# Fungal Grey Matter

Andrew Adamatzky[1] and Irina Petrova[2]

*Fungi are creatures with remarkably pronounced protocognition abilities. They control 'thinking' of trees. They open minds of humans. They help us to live in the world and to see the invisible. Recently we discovered that the electrical activity of fungi is similar to neurons. Fungi communicate with trains of spikes of electrical potential. Fungi respond to stimulation by changing their electrical properties and patterns of their electrical activity. Here, we briefly overview our discoveries on sensing and computing with fungi.*

**Fig. 1. Irina Petrova, *Deep Down the Rabbit Hole*. Installation with *Macrolepiota procera* fungi, 2020.**

Fungi are the first creatures which arrived on our planet. They are creatures of magic. They populate a thin layer of soil, just under the surface and implement chemical, and possibly electrical communication between trees and plants. There is a chance that when sending a message from one tree to another fungi do actually alter the meaning of the messages thus controlling 'thinking' of trees and ultimately governing a Mind of the Forest. To some degree fungi also shaped a Mind of Noosphere. From the beginning of civilisations fungi have been an essential component of the spiritual ceremonies, rituals, community building events, healing, mind opening inspirational trips and mental healings. No one will ever forget their first trip with Psilocybin mushrooms and will always be grateful to shrooms for showing unseeable. Here we discuss how electro-physiological properties of fungi can be used in sensing and information, in unconventional computing.

A vibrant field of unconventional computing aims to employ space-time dynamics of physical, chemical and biological media to design novel computational techniques, architectures and working prototypes of embedded computing substrates and devices. Interaction-based computing devices is one of the most diverse and promising families of the unconventional computing structures.[3] They are based on interactions of fluid streams, signals propagating along conductors or excitation wave-fronts. Typically, logical gates and their cascade implemented in an excitable medium are 'hand-crafted' to address exact timing and type of interactions between colliding wave-fronts. The artificial design of logical circuits might be suitable when chemical media or functional materials are used. However, the approach might be not feasible when embedding computation in living systems, where the architecture of conductive pathways may be difficult to alter or control. During the last decade we produced nearly forty prototypes of sensing and computing devices from the slime mould *Physarum polycephalum*, including shortest path finders, computational geometry processors, hybrid electronic devices.[4] We found that the slime mould is a convenient substrate for unconventional computing however geometry of the slime mould's protoplasmic networks is continuously changing, thus preventing fabrication of long-living devices, and the slime mould computing devices are confined to experimental laboratory setups. Fungi *Basidiomycetes* are now taxonomically distinct from the slime mould, however their development and behaviour are phenomenologically similar: mycelium networks are analogous to the slime mould's protoplasmic networks, and the fruit bodies are analogous to the slime mould's stalks of sporangia. *Basidiomycetes* are less susceptible to infections, when cultured indoors, especially commercially available species, they are larger in size and more convenient to manipulate than slime mould, and they could be easily found and experimented with outdoors. This makes the fungi an ideal object for developing future living computing devices. Availability and scalability of fungi is yet another advantage. The fungi is a largest, widely distributed and the oldest group of living organisms. Smallest fungi are microscopic single cells. The largest fungi, *Armillaria bulbosa*, occupies 15 hectares and weighs 10 tons, and the largest fruit body belongs to *Fomitiporia ellipsoidea* which at 20 years old is 11 m long, 80 cm wide, 5 cm thick and has estimated weight of nearly half-a-ton.

