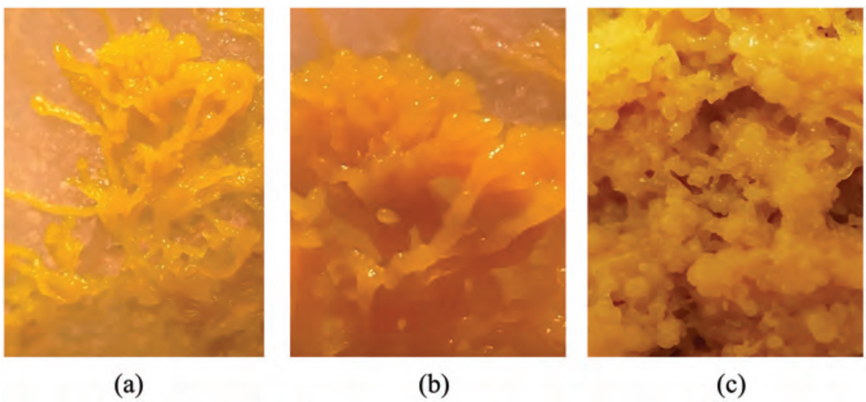

Figure 14.2 (a), (b) (left, center). Blob landscape developing at the end of a searching branch. Swelling blobs move forward through the oscillation of a liquid within the membrane–specimen magnified. (c) (right). Blob landscape. *Physarum polycephalum* has created a morphing liquid topography and continues growing–specimen magnified.

nutrients and sensor in constant exchange with its environment; its foraging is governed by the organism sensing influences alien to its own. In the case of our *Physarum* those are, e.g., noise (Meyer, 2017), light intensity, temperature, amount or nutrition in the substrate. Jakob von Uexküll's fundamental findings in the systematics of living systems being informed by their

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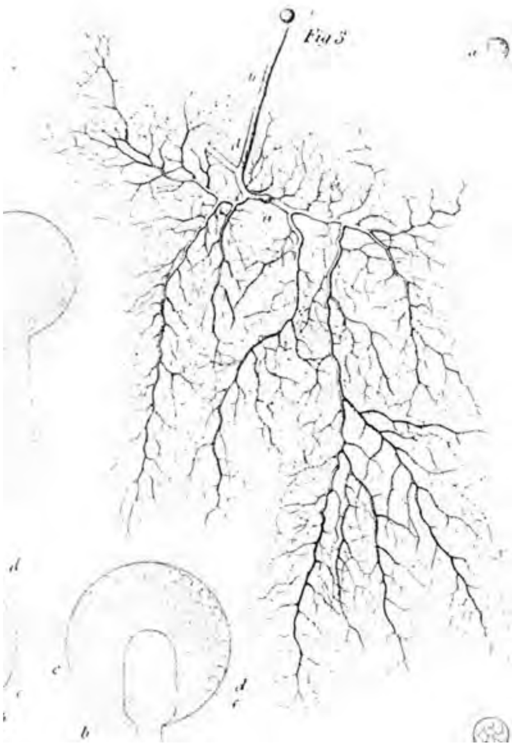

Figure 14.3 (a) (left), (b) (centre), (c) (right). 2D-branching to Voronoi *phase* 01, 02 and 03. Over the course of 3 days *Physarum polycephalum* has developed a network between the food sources.

environment, its *Umwelt* (Uexküll, 1909) come into effect. As a living organism, which is well described in Jakob von Uexküll's diagram on *Merkwelt* and *Wirkwelt* (1920), *Physarum* is assumed to also be equipped with sensorial capabilities, that receive information from 'the world as sensed'(Uexküll, 1909), an *organ* that can remember and an *organ* that can actuate reaction. Speed and direction of growth can be trained through the moulds capacity of memorizing externally (Reid, 2012). The cellular slime mould shows the behavioral pattern of a biological computer adapting cybernetic principle of learning through conversation with its environment. It "can be considered as a reaction-diffusion, or excitable medium encapsulated in an elastic growing membrane." (Adamatzky, 2009)

The wonder of form-making performed by the slime mold occurs in the stage of its life-cycle called *plasmodium stage.* The life cycle of the

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slime mold can be divided into three main stages with twelve sub-stages–summarized from (Stephenson, 1994): (a) the vegetative (plasmodium or slug) stage: a countless number of cells are aggregated and merged into a giant amoeba-like body, a multinucleate mass, enclosed in one membrane–this stage is relevant to the present research paper, (b) the fruiting stage, in which the mold transforms and develops spores to release in case 20% of the cells in the 'slug' have died. Individual spores turn into 'new' amoeba, (c) the sexual reproduction stage, where single amoeba aggregate and partly cannibalize each other in order to survive. The life cycle subsequently continues at the vegetative stage (a) as described in (a) as a new iteration.

