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Physarum machines for space missions

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Abstract. A Physarum machine is a programmable amorphous biological computer experimentally implemented in plasmodium of *Physarum polycephalum*. We overview a range of tasks solvable by Physarum machines and speculate on how the Physarum machines could be used in future space missions.

1 Prototypes of unconventional computers

An unconventional computing applies principles of informations processing in physical, chemical and biological systems in design of future and emergent computing paradigms, architectures and implementations [21, 2, 62]. The field is proud with its theoretical achievements, e.g. membrane computing, quantum computing, hyper-computation and artificial immune systems, yet can boast about only a few experimental laboratory prototypes of unconventional computers. They include chemical reaction–diffusion processors [1], extended analog computers [41], micro-fluidic circuits [28], gas-discharge systems [49], chemo-tactic droplets [35], enzyme-based logical circuits [33, 48], crystallization computers [9] (Fig. 1), geometrically constrained chemical computers [50, 42, 31, 64, 30], molecular logical gates and circuits [60, 39]. Slime mould *Physarum polycephalum* (Fig. 2) is one of the most recent candidates for a role of general-purpose amorphous living computer [13].

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2 *Physarum polycephalum*

P. polycephalum belongs to the species of order *Physarales*, subclass *Myxogastromycetidae*, class *Myxomycetes*, division *Myxostelida*. It is commonly known as a true, acellular or multi-headed slime mould. Plasmodium is a 'vegetative' phase, a single cell with a myriad of diploid nuclei. The plasmodium is visible to the naked eye (Fig. 3). The plasmodium looks like an amorphous yellowish mass with networks of protoplasmic tubes. The plasmodium behaves and moves as a giant amoeba (Fig. 5). It feeds on bacteria, spores and other microbial creatures and micro-particles [59].

Acellular slime mould *P. polycephalum* has a rich life cycle [59]: fruit bodies, spores, single-cell amoebas, and syncytium. In its plasmodium stage, *P. polycephalum* consumes microscopic particles, and during its foraging behaviour the plasmodium spans scattered sources of nutrients with a network of protoplasmic tubes (Fig. 8). The plasmodium optimises its protoplasmic network that covers all sources of nutrients and guarantees robust and quick distribution of nutrients in the plasmodium's body. Plasmodium's foraging behaviour can be interpreted as a computation [43, 44, 45, 46]: data are represented by spatial of attractants and repellents, and results are represented by structure of protoplasmic network [13]. Plasmodium can solve computational problems with natural parallelism, e.g. related to shortest path [44] and hierarchies of planar proximity graphs [3], computation of plane tessellations [53], execution of

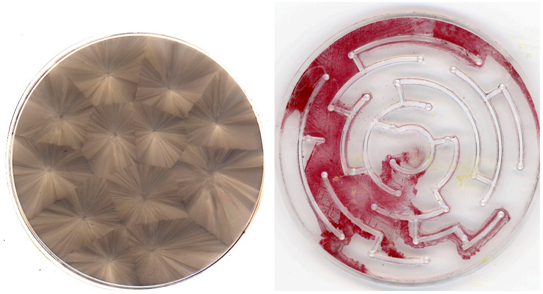

FIGURE 1. *Crystallisation based unconventional computer. (a) Hot ice computer approximates Voronoi diagram of a planar data set. Crystallisation was inoculated in several sites of planar data set. Edges of Voronoi diagram are represented by boundaries of crystallisation domains. (b) Potassium ferricyanide crystallisation computer approximates paths out of a labyrinth. Crystallisation was initiated in a central chamber of the labyrinth. Path between outside channel and the central chamber is represented by crystal needles. See deails in [9].*

logical computing schemes [63, 11], and natural implementation of spatial logic and process algebra [56].

Plasmodium can be cultivated on a non-nutrient or a nutrient agar. While grown on a nutrient agar the plasmodium propagates as an omnidirectional wave. On a non-nutrient agar plasmodium propagates as a travelling localisation (Fig. 5), and behaves like a wave-fragment in a sub-excitable medium [4, 5]. While presented with a configuration of attractants, e.g. oat flakes (Fig. 8), on a non-nutrient substrate, the plasmodium develops active zones that explore the substrate and propagate towards the oat flakes. Neighbouring oat flakes colonised by plasmodium are usually connected by protoplasmic tubes. Distribution of chemo-attractants and position of initial inoculation of plasmodium are input data for Physarum machines. Structure of the protoplasmic networks and/or domains occupied by plasmodium are results of computation in Physarum machines. Propagating active zones can be considered as elementary processors of Physarum machines.

3 Physarum machines

A Physarum machine is a programmable amorphous biological computing device experimentally implemented in plasmodium of *P. polycephalum* [13]. A Physarum machine is programmed by configurations of repelling and attracting gradients. A mechanics of Physarum machines is based on the following unique features of *P. polycephalum*:

- Physarum is a living, dynamical reaction-diffusion pattern formation mechanism.
- Physarum may be considered as equivalent to a membrane bound sub excitable system: excitation stimuli provided by chemo-attractants and chemo-repellents (Fig. 6).
- Physarum may be regarded as a highly efficient and living micro-manipulation and micro-fluidic transport device.
- Physarum is sensitive to illumination and AC electric fields and therefore allows for parallel and non-destructive input of information.
- Physarum represents results of computation by configuration of its body (Fig. 2).

Physarum is thus a computing substrate which transforms data represented in spatially extended chemical and physical stimuli to results represented in a topology of protoplasmic networks.

Plasmodium can be cultivated on a non-nutrient (e.g. Select agar, Sigma Aldrich) or a nutrient agar (e.g. Corn Meal Agar). While grown on a nutrient agar the plasmodium propagates as an omnidirectional wave. On a non-nutrient agar plasmodium propagates as a travelling finite localisation, and behaves like a wave-fragment in a sub-excitable medium [4, 5]; most implementations discussed in the paper are done on a non-nutrient agar. Thus by *active zone* we mean either omnidirectional growing pattern (on nutrient substrate) or — in majority of examples — a localised growing pattern (on non-nutrient substrate). While presented with a configuration of attractants, e.g. oat flakes (Fig. 8a), on a non-nutrient substrate, the plasmodium develops active zones (Fig. 8d) that explore the substrate and propagate towards the oat flakes. Neighbouring oat flakes colonised by plasmodium (Fig. 8b) are usually connected by protoplasmic tubes (Fig. 8c). Distribution of chemo-attractants and position of initial inoculation of plasmodium are input data for Physarum machines. Structure of the protoplasmic networks and/or domains occupied by plasmodium are results of computation in Physarum machines. Propagating active zones can be considered as elementary processors of Physarum machines.