**Fig. 2. Fungi *P. ostreatus* explores space while geometrically constrained.**

## Spiking fungi

Not only neurons spike. Action potential-like spikes of electrical potential have been discovered using intracellular recording of mycelium of *Neurospora crassa*[5] and further confirmed in intra-cellular recordings of action potential in hypha of *Pleurotus ostreatus* and *Armillaria bulbosa*[6] and in extracellular recordings of fruit bodies and of substrates colonized by mycelium of *Pleurotus ostreatus*.[7] While the exact nature of the travelling spikes remains uncertain we can speculate, by drawing analogies with oscillations of electrical potential of slime mould,[8] that the spikes in fungi are triggered by calcium waves, reversing of cytoplasmic flow, translocation of nutrients and metabolites. Studies of electrical activity of higher plants can bring us even more clues.[9] Thus, the plants use the electrical spikes for a long-distance communication aimed to coordinate an activity of their bodies. The spikes of electrical potential in plants relate to a motor activity, responses to changes in temperature, osmotic environment and mechanical stimulation. In experiments with *Pleurotus ostreatus*[10] we demonstrated that fruit bodies of oyster fungi exhibit trains of action-like spike of extracellularly recorded electrical potential. We observed two types of spikes: high-frequency spikes, duration nearly 3~min, and low-frequency spikes, duration nearly 14~min. The spikes are observed in trains of 10-30 spikes. The depolarisation and repolarisation rates of both types of spikes are the same. Refractory period of a high-frequency spike is one sixth of the spike's period, and of a low-frequency spike one third of the spike's period. We showed that fruit bodies respond with spikes of electrical potential in response to physical, chemical and thermal stimulation; not only a simulated body responds with a spike but other fruit bodies of the cluster respond as well. We believe the spikes of electrical potential travelling in mycelium networks play the same roles of information carriers as action potential travelling along neural pathways in *e.g.* human brains. Thus it would be advantageous to discover what types of information processing devices we could make from fungi. To make information processing devices from fungi we can either use fungi as electronic components of analog computers or employ internal dynamics of excitation in fungi directly. Both options are illustrated below.

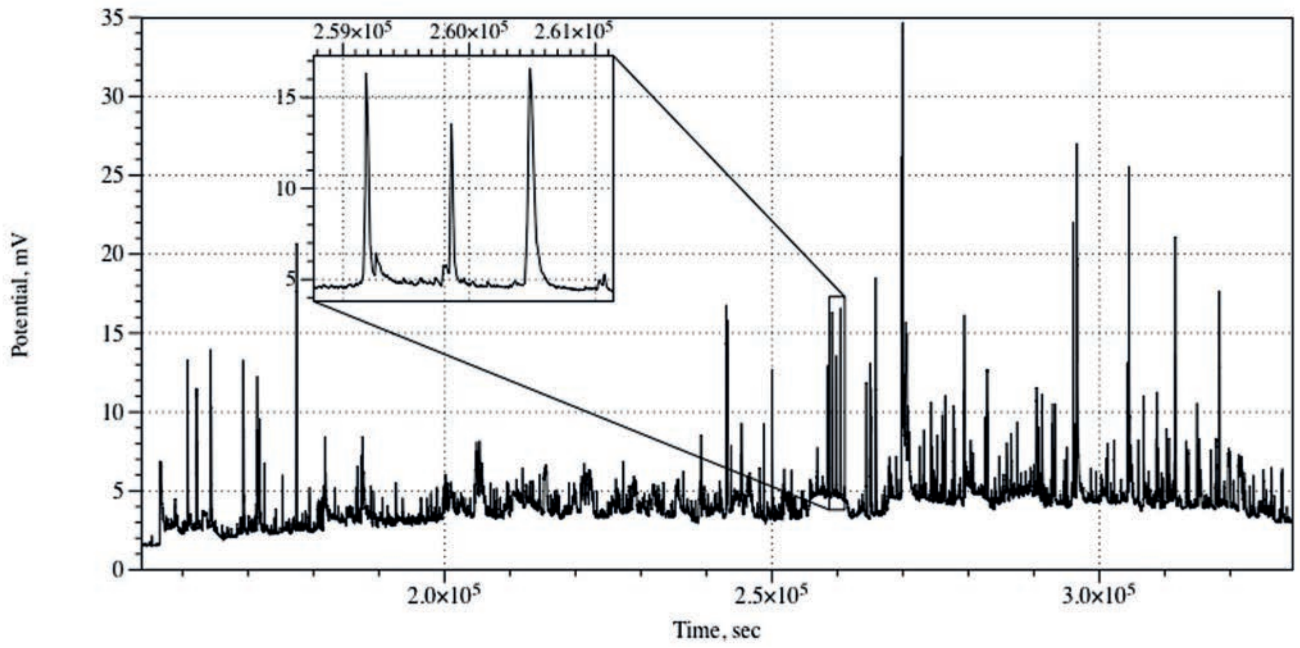

**Fig. 3. Example of electrical spiking activity recorded from a hemp substrate colonised by mycelium of *P. ostreatus*.**