Slime mould was discovered in 1869 by the German mycologist Oskar Brefeld, who described the 'new' species in his article "Dictyostelium mucoroides, ein neuer Organismus aus der Verwandtschaft der Myxomyceten" (Brefeld, 1869). In 1884, Brefeld revisited the slime mold and showed its 'cellular' behavior in "Botanische Untersuchungen über Schimmelpilze". Volume 1 of 2 includes corresponding hand-drawn illustrations of the relating organism *Mucor Mucedo*. They depict the branching behavior on one hand and its morphing to the sporangia stage, growing spore stalks, eventually leading to fruiting of the organism on the other (Figure 14.4) (Brefeld, 1884). The most notable 20th century scholar on the subject of slime mould is likely to be Kenneth Bryan Raper, who in the 1930s

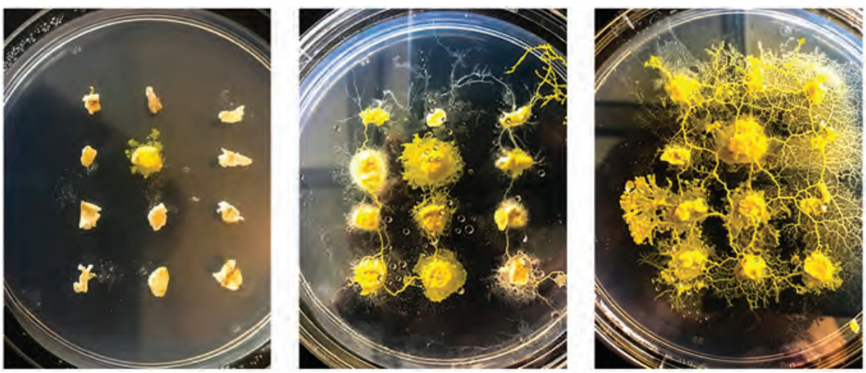

Figure 14.4 Illustration by ©Oskar Brefeld, showing the branching of a Mycelium of *Mucor Mucedo*, akin to *Physarum*. (Brefeld, 1872), p. 65.[4]

[4]Original description in Brefeld, Oskar, 1884: "Gestalt und Verzweigung eines ausgewachsenen Myceliums von Mucor Mucedo aus der Spore in Mistdecoct auf dem Objektträger gezogen." p. 57. Decoct = Sud/Abkochung; drawing see p. 65.

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revived the research on cellular slime mold. Raper's research built on that of E. W. Olive's research results (1902) in which Olive described all phases of the slime mold in detail. Raper later focused on multicellular migration and the subsequent process of sporing (Bonner). His work has culminated in "The Dictyostelids", first published in 1884 (Raper, 2014).

14.2 Literature and Project Review for Slime Mold in Architecture and Urban and Regional Planning and Design

In 2000, Toschiyuki Nakagaki published "Intelligence: maze-solving by an amoeboid organism" on the smartness of the slime mould *Physarum polycephalum* (Nakagaki, 2000). Nakagaki observed the intelligent decision-making behavior of the *Physarum polycephalum* plasmodium. The organism was challenged with a maze-solving problem in order to reach the vital food, deposited on either entrance of the maze. The question was how would the mold to 'decide' its path, which food source would it approach, or would it connect either, in order to ensure a balanced nutrition flow within its entire body. The organism grew one connection on the shortest path possible between both sources, retracting all other links it had created prior to realizing that the food sources were connected (Nakagaki, 2000). Nakagaki's findings illustrated how a problem of computational complexity could be managed by a living system without brain by applying biological intelligence. In architectural sciences we regard this particular problem as the *Botenproblem*, the *travelling salesman problem* (TSP); this might differ from the definition of the *TSP* in the hard sciences, life sciences or computer sciences. Research findings of Nakagaki's maze experiments, were complimented by experiments to serve urban and regional transport infrastructure. In 2010 Andrew Adamatzky and Jeff Jones in the UK, and Toschiyuki Nakagaki in Japan, triggered a new wave of experimentation with cellular slime mold in a variety of applications, including unconventional computing, art, network theory and urban planning and architecture (Adamatzky, 2010; Tero, 2010). From 2010 onwards, Adamatzky and Jones investigated in and compared the slime mold's intelligence in growing efficient 'road networks' for Germany and the USA in comparison to the country's actual motorway/autobahn system. In the case of the USA, food sources where placed on either side of the country in Boston and San Francisco, in order to observe how the slime mold would traverse across a 2D- and a 3D-terrain simulating the topography. In the case of Germany, the researchers placed