We illustrate mechanics of computation in Physarum on an approximation of Voronoi diagram of a planar set.

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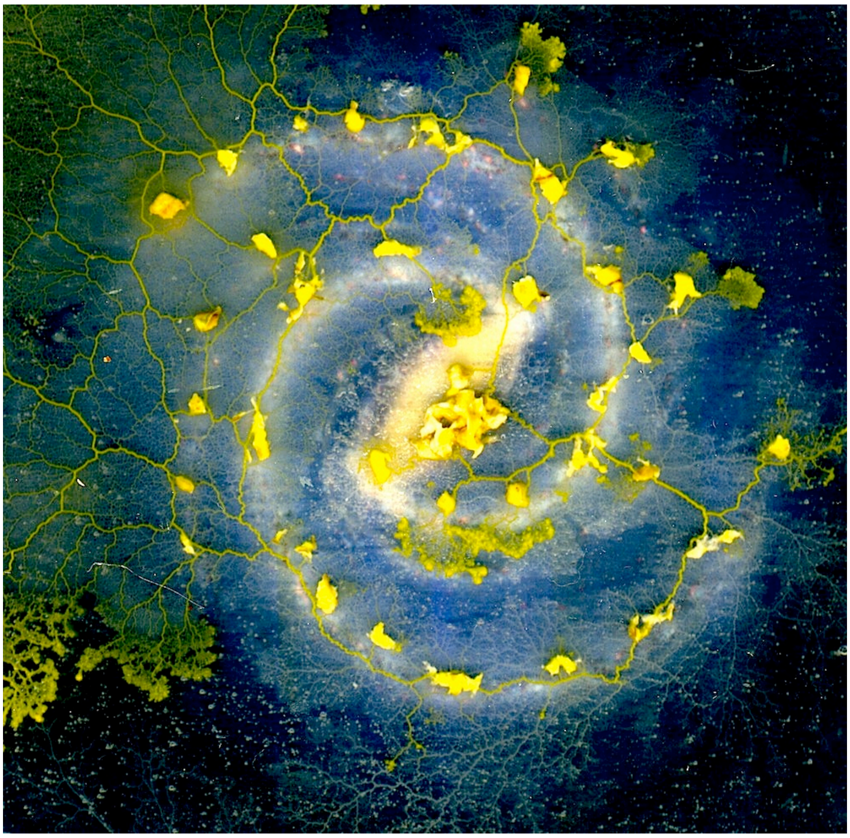

Figure 2. *Physarum propagating on an artistic impression of galaxy. See original picture in public domain NASA/JPL-Caltech [47].*

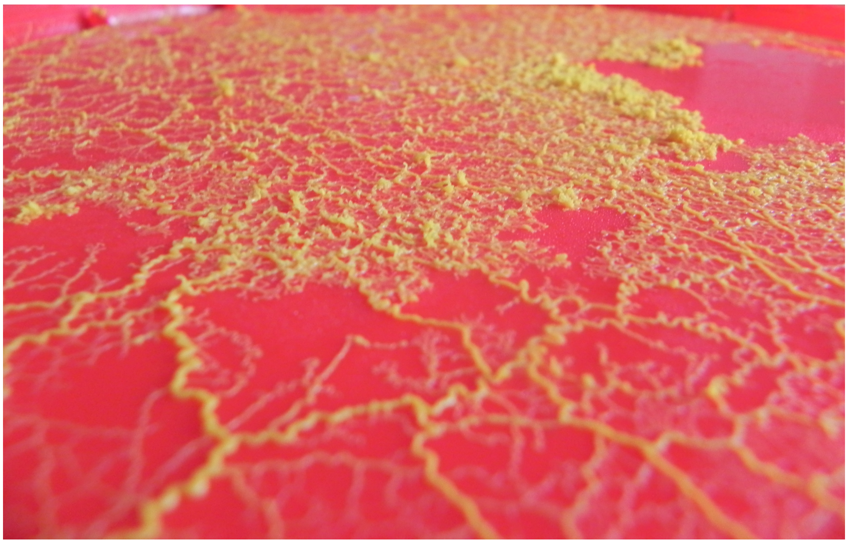

Figure 3. *Physarum propagates on a bare plastic surface.*

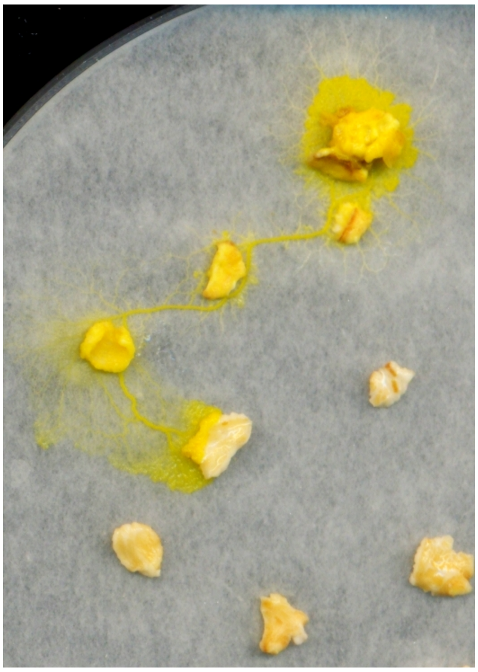

FIGURE 4. *Physarum spanning sources of nutrients with its protoplasmic network. Physarum was inoculated on the northmost flake. Physarum propagates source. Oat flakes not yet colonised by Physarum are in the south-east part.*

