Physarum computing devices: five examples

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A cellular slime mould Physarum polycephalum has sophisticated life cycle,[1] which includes fruit bodied, spores, single-cell amoebas, syncytium. At one phase of its cycle the slime mould becomes a plasmodium (this what we address Physarum further). The plasmodium is a coenocyte: nuclear divisions occur without cytokinesis. It is a single cell with thousands of nuclei. The plasmodium is a large cell. It grows up to tens centimetres when conditions are good. The plasmodium consumes microscopic particles and bacteria. During its foraging behaviour the plasmodium spans scattered sources of nutrients with a network of protoplasmic tubes. The plasmodium optimises it protoplasmic network to cover all sources of nutrients, stay away from repellents and minimise transportation of metabolites inside its body. I will provide a very brief introduction to actual working prototypes of Physarum based sensors, computers, actuators and controllers. Details can be found in pioneer book on Physarum machines[2] and the 'bible' of slime mould computing.[3]

Shortest path and maze

Given a maze we want to find a shortest path between the central chamber and an exit. This was the first ever problem solved by Physarum. There are two Physarum processors, which solve the maze. First prototype[4] works as follows. The slime mould is inoculated everywhere in a maze. The Physarum develops a network of protoplasmic tubes spanning all channels of the maze. This network represents all possible solutions. Then oat flakes are placed in a source and a destination site. Tube lying along the shortest (or near shortest) path between two sources of nutrients develops increased flow of cytoplasm. This tube becomes thicker. Tubes branching to sites without nutrients become smaller due to lack of cytoplasm flow. They eventually collapse. The sickest tube represents the shortest path between the sources of nutrients. The selection of the shortest protoplasmic tube is implemented via interaction of propagating bio-chemical, electric potential and contractile waves in the plasmodium's body.[5] The approach is not efficient because we must literally distribute the computing substrates everywhere in the physical representation of the problem. A number of computing elements would be proportional to a sum of lengths of the maze's channels. Second prototype of the Physarum maze solver is based on Physarum' chemoattraction.[6] An oat flake is placed in the central chamber. The Physarum is inoculated somewhere in a peripheral channel. The oat flake releases chemoattractants. The chemoattractants diffuse along the maze's

Fig. 1. Slimemould solves maze. Fertile oat flake was placed in the central chamber; oat flake colonized by slime mould in the outmost chamber.

channels. The Physarum explores its vicinity by branching out protoplasmic tubes into the opening of nearby channels. When a wave-front of diffusing attractants reaches Physarum, the Physarum halts lateral exploration. Instead it develops an active growing zone propagating along gradient of the attractants' diffusion. The sickest tube indeed represents the shortest path between the sources of nutrients (Fig. 1). The approach is efficient because a number of computing elements is proportional to a length of the shortest path.

Spanning tree

A spanning tree of a finite planar set is a connected, undirected, acyclic planar graph, whose vertices are points of the planar set. As algorithm for computing a spanning tree of a finite planar set based on morphogenesis of a neuron's axonal tree was initially proposed:[7] planar data points are marked by attractants (e.g. neurotrophins) and a neuroblast is placed at some site. Growth cones sprout new filopodia in the direction of maximal concentration of attractants. If two growth cones compete for the same site of attractants then a cone with highest energy (closest to previous site or branching point) wins. Fifteen years later we implemented the algorithm with Physarum.[8] Degree of Physarum branching is inversely proportional to a quality of its substrate. Therefore to reduce a number of random branches we cultivate Physarum not on agar but just humid filter paper. Planar data set is represented by a configuration of oat flakes. Physarum is inoculated at one of the data sites. Physarum propagates to a virgin oat flake closest to the inoculation site. Physarum branches if there are several virgin flakes nearby. It colonises the next set of flakes. The propagation goes on until a protoplasmic network spans all data sites. The protoplasmic network approximates the spanning tree (Fig. 2). The resulted tree does not remain static though. Later cycles can be formed and the tree is transformed into one of proximity graphs, e.g. relative neighbourhood graph or Gabriel graph.[9]

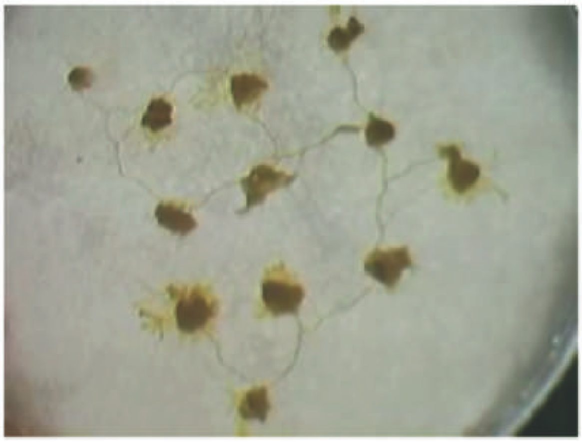

Fig. 2. Approximation of proximity graphs by Physarum. Oat flakes represent data points. Initially, slime mould was inoculated in the bottommost oat flake: (a) Approximation of spanning tree by slime mould.

