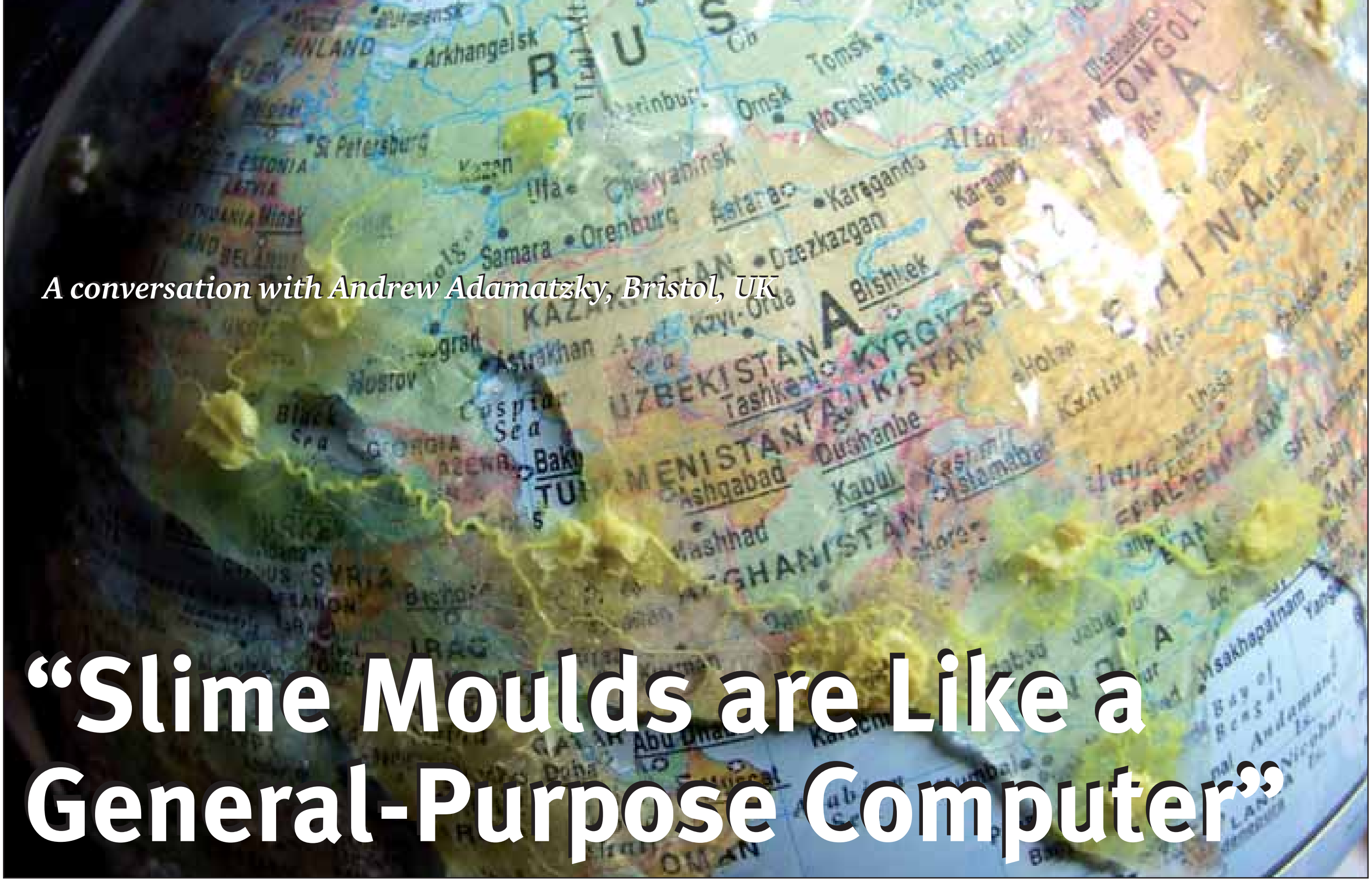

Photos (4): A. Adamatzky

A conversation with Andrew Adamatzky, Bristol, UK

"Slime Moulds are Like a General-Purpose Computer"

Revolutionary new computers incorporating living components may seem like the realm of science fiction but what are the realities of research into living computers? Andrew Adamatzky talks about his unconventional computing with the acellular slime mould, *Physarum polycephalum.*

Lab Times: What is unconventional computing?

Andrew Adamatzky: Unconventional, or nature-inspired, computing aims to uncover novel principles of efficient information processing and computation in physical, chemical and biological systems, and to develop novel non-standard algorithms and computing architectures.