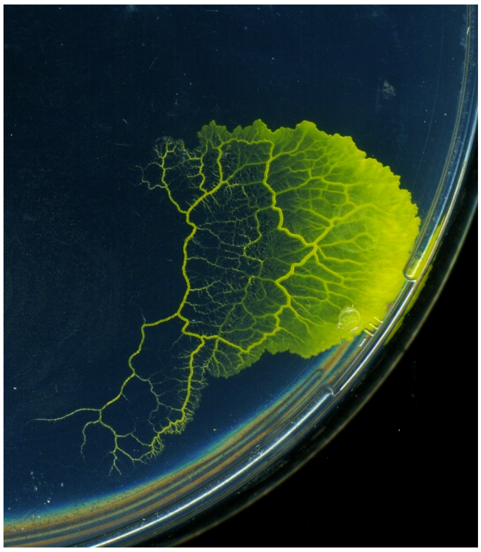

FIGURE 5. *Localised Physarum propagates on agar gel. This is example of how Physarum forms a dissipative soliton like structures. Slime mould active zone exhibits characteristic wave-front with tail of protoplasmic tubes trailed behind. The active zone resembles wave-fragments (dissipative solitons) in Belousov-Zhabotinsky medium [4, 13]. The active zone is an elementary processor of a multi-processor Physarum machine.*

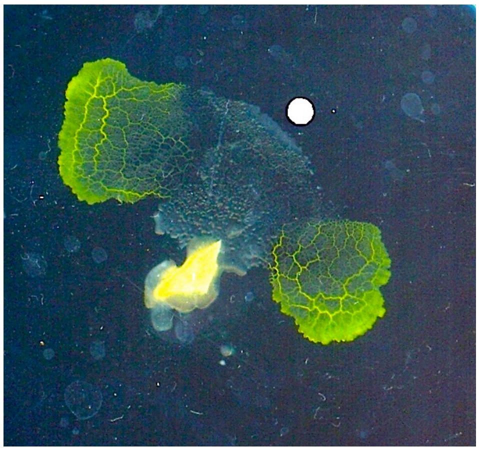

FIGURE 6. *Controlling Physarum with repellents. Physarum wave-fragment travelling north-east 'collides' with a grain of salt (white disc) and splits into two independent fragments; one fragments travels north-west another south-east.*

A planar Voronoi diagram (VD) of the set **P** is a partition of the plane into such regions that, for any element of **P**, a region corresponding to a unique point $p \in \mathbf{P}$ contains all those points of the plane which are closer to p than to any other node of **P**. Delaunay triangulation (DT) is a dual graph of VD [51].

On a nutrient substrate P. polycephalum approximates VD. On a non-nutrient substrate the plasmodium approximates DT. Plasmodium growing on a nutrient substrate from a single site of inoculation expands circularly as a typical diffusive or excitation wave. When two plasmodium waves encounter each other, they stop propagating. To approximate a VD with Physarum, we physically map a configuration of planar data points by inoculating plasmodia on a substrate (Fig. 9a). Plasmodium waves propagate circularly from each data point (Fig. 9bc) and stop when they collide with each other (Fig. 9d). Thus, the plasmodium waves approximate a VD, whose edges are the substrate's loci not occupied by plasmodia (Figs. 9d). The situation becomes different when Physarum machine is given the same set of data (planar points represented by oat flakes colonised by plasmodium) but placed on a non-nutrient substrate. Being driven by chemo-attractants the plasmodium in each planar point develops just few localised active zones, which grow towards geographically neigh-

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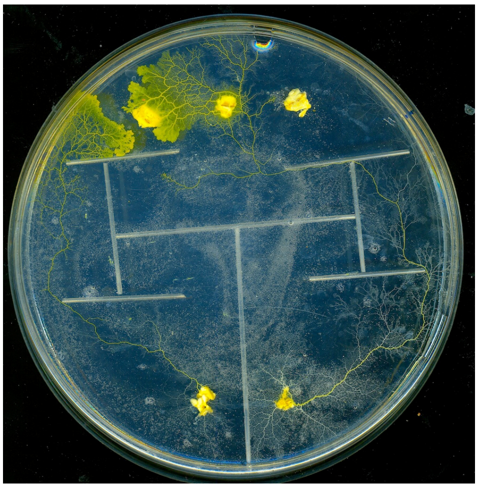

Figure 7. *Decentralised decision making by Physarum. Oat flakes with plasmodium were placed in south part of Petri dish. Virgin oat flakes were placed in the north part. Obstacles were represented by capillary tubes placed on an sagar surface. Optimal — from Physarum machine point of view — paths connected source and destination sites are seen as pronounced protoplasmic tubes.*

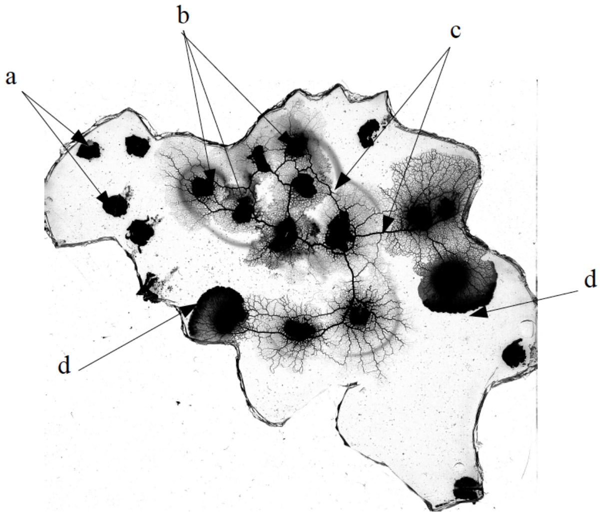

Figure 8. *Plasmodium of* P. polycephalum *on a data set on an agar gel. (a) Virgin oat flakes. (b) Oat flakes colonised by the plasmodium. (c) Protoplasmic tubes. (d) Active zones, growing parts of the plasmodium.*