## Fungal electronics

Fungi are memristors. The memristor is a device whose resistance changes depending on the polarity and magnitude of a voltage applied to the device's terminals. A memristor is a material logical implication. Therefore any logical circuits can be made purely from the memristors. We have examined the conducted current for a given voltage applied as a function of the previous voltage to fungi fruiting bodies and substrates colonised by fungi, and showed that the fungi exhibit remarkable memristive properties.[11] Indeed, demonstrating that a fruit body or a substrate colonised by fungi exhibit memristive properties is a just tiny step forward: cascading fungal memristors into function circuits will be the challenging task.

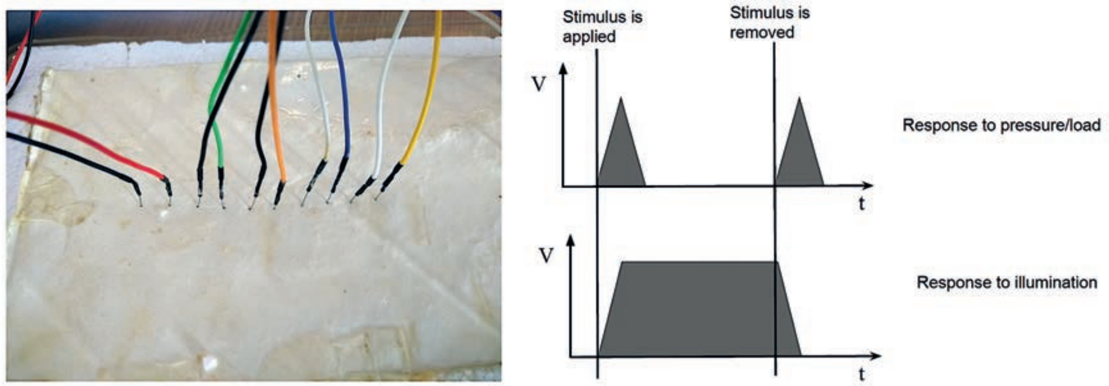

**Fig. 4. Responsive fungal skin.**
**Left, pairs of differential electodes inserted in the fungal skin of *G. resinaceum*.**
**Right, response of the fungal skin to pressure and illumination.**

Despite being logically universal, memristors might not be enough to build fully functional computing circuits. We might need to store energy, implement digital memory, do signal coupling and decoupling, make high-pass and low-pass filters, suppress noise. All these can be done with capacitors. Fungi are capacitors, albeit rapidly discharging. In laboratory experiments we showed that the capacitance of mycelium is in the order of hundreds of pico-Farads and the charge density of the mycelium decays rapidly with increasing distance from the source probes.[12] Nevertheless, the mycelium can be used as part of a capacitors array. A fungal electronic circuit could have chemical, mechanical or optical inputs.

A range of fungal responses to stimulation have been discovered in our experiments[13] with fungal skin[14] – a thin flexible sheet of a living homogeneous mycelium made by a filamentous fungus. We demonstrated that a thin sheet of homogeneous living mycelium of *Ganoderma resinaceum* shows pronounced electrical responses to mechanical and optical stimulation. It is possible to differentiate between the fungal skin's response to mechanical and optical stimulation. The fungal skin responds to mechanical stimulation with a 15 min spike of electrical potential, which diminishes even if the applied pressure on the skin remains. The skin responds to optical stimulation by raising its electrical potential and keeping it raised till the light is switched off. We can even differentiate the responses to loading and removal of the weight. Whilst amplitudes of 'loading' and 'removal' spikes are the same (0.4 mV in average) the fungal skin average reaction time to removal of the weight is 2.4 times shorter than the reaction to loading of the weight (385 sec versus 911 sec). Also 'loading' spikes are 1.6 times wider than 'removal' spikes (1261 sec versus 774 sec).