However, despite the profound potential offered by unconventional computing, only a handful of experimental prototypes are reported so far, e.g. gas discharge analogue path finders, maze-solving micro-fluidic circuits, and enzyme-based logical circuits. Unconventional computing is chock full of theoretical stuff, like quantum computation and dynamical systems computing but there are a just a handful of experimental laboratory prototypes. They are outstanding but difficult for non-experts to play with.

Why do you think there are relatively few hands-on experimenters in unconventional computing?

Adamatzky: It might be explained by technical difficulties and costs of prototyping novel computing substrates but there are also psychological barriers. Chemists and biologists do not usually aspire to experiment with unconventional computers because such activity diverts them from mainstream research in their own fields. Meanwhile, computer scientists and mathematicians would like to experiment but they are scared of laboratory equipment.

But slime mould could provide a practical solution?

Adamatzky: If there was a simple-to-maintain substrate that requires minimal equipment to experiment with, whose behaviour is understandable by, and appealing to, researchers from all fields of science, then progress in designing novel computing devices would be much more visible. We propose that the slime mould, *Physarum polycephalum*, could play a role as such a 'universal' computing substrate. With it, you could make a universal biological computer at home nearly for free. All you need is a slime mould, oat flakes and a camera. The rest is up to your creativity.

"Unconventional computing is chock full of theoretical stuff. It's difficult for non-experts to play with."

In a sense, your own research has 'evolved' towards the slime mould. Initially, in the 1990s, you worked on chemical reaction-diffusion computers. Then you began to use slime mould as a biological solution to the problems posed by chemical systems. What are reaction-diffusion computers?

Adamatzky: A reaction-diffusion computer is a spatially extended chemical system, which processes information using interacting growing patterns, excitation and diffusive waves. In reaction-diffusion processors, both the data and the results of the computation are encoded as concentration profiles of the reagents. Data is presented by an initial concentration profile. The information is transferred by spreading wave patterns, and the computation is implemented in the collisions of wave-fronts. The final concentration profile represents the results of the computation.

The plasmodium of* P. polycephalum *is a single monstrously large cell with many diploid nuclei, which behaves like an amoeba.

How does this compare to conventional computers?

Adamatzky: In terms of classical computing architectures, reaction-diffusion computers display massive parallelism because there are thousands of elementary processing units, micro-volumes, in a standard chemical vessel. There are also local connections since micro-volumes of a non-stirred chemical medium change their states, due to diffusion and reaction, relative to their closest neighbours. And there is parallel input and output. For example, in light-sensitive chemical reactions, data can be entered by localised illumination (input). And, for reactions with coloured products, the results (output) of the computation can be recorded optically.

These characteristics of reaction-diffusion chemical computers make them ideally tailored for the implementation of novel and emerging architectures of robotic controllers and embedded processors for smart structures. Reaction-diffusion computers can solve a great variety of tasks, from plane tessellation and shape skeletonisation to logical gates and robot control.

"With Physarum, you could make a universal biological computer at home nearly for free. All you need is oat flakes, a camera and some creativity."

But are there limitations to chemical reaction-diffusion?

Adamatzky: There still remains a range of problems where chemical reaction-diffusion processors could not cope without external support from conventional silicon-based computing devices. Shortest path and spanning tree problems are typical tasks failed by reaction-diffusion computers. Experimental setups which claim to directly compute a shortest path in chemical media, are employing external computing resources to store time-lapsed snapshots of propagating wave-fronts and to analyse the dynamics of the wave-front propagation. Such usage of external resources dramatically reduces the fundamental values of the computing with propagating patterns.

Essentially, to compute a spanning tree over a given planar set, a system must first explore the date space, then cover the data points, physically representing edges of the tree with the system's structure. This is not possible in excitable chemical systems because they are essentially memoryless and no stationary structure can be formed.

Unless you constrain the chemicals in a membrane?

Adamatzky: To overcome these difficulties, reaction-diffusion computers need to be geometrically self-constrained, while still capable of operating in geometrically unconstrained (architectureless or 'free') space. Encapsulating reaction-diffusion processes in membranes represents a possible solution. So, we went in search of an easy-to-experiment-with analogue of an encapsulated reaction-diffusion system and picked the plasmodium of *P. polycephalum* as a suitable example of an excitable chemical medium encapsulated in a growing elastic membrane.

In effect, your search for a means of constraining and better controlling a chemical computer led you to a living organism?

Adamatzky: The ultimate goal of our studies in unconventional computer architectures is to build working real-world prototypes of non-classical computers working on chemical or biological substrates. To make a shortcut towards the goal, I did not design a computer model of an excitable reaction–diffusion system enclosed in membrane, but instead found quite a close biological analogue of such a system – the plasmodium of slime mould.