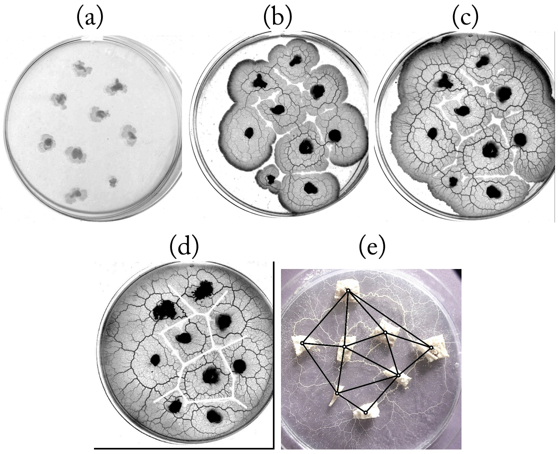

Figure 9. *Voronoi diagram and Delaunay triangulation computer by Physarum machines. (a–d) Approximation of VD by slime mould on nutrient agar gel. (a) Sites of plasmodium inoculation represent planar data points to be sub-divided by edges of VD. (bc) Experimental snapshots of growing plasmodia. (d) Bisectors of VD are represented by loci of substrate not occupied by plasmodium, bisectors computed by classical technique are shown by straight lines. (e) DT approximated by Physarum on a non-nutrient substrate.*

bouring oat flakes (planar points). Thus the flakes become connected by enhanced protoplasmic tubes, which — up to some degree of accuracy — represent edges of the DT (Figs. 9e) [3].

4 Application domains of Physarum machines

Future space missions could benefit from Physarum machines because living and hybrid functional materials made of *P. polycephalum* will play a role of specialised processors solving tasks of

- computational geometry (approximation of Voronoi diagram of arbitrary geometrical shape, concave and convex hulls),
- image processing (dilation, erosion, opening and closing, image expansion and shrinking, computing connected components of image, and image translation, edge detection, edge completion, boundary detection, feature tracking; and, image recognition),
- graph-theoretic computing (approximation of proximity graphs. Graph restructuring, transformation between cyclic graphs as Delaunay triangulation and Gabriel graph and acyclic graphs as minimum spanning tree and Steiner tree,
- optimisation (computation of spanning trees and

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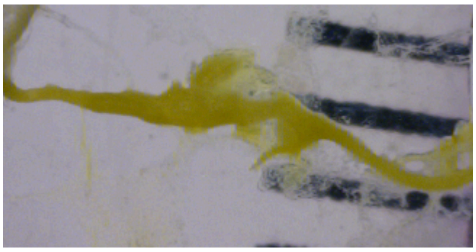

FIGURE 10. *Protoplasmic tube self-repaired after being ruptured by applying load of 0.2 g.*

obstacle free shortest paths),

- neuro-morphic processors (information processing and sensorial fusion on plasmodial trees), and
- general purpose computing devices with architecture of Kolmogorov-Uspensky storage modification machines.

The slime mould's computing potential and resistance to environmental factors can be increased by hybridising protoplasmic networks with new functional materials, biomorphic mineralisation, bio-synthesis of metal nano-particles, production of bio-wires, and coating protoplasmic networks with with conductive polymers.

Combined with conventional electronic components in a hybrid chip, Physarum networks will radically improve the performance of digital and analog circuits. Physarum machines are analogous to reaction-diffusion chemical systems encapsulated in a growing elastic membrane. The machines can be made hybrid, i.e. combining dead (but coated with conductors) and living parts of slime mould in communication channels. Physarum machines can be powered directly and efficiently by bio-chemical power, fabricated using self-growth and self-organisation, and controllably shaped into two- and three-dimensional structures. Physarum machines are robust to physical damage and exhibit a substantial degree of self-repair (Fig. 10).

Hybrid (live and coated with conductors) Physarum machines can perform computation by classical means of electrical charge propagation, by travelling waves of contraction, and by a physical propagation of the slime mould's body.

In terms of classical computing architectures, the following characteristics can be attributed to hybrid Physarum machine [6]:

- Massive parallelism: there are thousands of elementary processing units, oscillatory bodies, in a slime mould colonised in a Petri dish;
- Massive signal integration: Membrane of plasmodium is able to integrate massive amounts of complex spatial and time-varying stimuli to effect local changes in contraction rhythm and, ultimately, global behaviour of the plasmodium;
- Local connections: micro-volumes and oscillatory bodies of cytoplasm change their states, due to diffusion and reaction, depending on states of, or concentrations of, reactants, shape and electrical charges in their closest neighbours;
- Parallel input and output: Physarum computes by changing its shape, can record computation optically; Physarum is light sensitive, data can be inputted by localised illumination;
- Fault tolerance: being constantly in a shape changing state, Physarum machine restores its architecture even after a substantial part of its protoplasmic network is removed.

Development of Physarum machines bring benefits to several fields of science, technology and engineering, few are exemplified below.

Future electronic designs will be integrated at a cellular scale, where growing Physarum networks will be forming a skeleton of conductive and information processing elements of the circuits. Future bio-electronic designs require novel computational approaches: Physarum machines offer robust and reliable methods for controlled development of novel hardware components and systems, including high density of computing elements and very low power consumption.

Novel and emergent computing paradigms and architectures — laboratory prototypes and models of novel computing substrates will be based on prototypes of Physarum machines, thus enabling those working in nature-inspired computing to access original computing algorithms and experimental procedures. A bio-network based computers employing Physarum machines can be built on in broad variety of ways: change of interface (optical, electrical, chemical, mechanical); change of internal structure of growing networks for information transmission and processing; units can be mass-produced cheaply and can be shared among labs without incurring additional expenses; hybrid units combining several types of biological substrates and conventional hardware can be made with units shared among labs.

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The complex systems community will benefits from Physarum computing for the control of the growing architecture and functions of disordered unreliable networks, and computational paradigms of growing, and structurally dynamic, random computing networks.

Theory of computation — logical schemes and computational circuits developed in Physarum machines will belong to a class of hybrid, digital-analog systems, which are a fertile subject of research at the edge of analog, mechanical and discrete computation. Benefits are envisaged also in the fields of self-assembly, self-regenerative systems, survivability and fault-tolerance of novel computing schemes. Physarum is capable of relatively quick recovery after damage and constantly explore space available and competition for resources.