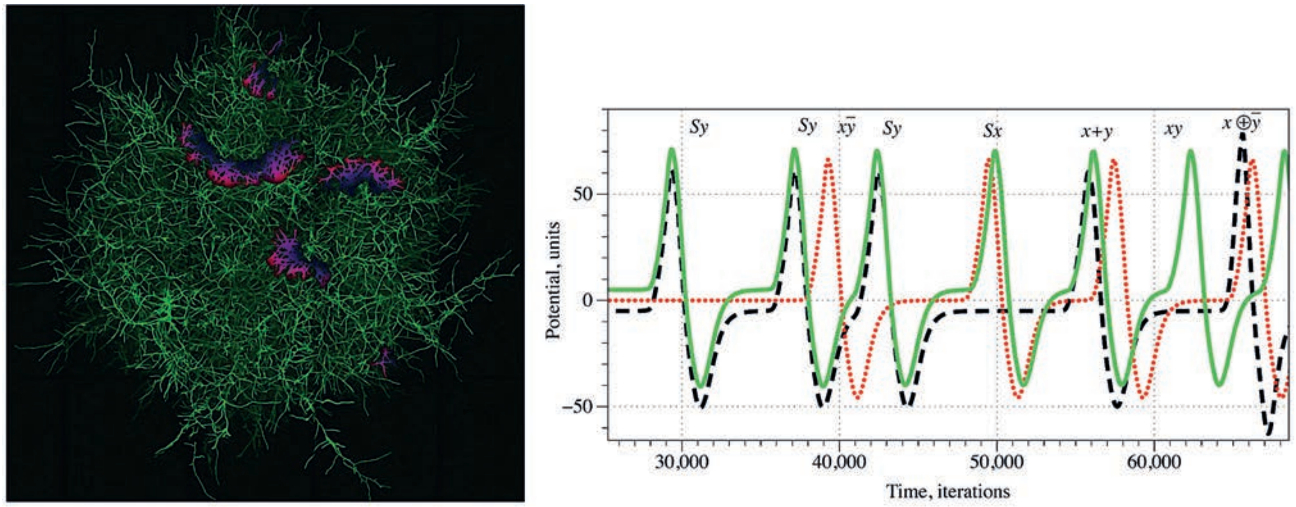

**Fig. 5. Computing with travelling spikes in mycelium networks. Left, a snapshot of an excitation waves propagating in the network. Right, encoding of the spiking response to Boolean gates.**

## Fungal computing

Mycelium networks are disorganized and difficult to program at a fine-grained level. Thus direct design of computing circuits might be impossible. In such situations an opportunistic approach to outsourcing computation can be adopted. The system is perturbed via two or more input loci and its dynamics if recorded at one or more output loci. A spike appearing at one of the output loci is interpreted as logical Truth or '1' and absence of the spike as logical False or '0'. Thus a system with relatively unknown structure implements a mapping $\{0, 1\}^n \to \{0, 1\}^m$, where $n$ is a number of input loci and $m$ is a number of output loci, $n$, $m>0$. Using numerical modelling of excitation wavefronts propagating on images of real colony of *Aspergillus niger* we have demonstrated how sets of logical gates can be implemented in single colony mycelium networks via initiation of electrical impulses.[15] The impulses travel in the network, interact with each other (annihilate, reflect, change their phase). Thus for different combinations of input impulses and record different combinations of output impulses, which in some cases can be interpreted as representing two-inputs-one-output functions. To estimate a speed of computation we refer to Olsson and Hansson's original study,[16] in which they proposed that electrical activity in fungi could be used for communication with message propagation speed 0.5 mm/sec. Diameter of the colony, which experimental laboratory images have been used to run the model, is *c.* 1.7 mm. Thus, it takes the excitation waves initiated at a boundary of the colony up to 3-4 sec to span the whole mycelium network (this time is equivalent to *c.* 70K iterations of the numerical integration model). In 3-4 sec the mycelium network can compute up to a hundred logical gates. This gives us the rate of a gate per 0.03 sec, or, in terms of frequency, this will be *c.* 30 Hz.