Is the plasmodium of Physarum *a good analogue of an excitable reaction-diffusion system enclosed in a membrane?*

Adamatzky: *P. polycephalum* is an acellular slime mould. Its main vegetative phase is the plasmodium (the active streaming form of slime moulds). This is a single monstrously large cell with many diploid nuclei, which behaves like an amoeba. In effect, the plasmodium behaves as a non-linear medium, an excitable soft matter, encapsulated in an elastic and growing membrane.

"We want to build real-world prototypes of non-classical computers working on chemical or biological substrates."

The cell is visible to the naked eye and can grow for many centimetres when properly cared for. When it is placed in an environment with distributed nutrients, it develops a network of protoplasmic tubes spanning the nutrients' sources. The growing and feeding plasmodium exhibits characteristic rhythmic contractions with articulated sources. The contraction waves are associated with waves of potential change and the waves observed in plasmodium are similar to the waves found in excitable chemical systems.

The slime mould is like a reaction-diffusion (and excitable) system encapsulated in an elastic growing membrane. Thus, we can use all the advantages of reaction-diffusion, wave-based computers and also handle the computing substrate (slime mould) with ease.

Numerous videos of your experiments with Physarum are available on the Internet. Does the plasmodium explore its environment by extending protoplasmic processes?

Adamatzky: When the plasmodium is placed on a substrate populated with sources of nutrients, it starts to explore the surrounding space. Numerous pseudopodia

Andrew Adamatzky

...is Professor of Computer Science at the University of the West of England, Bristol. He is Director of the Unconventional Computing Centre and a member of Bristol Robotics Lab. He employs the complex dynamics of physical, chemical, and biological media to design novel computational techniques and architectures for non-linear media based computers. During the last decade, Adamatzky has performed extensive research on the acellular slime mould, *Physarum polycephalum*, demonstrating how *Physarum*'s natural information processing and analysis can be used to solve complex computational tasks and logical calculations (*Nat Comput,* 8:431–47 and his book, "*Physarum* Machines: Making Computers from Slime Mould"). Working prototypes of parallel computing devices based on *Physarum* that exploit the complex dynamics of non-linear media have already been designed.

emerge, frequently branch and proceed. These detect, by chemotaxis, the relative locations of the closest sources of nutrients. When another source of nutrients, element of the given planar set, is reached, the relevant part of the plasmodium reshapes and shrinks to a protoplasmic tube. This tube connects the initial and newly-acquired sites and it represents an edge of the computed spanning tree. The plasmodium optimises the network to efficiently transport protoplasm with nutrients.

Is it true that some of the first uses of Physarum *in solving mazes were reported by Japanese researchers?*

Adamatzky: Nakagaki, Aono, Tsuda and others have been exploring the power of *Physarum* computing since 2000 (e.g. Nakagaki et al. *Nature,* 407:470). They proved experimentally that the plasmodium is a unique, fruitful object to design various schemes of non-classical computation. In its foraging behaviour, the plasmodium approximates shortest path calculations and can compute planar proximity graphs and plane tessellations. It exhibits primitive memory, realises basic logical computing and can control robot navigation. The plasmodium can be considered as a general-purpose computer because it simulates the Kolmogorov-Uspenskii machine, a storage modification machine operating on a labelled set of graph nodes.

Scan the QR code to watch a video of slime mould traverse hilly Germany.

You've drawn a lot of media attention with your use of slime moulds to model road and transport systems (summarised in Adamatzky et al. *(2012) 'Are motorways rational from slime mould's point of view?' arXiv:1203.2851v1). Why did you decide to investigate human transport networks?*

Adamatzky: To uncover analogies between biological and human-made transport networks and to project behavioural traits of biological networks onto development of vehicular transport networks. Motorway networks are designed for efficient vehicular transportation of goods and passengers, protoplasmic networks are developed for efficient intracellular transportation of nutrients and metabolites. Is there a similarity between these two networks?

"We found that the network of protoplasmic tubes grown by plasmodium matches, at least partly, the network of human-made transport arteries."

We conducted a series of studies on slime mould's evaluation and approximation of motorway networks, e.g. in Australia, Belgium, Germany, Italy, the UK and USA.

We represented each region with an agar plate and imitated major urban areas with oat flakes. We inoculated plasmodium in a capital, then analysed the resulting structures of the developed protoplasmic networks. For all regions studied in laboratory experiments, we found that the network of protoplasmic tubes grown by plasmodium matches, at least partly, the network of human-made transport arteries.

Then you moved onto 3-D maps. Does slime mould imitate man-made transport networks on three-dimensional terrain as well as it does on a flat substrate?

Adamatzky: We simplified the problem to a single transport route. In laboratory experiments with 3D Nylon terrains of the USA and Germany, we imitated the development of route 20 (the longest road in the USA) and autobahn 7 (the longest national motorway in Europe). We found that slime mould builds longer transport routes on 3D terrains, compared to flat agar plates, yet sufficiently approximates the man-made transport routes.