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food sources on points furthest north (Flensburg) and furthest south (Füssen) of the country to observe the moulds travel behaviour across the 2D- and 3D-terrains of Germany (Adamatzky, 2014). The experiment describes one out of a series testing, if and how *Physarum* approximates man-made travel routes, by finding the shortest path. Countries taken in consideration include e.g., Mexico, the Netherlands, Australia, Brazil, the UK, Russia (Adamatzky, 2011; Adamatzky, 2013; Adamatzky, 2012; Adamatzky, 2011). Part of the research included the 'reaction' of *Physarum polycephalum* of unforeseen obstacles in a regional terrain, such as sudden floods. The analysis shows great potential for transfer into the applied field of urban design, regional planning and architecture.

The rise of the relevance of emergence and system-based design strategies enforced experimenting with the biological liquid geometry machine. Similarly to the team around Adamatzky and Jones, the team around Atushi Tero and Toshiyuki Nakagaki also focused on solving network problems in urban planning by 'testing' the efficiency of the Tokyo railroad system utilizing the intelligence of slime mold; first in material tests, later as prove of concept in their paper "Traffic optimization in railroad networks using an algorithm mimicking an amoeba-like organism, *Physarum plasmodium*" (Watanabe, 2011). The Tokyo railroad project was the first of its kind that found entry into schools teaching experimental computational architecture.

In 2016 Pedro Veloso and Ramesh Krishmanturi[5] took the idea of the slime mold algorithm on board for generating, designing and optimizing corridors in architectural spatial arrangements. The publication "On Slime mould and Corridors" results of a collaboration between the Computational Biology Department and the School of Architecture at Carnegie Mellon University in Pittsburgh, USA. The research links biological computation with circulation problems in buildings and urban spaces focusing on the development of networking methods, such as *Adjacency Graph Selection* (AGS) the authors developed (Veloso, 2016).

The rise of the slime mold around 2010 coincided with a global fascination and engagement – of architects, architectural scholars and students – in generative design tools, such as the computer language *Processing* or visual

[5]Prof. Krishmanturi, Ph.D, joined the faculty of the School of Architecture at Carnegie Mellon University in 1989 to become a full professor in 1994. In 2000–01 and 2002–03, I served as the Chair of the Department's graduate program. Krishmanturi's research topics included object-agents in design environments, knowledge-based design systems, the integration of natural language and graphics, spatial algorithms, robotic construction, computer simulation.

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scripting in *Grasshopper for Rhinoceros*. A snowball effect of investigations into self-organizing and systems based on the algorithms, partly utilized by slime mould, began. However, only few research results and experiments carried out or published were directly connected to slime mold and have been since. A large number of users may have known about the bio-computer or may not have realized that they were dealing with slime mold in its virtual flesh. We have applied – and still do – an algorithm to simulate the pattern generation of the slime mold: diffusion-limited aggregation (DLA), swarm intelligence or collective cell migration based on the *Boids*, developed by Craig Reynolds in 1986, and cellular automata. The keyword was and still is *self-organization*.[6] The reader may note that I am referring to the simulation of the pattern growth and not to the actual physical growth of the material slime mold. The material growth is an additive process whereby material is produced by the organism. In contrast to the natural growth of *Physarum* the virtual growth is simulated through adding particles from a source of attraction; meaning that the natural material growth from within and the virtual material is added to from an external source.

In 2015, Barbara Imhof and Petra Gruber have been envisioning and explorative testing possibilities of “Blending Architecture and Biology” at the architecture school, *die angewandte* in Vienna (Imhof, 2015). Growth and structure of slime mould was tested in a variety of environments and directions, e.g., vertical growth on a 3-dimensional matrix. In her book, Imhof refers to the project ‘Convergent Ambiguities | From Slime Mold to Temporary Autonomous Architecture’, 2012, carried out in the author’s studio *Codes in the Clouds* – run by the author at DIA[7] – by Andrea Rossi and Lila Panahi Kazemi, extensively simulating the behavior of slime mould in 3D virtual space and transferring it to a visionary architectural proposal (Figure 14.5). Rossi and Panahi Kazemi suggest the project

“Convergent Ambiguities’ explores [...] biological organisms [...] as repertoire of active production systems. [...] Situated in the near future, where censorship and repression are harming the freedom and the self-organized nature of the biggest network ever built by humans, the World Wide Web, we envisioned an architecture able to host the operations of the

[6]at that time, approx. 2010, the notion of feedback, learning systems and artificial intelligence re-arose after decades of absence, left behind in the 1960s.