Growing protoplasmic tubes of slime mould could be used as the architectural skeleton to build bio-electronic circuits to provide connections between living tissue and computers, such as brain-machine interfaces. Similar devices made with conventional technology tend to be rigid and must be encapsulated to protect the electrical circuits from the moisture inherent in biology.

Further we illustrate computing abilities of Physarum — which could be useful in future space missions — in few examples of experimental laboratory studies.

5 Physarum logical gates

Given cross-junction of agar channels and plasmodium inoculated in one of the channels, the plasmodium propagates straight through the junction [11]; the speed of propagation may increase if sources of chemo-attractants present (however presence of nutrients does not affect direction of propagation). An active zone, or a growing tip, of plasmodium propagates in the initially chosen direction, as if it has some kind of inertia. Based on this phenomenon we designed two Boolean gates with two inputs and two outputs, see Fig. 11ab. Input variables are x and y and outputs are p and q. Presence of a plasmodium in a given channel indicates Truth and absence — False. Each gate implements a transformation from $\langle x, y \rangle \to \langle p, q \rangle$. Experimental examples of the transformations are shown in Fig. 11.

Plasmodium of *P. polycephalum* implements two-input two-output Boolean gate P_1: $\langle x, y \rangle \to \langle xy, x + y \rangle$. Plasmodium inoculated in input y of P_1 propagates along the channel yq and appears in the output q (Fig. 11c). Plasmodium inoculated in input x of P_1 propagates till junction of x and y, 'collides' to the impassable edge of channel yq and appears in output q (Fig. 11d). When plasmodia are inoculated in both inputs x and y of P_1 they collide with each other and the plasmodium originated in x continues along the route xp. Thus the plasmodia appear in both outputs p and q (Fig. 11e).

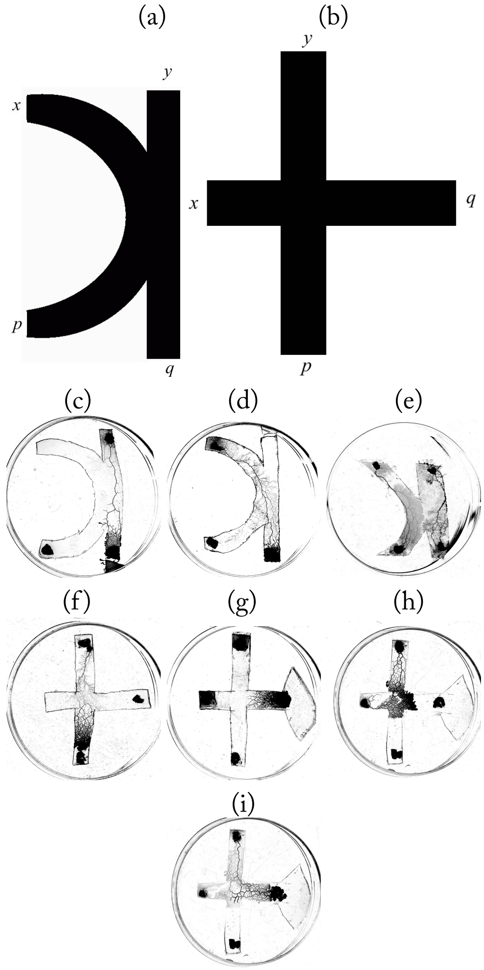

Figure 11. *Physarum logical gates. (ab) Geometrical structure of Physarum gates* P_1 *(a) and* P_2 *(b):* x *and* y *are inputs,* p *and* q *are outputs. (c–e) Experimental examples of transformation* $\langle x, y \rangle \to \langle p, q \rangle$ *implemented by Physarum gate* P_1. *(c)* $\langle 0,1 \rangle \to \langle 0,1 \rangle$. *(d)* $\langle 1,0 \rangle \to \langle 0,1 \rangle$. *(e)* $\langle 1,1 \rangle \to \langle 1,1 \rangle$. *(f–i) Experimental examples of transformation* $\langle x, y \rangle \to \langle p, q \rangle$ *implemented by Physarum gate* P_2. *(f)* $\langle 0,1 \rangle \to \langle 1,0 \rangle$. *(g)* $\langle 1,0 \rangle \to \langle 0,1 \rangle$. *(hi) Two snapshots (taken with 11 h interval) of transformation* $\langle 1,1 \rangle \to \langle 0,1 \rangle$.

Plasmodium of *P. polycephalum* implements two-input two-output gate P_2: $\langle x, y \rangle \to \langle x, \overline{x}y \rangle$. If input

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x is empty, plasmodium placed in input y of P_2 propagates directly towards output p (Fig. 11f). Plasmodium inoculated in input x of P_2 (when input y is empty) travels directly towards output q (Fig. 11g). Thus transformations $\langle 0, 1\rangle \to \langle 1, 0\rangle$ and $\langle 1, 0\rangle \to \langle 0, 1\rangle$ are implemented. The gate's structure is asymmetric, x-channel is shorter than y-channel. Therefore the plasmodium placed in input x of P_2 usually passes the junction by the time plasmodium originated in input y arrives at the junction (Fig. 11h). The y-plasmodium merges with x-plasmodium and they both propagate towards output q (Fig. 11i). Extension of gel substrate after output q does usually facilitate implementation of the transformation $\langle 1, 1\rangle \to \langle 0, 1\rangle$.

6 Path finding and routing

Maze-solving is a classical task of bionics, cybernetics and unconventional computing. A typical strategy for a maze-solving with a single device is to explore all possible passages, while marking visited parts, till the exit or a central chamber is found. Several attempts have been to outperform Shannon's electronic mouse Theseus [52] using propagation of disturbances in unusual computing substrates, including excitable chemical systems, gas-discharge, and crystallisation. Most experimental prototypes were successful yet suffered from the computing-substrates specific drawbacks [14]. Below we briefly outline laboratory experiment on path finding with Physarum guided by a diffusion of an attractant placed in the target site.