"One day of slime mould's propagation roughly corresponds to 3-5 hours of real-life driving along the autobahn 7 in Germany."

Usually it takes slime mould 4-5 days to cover the distance between Newport and Boston and 2-3 days to propagate from Flensburg to Fussen (such differences in propagation time are possibly due to the steep elevations in the West of the USA, which prevent the slime mould from gaining speed and momentum when starting colonisation of the terrain). In experiments with Germany, one day of slime mould's propagation roughly corresponds to 3-5 hours of real-life driving along the autobahn 7, and in experiments with the USA to about 10 hours driving along route 20.

You noted that they may have had problems finding the shortest routes since they do not have the capacity to engineer bridges over gaps or to drill tunnels through mountains. Does this reflect a weakness in your experimental system? Do you think your system could be used to create new transport networks?

Adamatzky: It is not a weakness, just a feature :) No, it will never be used to create new transport networks, unless the world goes insane...

What are Physarum *machines?*

Adamatzky: A *Physarum* machine is a programmable amorphous biological computing device incorporating plasmodium of *P. polycephalum*. It is programmed by configurations of repelling and attracting gradients.

The distribution of chemo-attractants and position of the initial inoculation of plasmodium are input data for *Physarum* machines. The structure of the protoplasmic networks are the results of computation. Propagating active zones can be considered as elementary processors of *Physarum* machines and active zones can be manipulated by dynamical addition of attractants. But programming with chemo-attractants is not really efficient because once the source is placed in the computing space, it irreversibly changes the configuration of attracting fields.

Light inputs allow for an online reconfiguration of obstacles and thus provide increased opportunities for embedding complex programmes in *Physarum* machines because *P. polycephalum* exhibits photoavoidance. Thus, we expect the plasmodium to change its velocity after entering an illuminated domain. A propagating plasmodium wave or a pseudopodium can be split by a suitably-shaped domain of illumination. Thus, the active zone splits into two independent active zones and so on.

How might these Physarum *machines further develop?*

Adamatzky: Being encapsulated in an elastic membrane, the plasmodium can be capable of not only computing over spatially-distributed datasets but also physically manipulating elements of the datasets. If a sensible, controllable and, ideally, programmable movement of the plasmodium was achieved, we would get experimental implementations of amorphous robotic devices.

In 2009, we designed and tested, in real-world experiments, the first ever plasmodium robot. We showed that, when adhered to a light-weight object resting on a water surface, the plasmodium can propel the object by oscillating its protoplasmic pseudopodia (arXiv:0901.4466v1).

Do you think slime moulds have an applied, practical future in some kind of living bio-computer?

Adamatzky: Yes, they can be used as model examples of future self-growing electronic circuits. But, *Physarum* machines have one significant disadvantage. They are very slow. For example, it can take a few days for the slime mould to approximate a proximity graph or a Voronoi diagram in a standard Petri dish. The efficiency of *Physarum* machines can be improved by 'hybridising' the slime mould with conventional conductive materials.

Our future research focuses on the design and manufacture of a *Physarum* chip – a network of processing elements made of the slime mould's protoplasmic tubes coated with conductive substances. A living network of protoplasmic tubes acts as an active non-linear transducer of information, while templates of tubes coated with conductor act as fast information channels.

The *Physarum* chip will have parallel inputs (optical, chemo- and electro-based) and outputs (electrical and optical). It will be capable of solving a wide range of computation tasks, including optimisation on graphs, computational geometry, robot control, logic and arithmetical computing.

Physarum computers could be used as embedded controllers for non-silicon (e.g. gel-based) reconfigurable robots and manipulators. They are reasonably robust and can live on almost any non-aggressive substrate (including plastic, glass, and metal foil) in a wide range of temperatures. They do not require special substrates or sophisticated equipment for maintenance and are programmable computing devices.

Unique behaviour of a slime mould when encountering a half-pill of Kalms Tablets/Sleep, a natural stress reliever (arXiv:1106.0305v1).

"Physarum machines have one significant disadvantage. They are very slow."

Are there other examples of living computers?

Adamatzky: In principle, we can make a living computer from any living substrates, we just need to encode inputs and outputs and represent the substrate's behaviour in terms of computation.

Can human society also be considered a model for unconventional computing? For example, in the book 'Hitchhikers Guide to the Galaxy', the whole planet Earth and all its biosphere was presented as one gigantic computer.

Adamatzky: Yes, now everyone can tell you that "nature computes" but only few people do really make computers from living substrates.

INTERVIEW: JEREMY GARWOOD