[7]Computational Design Studio *Codes in the Clouds*, 2010–2016, led by Liss C. Werner, Dessau International Architecture Graduate School, Anhalt University of Applied Sciences, Germany.

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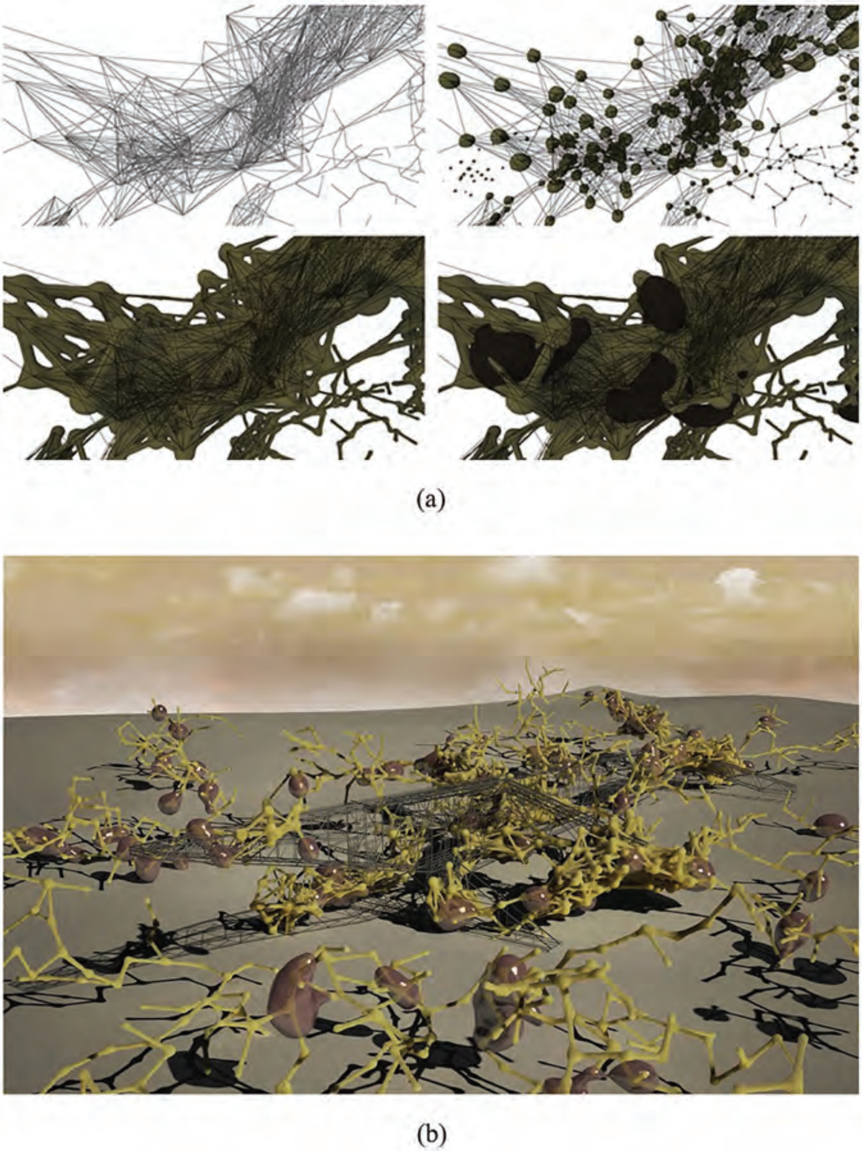

Figure 14.5 (a): Cluster formation, (b): Conceptual architectural proposal based on swarm intelligence as found in the behaviour of slime mould. 5a and b by ©Andrea Rossi and Lila Panahi Kazemi, DIA, *Codes in the Clouds II, Convergent Ambiguities.*

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rebels of the new millennium. The network logic derived from Slime Mold informs [...] a virtual communication network between the different abandoned buildings [...], transforming them into pulsating nodes of an alternative topography of insurrection, hiding them and at the same time connecting them to the common world through the virtual realm of the internet. The nodes created become the place of birth of a new kind of architecture: non-planned, self-growing and self-sustaining, these "living organisms"" [...] (Rossi, Panahi Kazemi, 2012)

In the studio, we applied multi-agent systems as intensely as diffused-limited aggregation in order to generate and understand self-organization as architectural design strategy. Projects included problem solving propositions in a variety of scales, e.g., for directionally steered urban growth (Maribor), optimization of circulation in urban spaces (Venice, Italy) (Figure 14.6), and led to current research on façade and building designs to reduce noise pollution (Berlin, Germany).