## Programmability

To program fungal computers we must control the geometry of mycelium network. The geometry of mycelium network can be modified by varying nutritional conditions and temperature, especially a degree of branching is proportional to concentration of nutrients, and a wide range of chemical and physical stimuli. Also, we can geometrically constrain it. A feasibility of shaping similar networks has been demonstrated by us previously: high amplitude high frequency voltage applied between two electrodes in a network of protoplasmic tubes of slime mould *P. polycephalum* leads to abandonment of the stimulated protoplasmic without affecting the non stimulated tubes, and low amplitude low frequency voltage applied between two electrodes in the network enhance the stimulated tube and encourages abandonment of other tubes.

## Application domain: distributed networks of ecological sensors

Likely application domains of the fungal devices could be large-scale networks of mycelium which collect and analyse information about the environment of soil and, possibly, air, and execute some decision making procedures. Fungi sense light, chemicals, gases, gravity and electric fields. Fungi show a pronounced response to changes in a substrate pH, demonstrate mechanosensing; they sense toxic metals, $CO_2$ and direction of fluid flow. Fungi exhibit thigmotactic and thigmomorphogenetic responses, which might be reflected in dynamic patterns of their electrical activity. Fungi are also capable of sensing chemical cues, especially stress hormones, from other species, thus they might be used as reporters of health and well-being of other inhabitants of the forest. Thus, fungal computers can be made an essential part of distributed large-scale environmental sensor networks in ecological research to assess not just soil quality but an over health of the ecosystems. Interaction of voltage spikes, travelling along mycelium strands, at the junctions between strands is a key mechanism of the fungal computation. We can see each junction as an elementary processor of a distributed multiprocessor computing network. We assume a number of junctions is proportional to a number of hyphal tips. There are estimated 10-20 tips per 1.5-3 $mm^3$ of a substrate. Without knowing the depth of the mycelial network we go for a safest lower margin of 2D estimation: 50 tips/$mm^2$. Considering that the largest known fungus *Armillaria bulbosa* populates over 15 hectares we could assume that there could be $75 \cdot 10^{17}$ branching points, that is nearly a trillion of elementary processing units. With regards to a speed of computation by fungal computers, electrical activity in fungi could be used for communication with message propagation speed 0.5 mm/sec (this is several orders slower than speed of a typical action potential