In laboratory experiments we used plastic mazes [14], 70 mm diameter with 4 mm wide and 3 mm deep channels (Fig. 12a). We filled channels with agar gel as a non-nutrient substrate. An oat flake was placed in the central chamber of the maze and the plasmodium was inoculated in the most peripheral channel of the maze.

A typical experiment is illustrated in Fig. 12. After its inoculation the plasmodium started exploring its vicinity and at first generated two active zones propagating clock- and contra-clockwise (Fig. 12ab). Several active zones are developed to explore the maze (Fig. 12d). By the time diffusing chemo-attractants reached distant channels, one of the active zone already became dominant and suppressed another active zones (Fig. 12c). In example shown active zone travelling contra-clockwise inhibited active zones propagating clockwise. The dominating active zone then followed the gradient of chemo-attractants inside the maze, navigated along intersections of the maze's channels and solved the maze by entering its central chamber (Fig. 12c). Physarum machines do not always fine an optimal solution but they always find some solution, rather optimal for given conditions and efforts, and rarely fail (Fig. 2).

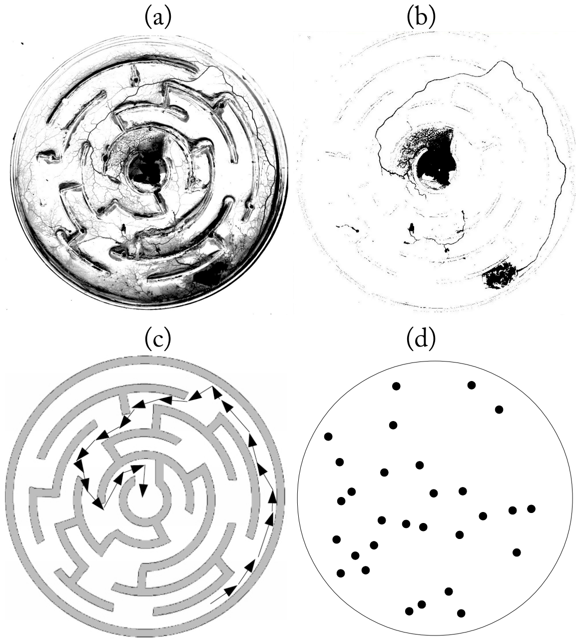

FIGURE 12. *Experimental maze-solving with plasmodium of* P. polycephalum. *Plasmodium is inoculated in peripheral channel, east part of the maze, and a virgin oat flake is placed in central chamber. (a) Scanned image of the experimental maze, protoplasmic tubes are light-coloured. (b) Binarised image, major protoplasmic tubes are thick black lines. (c) Scheme of plasmodium propagation, arrows symbolise velocity vectors of propagating active zone. (d) Locations of active growing zones, sprouted by plasmodium during exploration of the maze. See details in [14].*

Physarum machines can well act in an open air, proceed to long distances on a non-friendly substrates and yet perform tasks satisfactory. Thus, slime mould path finding on three-dimensional nylon terrains of Germany, Russia, UK and USA is discussed in [18]. Two snapshots of Physarum propagation are shown in Fig. 13.

7 Wires, transportation and building

When inoculated on a substrate with scattered sources of nutrients Physarum propagates towards the sources

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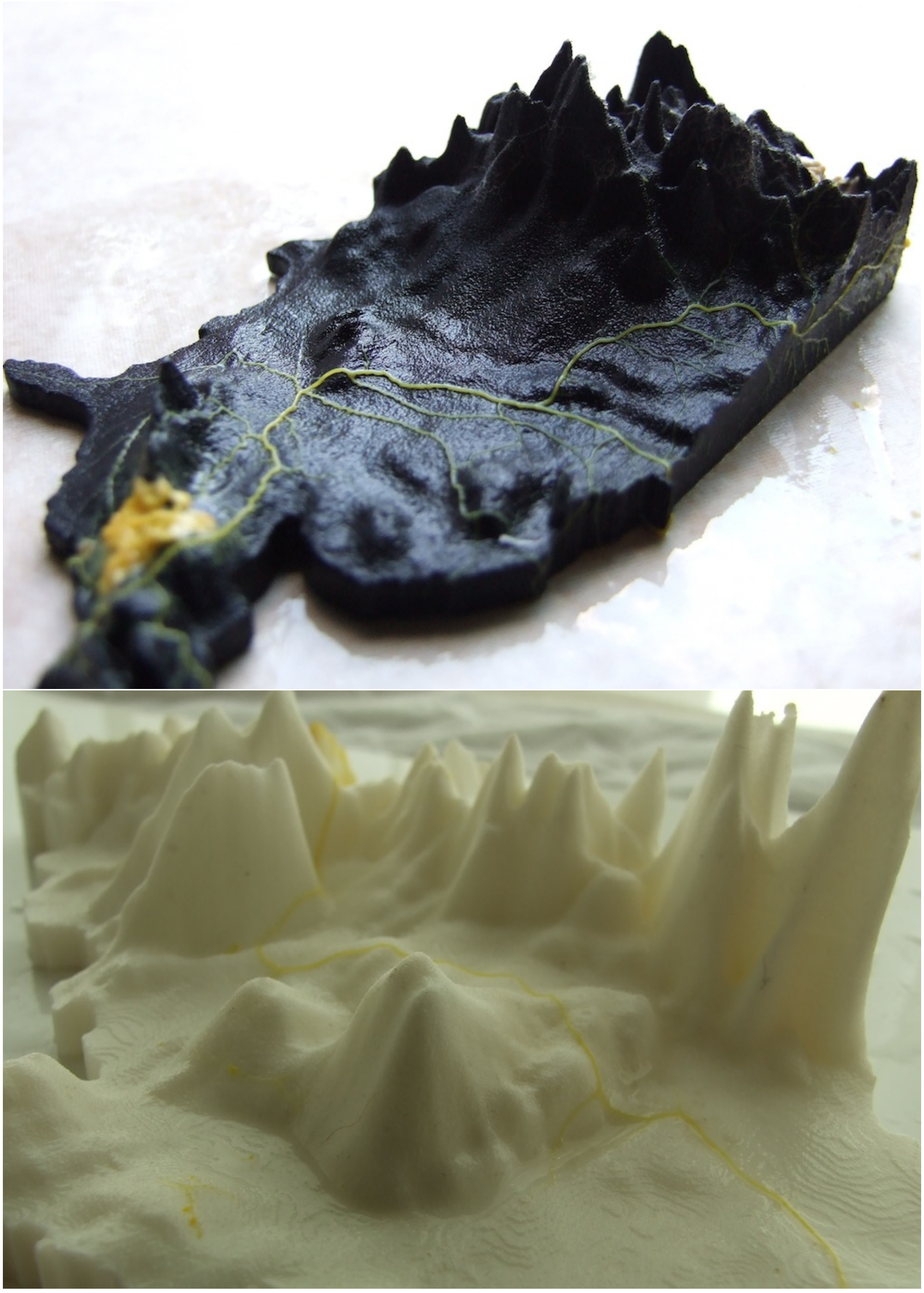