'Cities as biological computers', developed in the *Urban Morphogenesis Lab* at UCL in London in 2015/16 by Claudia Pasquero, Marco Poletto, suggests a biotechnological one-ness where human infrastructure, biological infrastructure and energy infrastructure converge (Pasquero, 2016). The authors present physical model of their project activating the idea of the

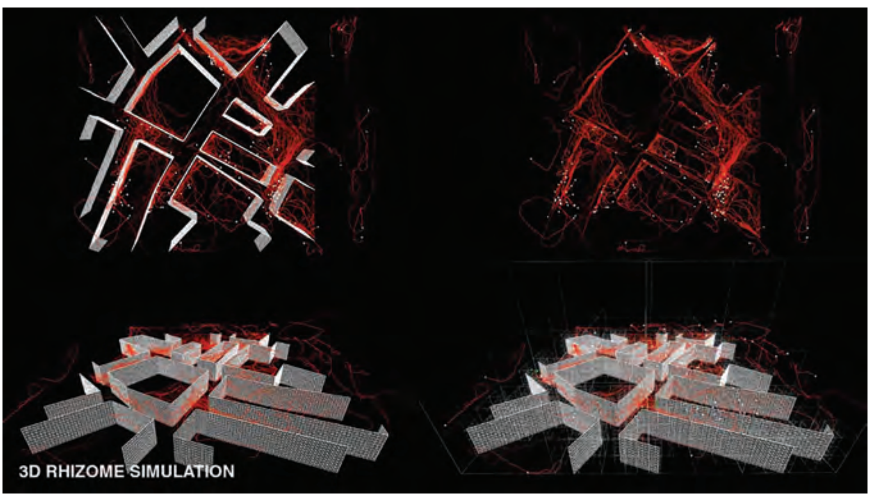

Figure 14.6 Simulation of circulation in Venice, ©Jordan C. Parsons, CMU, The Rhizome, *Codes in the Clouds IV, Atrophic [Re]Topography*. The project utilized swarm algorithms, also being used in the simulation of slime mold.

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Physarum Machine. On a smaller, architectural/interior scale the *Advanced Architecture Group at IAAC* (Institute for advanced architecture in Catalonia) has been cultivating slime mold to research the growth algorithms, the organism's food 'preferences' (attractors and repellents). One possible architectural application is a living screen, where *Physarum* is re-directed through automated redistribution of food (IAAC editor, 2017).

The increase of researching slime mold, *Physarum polycephalum*, and its possibilities for architecture and urban design is reflected through an observable convergence of the fields *research by making* in experimental computational architecture together with unconventional computation, network theory and biological robotics. Correlating publications, projects and collaborations between research institutions reflect the interdisciplinary nature of the subject.

14.3 Digital Theory of *Physarum*

The discovery of *Physarum polycephalum* does raise questions and open up opportunities for optimization of architectural networks of all kinds and scales, physically and digitally. Apart from technology based and driven research to come, the phenomenon winds itself into one equally relevant domain of architecture, namely the one intertwined and strongly linked with how we understand architecture as component of our culture, manifested embodiment of the evolution of man, archive for craftsmanship and the heritage of technology and technique. Architectural theory, which embraces the above, has, similarly to the perspective to (digital) craftsmanship experienced a revival. Digital theory in architecture certainly existed before August 23^{rd} 1991, the day when the World Wide Web (WWW) became available to the general population of planet Earth; it was however that era, when computers became available, scripting started invading the designer space and 3D-modelling programs were introduced in architecture schools.[8] In 1991, Michael Benedikt introduced projects related to the fantastic and eternal spaces with unforeseen and emergent changes in spatial configuration as seen in Walt Disney's *Tron,* produced in 1982. "Cyberspace–First Steps"[9]

[8]First 2D-drafting and 3D-modelling software existed as early as the 1960s (e.g., Sketchpad by Ivan Sutherland), AutoCad released their first version in 1982, '3Ds Max' was released first time in 1988 as '3D Studio Prototype'.