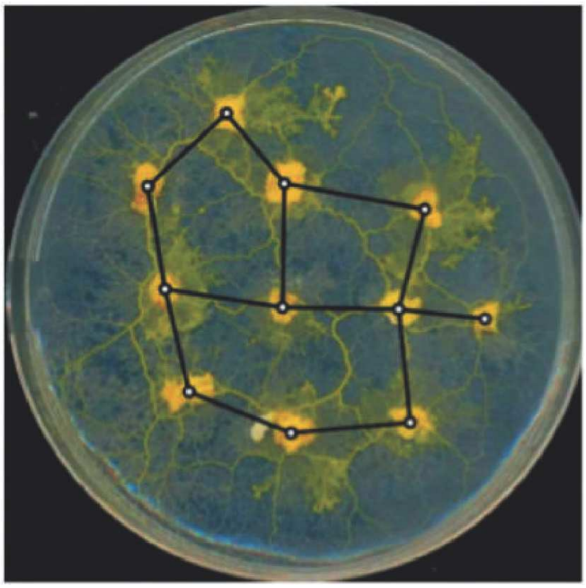

Fig. 2 : (b) Approximation of a Relative Neighbourhood Graph.

Approximation of transport networks

To uncover similarities between biological and human-made transport networks and to project behavioural traits of biological networks onto development of vehicular transport networks we conducted an evaluation and approximation of motorway networks by Physarum in fourteen geographical regions: Africa, Australia, Belgium, Brazil, Canada, China, Germany, Iberia, Italy, Malaysia, Mexico, The

Netherlands, UK, and USA.[10] We represented each region with an agar plate, imitated major urban areas with oat flakes, inoculated Physarum in a capital, and analysed structures of protoplasmic networks developed. We found that the networks of protoplasmic tubes grown by Physarum match, at least partly, the networks of human-made transport arteries. The shape of a country and the exact spatial distribution of urban areas, represented by sources of nutrients, play a key role in determining the exact structure of the plasmodium network. In terms of absolute matching between Physarum networks and motorway networks the regions studied can be arranged in the following order of decreasing matching: Malaysia, Italy, Canada, Belgium, China, Africa, the Netherlands, Germany, UK, Australia, Iberia, Mexico, Brazil, USA. When a fragment of protoplasmic tube is mechanically stimulated, e.g. gently touched by a hair, a cytoplasmic flow in this fragment halts and the fragment's resistivity to the flow dramatically increases. The cytoplasmic flow is then directed via adjacent protoplasmic tubes. In the article *Slime mold microfluidic logical gates*, we demonstrate how logical operations can be implemented in ensembles of protoplasmic tubes.[11] The tactile response of the protoplasmic tubes is used to actuate analogs of two- and four-input logical gates and memory devices. The slime mold tube logical gates display results of logical operations by blocking flow in mechanically stimulated tube fragments and redirecting the flow to output tube fragments.[12]

Fig. 3. Physarum approximate Route 20 in USA.
Micro-fluidic logical gates.

Kolmogorov-Uspensky machine

In 1950s Kolmogorov outlined a concept of an algorithmic process, an abstract machine, defined on a dynamically chang- ing graph.[13] The structure later became known as Kolmogorov-Uspensky machine.[14] The machine is a computational process on a finite undirected connected graph with distinctly labelled nodes.[15] We implement the Kolmogorov-Uspensky machine in the Physarum as follows.[16] Stationary nodes are represented by sources of nutrients. Dynamic nodes are assigned to branching site of the protoplasmic tubes. Food colourings label the stationary nodes because Physarum exhibits a hierarchy of preferences to different colourings (Fig. 4). An active zone in the storage graph is selected by inoculating the Physarum on one of the stationary nodes. An edge of the Kolmogorov-Uspensky machine is a protoplasmic tube connecting the nodes.

Will we ever see the Physarum in commercial computing or sensing devices?

Not tomorrow. In no way Physarum can win over the silicon technology, which has been optimised non-stop for decades and decades. But a success depends on many factors, not just technological ones. Success is in finding a vacant niche and flourishing there. More likely applications of Physarum computers will be in disposable hybrid processing devices used for sensing and decision-making in environments and situations where speed does not matter but being energy efficient, adaptable and self-healing is important.

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[12] More details on XOR and NOR gates and memory devices can be found in Ibid.

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Fig. 4. Operation of address selected nodes, as specified by food colourings, in Physarum implementation of Kolmogorov-Uspensky machine.