Figure 13. *Physarum machines navigate elevations on three-dimensional nylon models of continents. (a) Slime mould navigate around mountains in USA. (b) Slime mould passes through Central Siberian Plateau north of Enashimsky mountain, in the region of Tura city. See details in [18].*

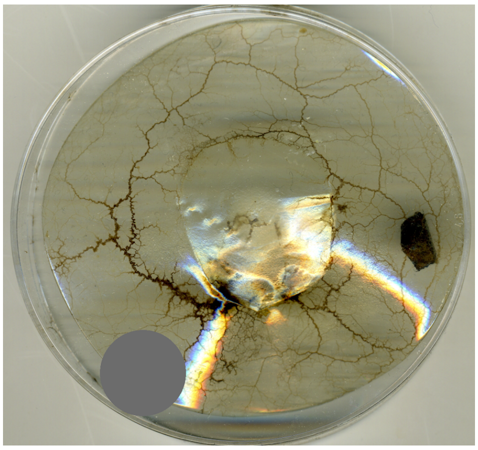

Figure 14. *Towards Physarum wires. Control of magnetic nanoparticles in protoplasmic network. Position of 25×20 mm N52 neodymium magnet is shown by grey disc. Segments of the tubes closest to the magnet exhibit black colour indicating a high concentration of the internalised magnetic material.*

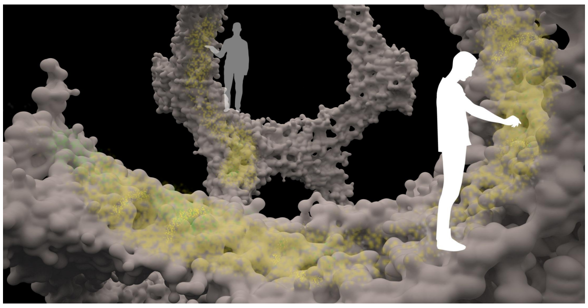

Figure 15. *Bio-inspired architectures designed by Team:Spores. Courtesy of Team:Spores [58].*

Figure 16. *Physarum derived wearable devices. Drawing by Theresa Schubert, Bauhaus-Universität Weimar, Germany [55].*

and spans them with a network of protoplasmic tubes. Structure of the network may vary between experiments however statistically most common planar graphs approximated are proximity graphs: relative neighbourhood graph, Gabriel graph and β-skeletons [13]. A topological structure of protoplasmic network is always in a flux but a general tendency is that typically an acyclic proximity graph — a spanning tree is built at first. The spanning tree is then transformed into a relative neighbourhood graph or a Gabriel graph. Further development of the protoplasmic network leads to formation of a Delaunay triangulation.

When configuration of nutrients matches a configuration of major urban areas of a country, the plasmodium of *P. polycephalum* approximates a human-made transport network, motorways and highways of the country. In [17] we developed a simple and user-friendly technique for evaluating man-made transport systems using slime mould *P. polycephalum*. The experimental laboratory methods are cost efficient and require little if any specialised equipment. We found that the slime mould *P. polycephalum* approximates best of all motorways in Belgium, Canada and China. The countries studied can be arranged in the following descending order of biorationality: Belgium, Canada, China, Italy, Malaysia, The Netherlands, Brazil, Germany, Mexico, UK, Africa and USA [17].

In [17] we undertook a comparative analysis of the motorway and protoplasmic networks. We found that in terms of absolute matching between slime mould 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. We compared the Physarum and the motorway graphs using such measures as average and longest shortest paths, average degrees, number of independent cycles, the Harary index, the Π-index and the Randić index. We found that in terms of these measures motorway networks in Belgium, Canada and China are most affine to protoplasmic networks of slime mould

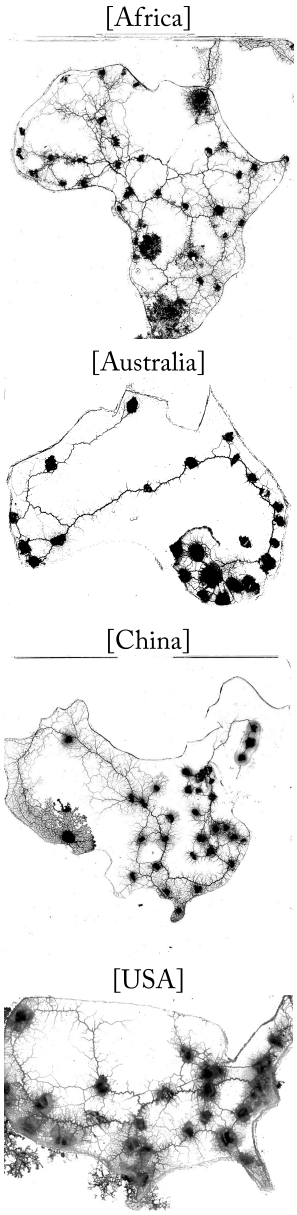

Figure 17. *Exemplar configurations of protoplasmic networks developed by slime mould* P. polycephalum *on major urban areas* **U** *obtained in experimental laboratory studies [17].*