[9]Michael Benedikt, in 1991, defines Cyberspace as "a globally networked, computer-sustained, computer-accessed, and computer-generated, multidimensional, artificial, or "virtual" reality." (Benedikt, 1994)

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introduces the leap from *Euclidean Space* to *Cyberspace.* He features projects and visions by Marcos Novak on *Liquid Architectures in Cyberspace (*Novak, 1991*)* and *The Excess of Possibility*. The 1990s presented the time of the first digital turn, followed by a phase of developing, testing and playing with software, hardware, matter and thought. In 2010 Krista Sykes and Michael Hays published an anthology of essays discussing the new agenda that had developed between 1993 and 2010 (Sykes, 2010). Essays included the key texts "Field Conditions" by Stan Allen (Allen, 1999) "Architectural Curvilinearity: The Folded, the Pliant and the Supple" by Greg Lynn (Lynn, 1993) and "Design Intelligence" by Michael Speaks (Speaks, 2002). The book followed a previous influential publication by Kate Nesbitt on architectural theory between 1965 and 1995 (Nesbitt, K. 1996). During the 2010s, architecture has started to liberate itself from what we could call the era of *Genetic and bio-digital Architecture* (Werner, 2014). Beyond the goal of creating images (1980s)[10] and later on objects inspired by and mimicking biological form stands the desire for creating and building biological architecture with cognitive features, networking capabilities and material intelligence. Experimental architecture and urban design is longing for an (un)conscious habitat, efficient, balanced, sustainable and beautiful at the same time. Over the last decade, we have proved that the architect is increasingly designing with and through a systemic understanding, using digital tools, that allow for creating architecture, urban spaces and programs as nodes, edges or cells in distributed morphing networks. Currently this mainly applies to large-scale networks, urban, small-scale interventions[11] or building components such as cellular envelopes. The aim, however, is to create projects on all scales that combine parametric digital tools for design, material intelligence though embedded mechanisms, tactile and other sensoria, internal connectivity through microprocessors and external networking via the Internet. While architectural still remains in the age of the mechanical and pre-industrial by refraining from engulfing industrial pre-fabrication, mass-customization and modularized construction and assembly techniques, digital architectural theory and research has started learning about and implementing networked, metabolic and biological architecture. The vision of liquid architecture in Cyberspace by Marcos Novak at the end of the last century as "an architecture

[10]Christian Norberg-Schulz points out that "[. . .] architectural practice, where functionalism is abandoned while new architectures of images is emerging." (Norberg-Schulz, 1983)

[11]As seen in the numerous parametric pavilions designed, scripted and digitally fabricated globally, e.g., at the Architectural Association, Polytech Milano, ICD Stuttgart, Michigan University and more

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that breathes, pulses, leaps as one form and lands as another [...] whose form is contingent on the interests of the beholder: [...] an architecture without doors and hallways, where the next room is always where I need it to be and what I need it to be" has provided a script for future development, can presents one foundational column for digital theory in architecture now and computational architectural practice in the future. Around 2010, the advent of the second digital turn in architecture, allowed the notion of feedback, learning systems and artificial intelligence to be included into (digital) architectural projects) after decades of absence, left behind in the 1960s. Cybernetics re-rose from the ashes (Werner, 2011); cybernetic systems, in large scale smart and/or digital cities were envisaged (Leach, 2009; Handlykken, 2011), ideas suggested by William Gibson (Gibson, 1986) landed in the 'real' world, and 'emergence' (DeLanda, 2011; Johnson, 2011) became a driver for computational design strategies and digital theory in architecture.

The emergence of slime mold as inspiration and blueprint for the architecture of the 21st century is one of the triggers for the emphasis on digital theory. Since the 1990s, the relationship to material and hence the 'stuff' buildings and cities are made of has changed. The notion of phenomenology in the 1980s and 1990s as discussed by Christian Norberg-Schulz (Norberg-Schulz, 1980), especially through his theories on the *Genius Loci*, the spirit of the place, has been extended. Norberg-Schulz discussed architectural theory through Louis Khan and Martin Heidegger, both concerned with the human being-in-the-world; Khan through an understanding that the psyche[12] is the source of form, order and design, Heidegger through an understanding of an underlying structure, of the world's elements. The extension stretches in fact back to the treatises by Herman von Helmholtz, Jakob von Uexküll, Ludwig von Bertalanffy or D'Arcy Wentworth Thompson on theoretical biology. All of them laid the foundations for reaction, interaction, networked communication and the generation of form as a process of convergence between a genetic code (algorithm) internal and external forces (parameters)[13] (Thompson, D.W. 1961). Parameters drive function (utilitas), vitality (including structural stability – firmitas), form and appearance (venustas). The difference to an architectural understanding before the (bio-)digital and after is that

[12]"Kahn's *weltanschauung* was founded upon an intuition of a transcendent and omnipresent ground within and behind all physical reality – a World Soul that he called **psyche.**" (Burton, 1998)

[13]All of them also have laid the foundations for cybernetics, which in the era of information exchange and attempts to create architecture on a 'molecular' level in conjunction with the digital, is becoming increasingly relevant.