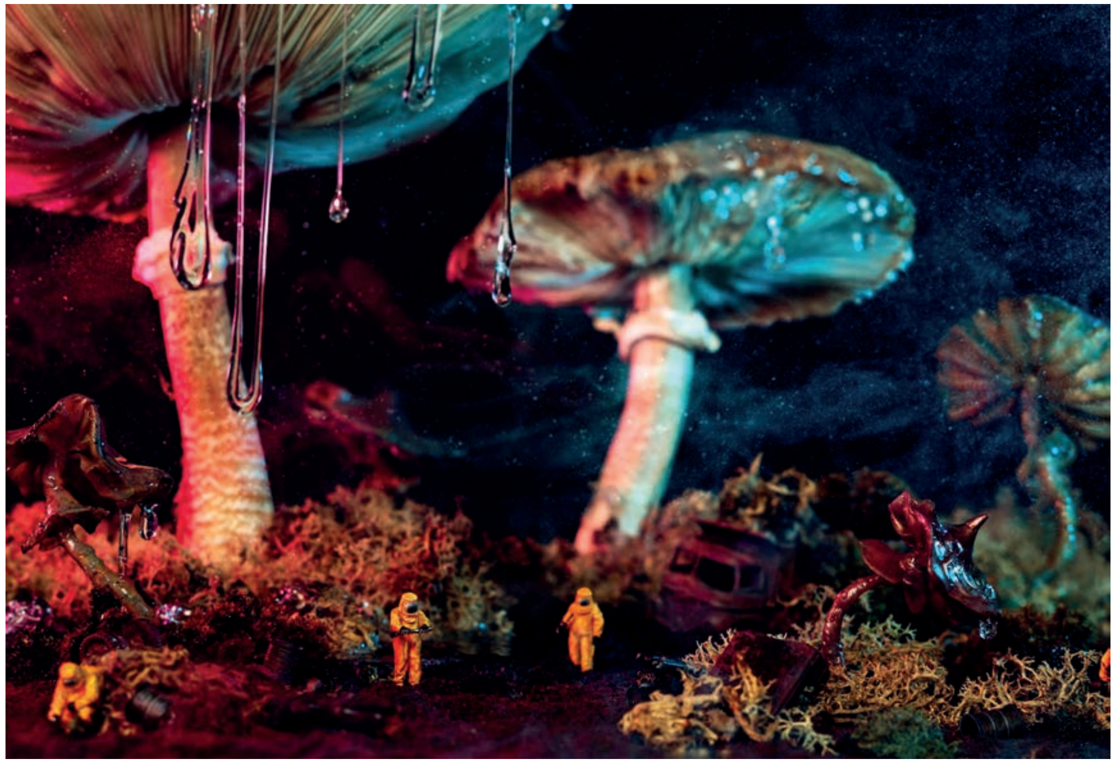

**Fig. 6. Irina Perova, *The X-Files. Ecological Disaster in an Industrial Wonderland.* Installation with *Macrolepiota procera* fungi, 2020.**

in plants: from 0.005 m/sec to 0.2 m/sec). Thus it would take about half-an-hour for a signal in the fungal computer to propagate one meter. The low speed of signal propagation is not a critical disadvantage of potential fungal computers, because they never meant to compete with conventional silicon devices. The mycelium network computing can not compete with existing silicon architecture however its application domain can be a unique of living biosensors (a distribution of gates realised might be affected by environmental conditions) and computation embedded into structural elements where fungal materials are used[18] and fungal wearables.[19]

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# Le vignoble cosmique

Alessandro Chiolerio[1]

**Gianni Verna, « Digradano su noi pendici / di basse vigne », gravure sur bois, 1360x480 mm, 1991.**

*Tout est si ouvert, même à la pluie poussée par le vent et aux rayons clairs du soleil, tout est aussi silencieux que le regard du spectateur, seul un spectateur patient pourrait voir un outil poussiéreux, un reste de guerre très bruyant, ou un tracteur moderne brillant, une créature technologique parcourir les rangs.*
*Pourtant, cette même technologie pourrait nous aider à voir une colline d'une manière différente, le vignoble reposant harmonieusement dessus, la plantation ordonnée des vignes, leur production de sucre obstinée, enfin savamment transformée en or rouge liquide. Le vignoble étant constamment soumis aux champs électromagnétiques naturels, aux signaux radio que les étoiles nous envoient. Ce chuchotement électrique polarise nos vignes, se disperse dans une symphonie d'impulsions, détermine leur métabolisme, peut-être leur humeur. Et qu'affinons-nous sinon leur humeur, à l'aide d'enzymes et de bactéries, pour en faire du vin ? Le vin est le résultat de ce calcul de proportions cosmiques et holistiques, qui finit par nous envahir et nous enivrer d'étincelles d'étoiles.*

## La complexité d'une vigne

La vigne se développe au fil des saisons, par la fatigue et le travail du paysan. Mais on cache beaucoup de secrets invisibles. La vigne a une histoire fascinante, qui accompagne l'histoire de l'homme et de ses migrations depuis des millénaires. Des découvertes récentes montrent que la production de vin est documentée à partir du VIe millénaire avant J.-C. dans des endroits très éloignés les uns des autres, comme le Caucase[2], la Sicile[3] et la Sardaigne[4] (Fig. 1). La production de vin était si importante que lorsque l'épidémie de phylloxéra a détruit la plupart des vignobles européens, on a appris à créer des chimères avec les vignes américaines les plus résistantes. Et une partie de cette histoire reste à écrire, car de nouveaux hybrides résistants aux maladies sont en cours de développement pour assurer un avenir durable à nos vignerons[5].

Un vignoble est un système extrêmement complexe dans lequel les principales espèces