P. polycephalum. With regards to measures and topological indices we demonstrated that the Randić index could be considered as most bio-compatible measure of transport networks, because it matches incredibly well the slime mould and man-made transport networks, yet efficiently discriminates between transport networks of

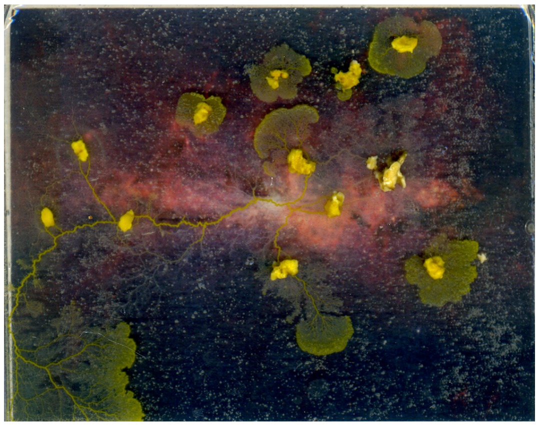

Figure 18. *Physarum spanning oat flakes imitating stars clusters on the infrared image of the Centre of the Milky Way Galaxy. See source at [40].*

different regions.

The biological mechanisms [17], underlying the optimal network formation in Physarum machines could be employed in design of large scale transportation and communication networks, when e.g. major clusters, stars and matter formations are represented by sources of chemo-attractants and nutrients (Figs. 2 and 18). The Physarum built transportation networks will assist path planning tasks [29, 66, 34, 19] for space ships and space stations, intra-planetary transportation [36]. The dynamical graphs developed by the slime mould may form a basis for future and emergent routing protocols and topology control of communication networks [37, 57] and optimisation of wireless networks [67].

These behavioural trait of Physarum can be used to

- execute bio-inspired routing of conductive pathways in Physarum-built electronic circuits, e.g. by loading the slime mould with conductive nanobeads (Fig. 14), see also [38]
- growing of a large-scale dwellings which architecture can be tuned depending on environmental conditions (Fig. 15), structures build by another single cell organism *Syringammina fragilissima* [61] prove feasibility of the approach, and
- growth of wearable bio-hybrid networks of distributed sensorial, computing and actuating elements (Fig. 16), first attempts of growing functional networks for transportation of substances were successful [13].

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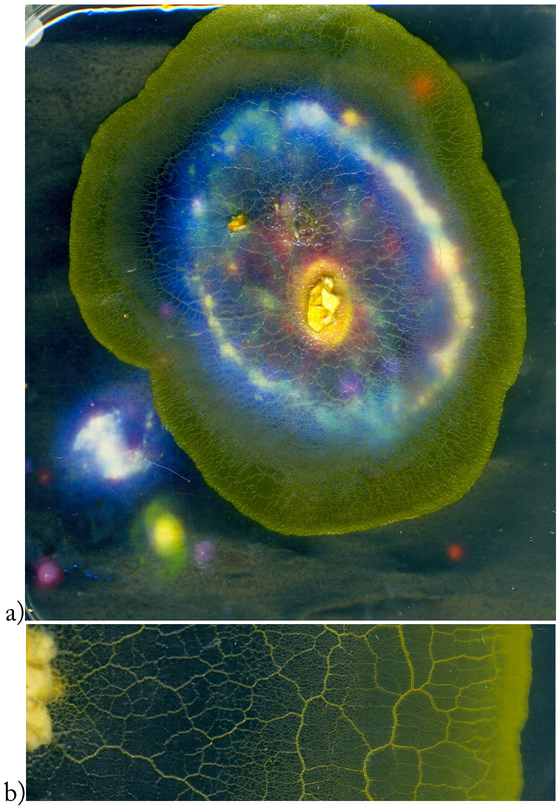

FIGURE 19. *Image of Physarum growing on a nutrient agar superimposed on an false colour composite image of Cartwheel galaxy. PIA03296: A Stellar Ripple. NASA/JPL-Caltech [23]. (a) Image of the whole Physarum expanding pattern. (b) Zoomed segment of Physarum showing changing topology of protoplasmic tubes: inoculation site is on the left and wave front is on the right.*

8 Physarum networks and Cosmic Web

On a nutrient substrate Physarum expands as an omnidirectional wave, e.g. as a classical excitation wave in a two-dimensional excitable medium (Fig. 19a). It shows a pronounced wave front, comprised of a very dense network of protoplasmic tubes. There are several orders of tubes which are seasily differentiable by their width (Fig. 19b). Density of the protoplasmic network decreases towards inoculation site, the epicentre of the wave pattern. Morphological transitions of the slime mould's network s during expansion, colonisation and development bear remarkable resemblance to the Cosmic Web [65, 8, 24]. Weblike spatial arrangement of galaxies and masses into elongated filaments of Cosmic Web [65] are represented by wave-fragment like active growing zones and colonies of Physarum. Morphologies of sheetlike walls and dense compact clusters [65] are typical for the slime mould growing on a nutrient agar. Large near-empty void regions [65] are formed in the protoplasmic networks due to release of metabolites into a substrate surrounding protoplasmic sheets and competition between the protoplasmic tubes. A hierarchical nature of mass distribution in Cosmic Web [65] is represented by hierarchies of protoplasmic tubes and their degrees of branching.

9 Conclusion

Slime mould of *P. polycephalum* is a unique living substrate which implements distributed sensing, massive-parallel information processing, decentralised decision making and concurrent actuation and manipulation. Physarum machines are experimental prototypes of unconventional computing devices implemented in the slime mould of *P. polycephalum*. We briefly introduced Physarum machines and exemplified their functionality on Boolean logic and path finding tasks. We speculated that in future space missions Physarum machines could be used as onboard amorphous computers for route planning and network communication, as well as smart living materials for growing electrical computing circuits, developing dwellings and inhabitable enclosures, and fabrication of wearable sensing, computing and actuating devices. Moreover, the slime mould *per se* can be an ideal analog modelling substrate to study a development of galaxies and evolution of cosmic matter.

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