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of a more direct, connectivity between soft and hard matter, between atoms and bits. The exchange of information between organisms and environment enhanced networked intelligence may lead to architecture becoming a cybernetic bio-computer. Slime mould, "where [. . .] the intelligence (is) encoded inside this organism [. . .] into the physical mechanisms that the slime mould uses to move in space." describes one of many species showing intelligent and self-organizing structural, mechanical and networking behaviour patterns, like ants, birds and fish, corals or the Internet (Redd, 2017). It allows a shift from formal architecture to an architecture of soft matter robotics.

14.4 Concluding Discussion: *Physarum* as Liquid Geometry Computer and Disruptive Bio-cybernetic System for Architectural Applications

Physarum is a system describing the characteristics of a liquid geometry computer – in conversation with its environment. Every system and every conversation is goal-driven – so is slime mould in conversation/interaction (Ashby, 1957; Glanville, 2004; Werner,)[14]. The organisms goal is survival. It seeks achieving its goal by organizing the intake and distribution of nutrition through its entire multinuclear body most efficiently for its capabilities. The molds behavior results in forming geometric patterns, namely (a) branching and (b) Voronoi/Delaunay. Their generation can and has been simulated through activating multi-agent systems. In the early stages of growth, the mold shows a branching algorithm (Figure 14.1). The latter can be achieved through applying different types of cellular automata to assist the seemingly self-organizing multi-agent system (Jones, 2016). One is diffusion-limited aggregation (DLA), which presents one way of creating the form of branching; This is achieved by agents 'randomly' wandering through space directed by Brownian motion and aggregating once close to each other. The aggregating behavior is the result of attraction of the agents to each other. In a multi-agent system simulation, the attraction force between agents can be varied. While the first phase (branching), as shown in Figures 14.2 and 14.7, is driven by attraction, the second phase (forming the Voronoi pattern) is driven by the generation of repulsive fields (Jones, 2016; Dourvas, 2015; Tsompanas, 2012; Tsompanas, 2015).

[14]A discussion on the cybernetics of slime mold is envisaged in depth at a later stage.

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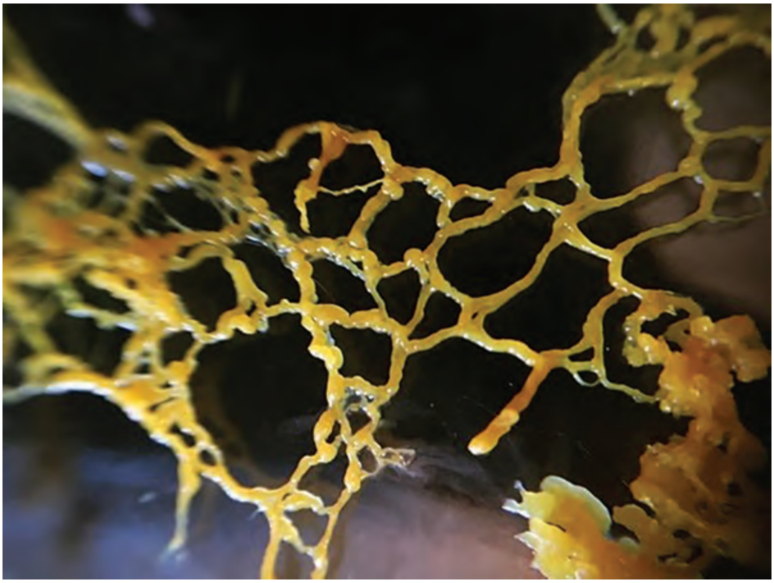

Figure 14.7 (left): Voronoi close-up of *Physarum* on the glass lid of a Petri dish – no Agar substrate.

Source: http://tactile-architecture.com

Beyond the graphic aspect, the structure of slime mold expresses intelligence in growing one network for efficient nutrition intake and dissemination. The mold successfully combines morphology, structure, infrastructure and metabolism. *Physarum*s algorithmic and parametric design strategies for architectural optimization and computational urban planning for a lean networked *conscious city* or *unconscious city*. In addition to the morphing Voronoi-like construction, that guarantees vitality throughout the system, the organism shows the creation of intricate nest-like 4-dimensional (time- and space-related) complex structure (Figure 14.7). Those structures are hardly visible with the naked eye but become visible through a 10-fold magnification. The mould spans diagonals from horizontal to vertical surfaces (Figure 14.8) and can build up vertical columns. Geometrically the emergent and morphing 4-dimensional structure is akin to the glue-experiment where a similar pattern formation of glue becomes visible during a the process of stretching (http://tactile-architecture.com).

I will conclude by raising the question of *Physarum* serving as – truly disruptive – bio-cybernetic system for architectural applications.

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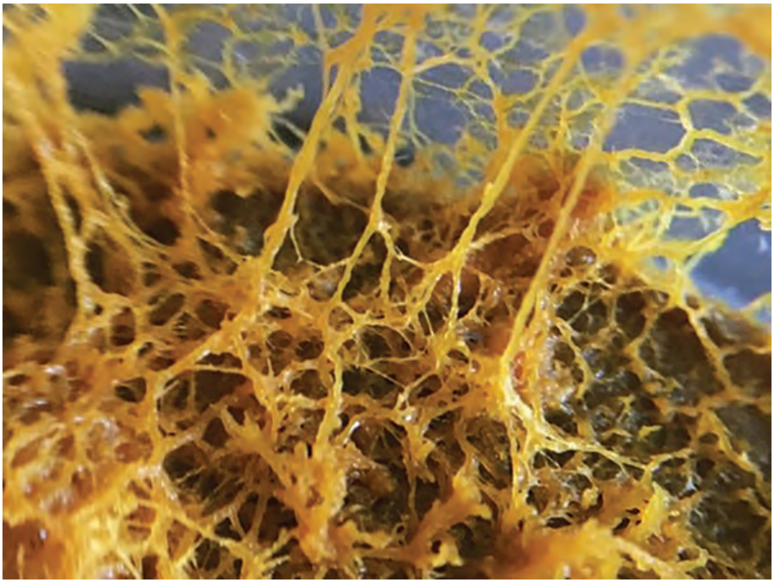

Figure 14.8 (right): grown nest-structure of which branches space diagonally to a vertical glass-surface without Agar; growth process approximately 7 days in a dark, 20 °C warm space. (Werner, 2018).

The organisms *protoplasmic network* paired with its structural abilities, embedded intelligence of physically behaving towards growth and survival and learning/training capabilities suggests a novel field of interdisciplinary research for (a) bio-architectural design methods and strategies and (b) advanced computing material on a human scale for e.g., surfaces and building scale for, e.g., construction or spatial changes according to the needs of the inhabiting actors. A variety of disciplines, including architects, may take the opportunity to test and understand the principles *Physarum polycephalum* utilizes, to work in joined forces towards a sustainable built Cyberspace. If we regard *Physarum polycephalum* as a bio-logical computer of Cyberspace, current definitions created in era of digital architectural archaeology–such as Michael Benedikt's from 1991–may want to be re-interpreted. Benedikt defines Cyberspace as

> “a globally networked, computer-sustained, computer-accessed, and computer-generated, multidimensional, artificial, or “virtual” reality. In this reality, to which every computer is a window, seen or heard objects are neither physical nor, necessarily, representations of physical objects but are, rather, in form, character and action,

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made up of data, of pure information. This information derives in part from the operations of the natural, physical world, but for the most part it derives from the immense traffic of information that constitute human enterprise in science, art, business, and culture." Benedikt, 1994)

Benedikt suggests a high complexity network in which information is created through data that is produced by interaction of all kinds. I suggest that the integrating bio-computers into the multi-dimensional dynamic conversations between physical and virtual will extend the recursive feedback loops in human–machine networks (HMN) as we know them today. Through the rise of the *Internet of Things* building and the construction of such the discipline of architecture, as well as the construction industry, is slowly starting to adapt and embrace novel networked technologies driven by AI. Fields such as the Molecular Sciences and Nanotechnology have investigated the functions and cognitive potential of bio-materials paired with data-networks (body-internally) for, e.g., medical applications (Khan, 2017; Ebara, 2014). Such research offers a disruptive paradigm shift in designing, producing, constructing buildings; questions of energy resources, possibly water resources or material disposal at the end of a buildings life cycle are but a few to be tackled by creating a discipline between bio-computers and building architecture.

The outlook I am sketching out in this chapter invites to a joined investigation into an extended digital theory in architecture through the parallels of bio-computers to the digitally networked cyberspace and to joined research for truly *smart*, urban spaces and efficient infrastructures of mobility, production and food and *intelligent cyber-physical* building components made of soft and hard matter, partly regulated through liquid bio-computers.

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