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Slime mould imitates development of Roman roads in the Balkans

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ABSTRACT

Due to its unexpected computing abilities, *Physarum polycephalum*, a vegetative stage of acellular slime, has been repeatedly used during the last decade in order to reproduce transport networks. After conducting a series of biological experiments and with the help of a Cellular Automata (CA) model we try to explore the ability of the slime in order to imitate the Roman road network in the Balkans, an area which was of great strategic importance for the stability of the Roman Empire in the East. The application of *Physarum* machines hopes to offer a first step towards a new interdisciplinary, almost unconventional, approach to archaeology.

1. Introduction

In recent years network analysis (Graham, 2006) has been applied in archaeological research in order to detect or analyse patterns of relationship mostly between sites of archaeological interest (Isaksen, 2008). However in a way similar to the applications of computers in archaeology, a number of intriguing questions have surfaced mostly focusing on the methodological use of these techniques as sophisticated archaeological tools (Brughmans, 2010). As with other quantitative methods the basic limitation lies in the ability of mathematic models to describe and interpret networks made by humans, the decision strategy of which depends on a variety of factors, not necessarily countable or predictable (Knappet and Nikolakopoulou, 2005). Although there is a long ongoing theoretical discussion about the different ways that archaeology can harness the full potentials of these approaches, everybody seems to agree that a network analysis, which hopes to evolve into something more than an elaborate visualization technique, must depend on solid archaeological data. Simply put, it is archaeology that should set the questions and network analysis the one to provide a variety of answers deeply grounded in archaeological analysis. In this theoretical context and having in mind the considerations mentioned above we tried to experiment with the application of "*Physarum* machines", one of the most characteristic manifestations of unconventional computing, in archaeological research.

Physarum polycephalum, a vegetative stage of acellular slime mould, has repeatedly, during the last decade, demonstrated its unexpected computing abilities (Adamatzky, 2010) especially for reproducing road networks. *Plasmodium* is nothing else but a single cell with many nuclei, which feeds on microscopic particles (Stephenson and Stempen, 2000). When foraging for its food the plasmodium propagates towards sources of food, surrounds them, secretes enzymes and digests the food by forming a congregation of protoplasm which covers the food source. When several sources of nutrients are scattered in the plasmodium's range, the plasmodium forms a network of protoplasmic tubes connecting the masses of protoplasm with the food source. A structure of the protoplasmic networks is apparently optimal, in the sense that it covers all sources of nutrients and provides a robust and speedy transportation of nutrients and metabolites in the plasmodium's body (Nakagaki, 2001; Nakagaki et al., 2001, 2007). The *Plasmodium*'s foraging behaviour can have a computation aspect (Nakagaki et al., 2001, 2007): data are represented by spatial configurations of attractants and repellents and results are represented by the structure of protoplasmic network (Adamatzky, 2010). Hence *Plasmodium* can solve computational problems with natural parallelism (Adamatzky, 2007, 2010), e.g., related to shortest path (Nakagaki et al., 2001) and hierarchies of planar proximity graphs (Adamatzky, 2008), computation of plane tessellations (Shirakawa et al., 2009, 2011), execution of logical computing schemes (Tsuda et al., 2004; Adamatzky, 2012a), planar shapes and concave hulls (Adamatzky, 2012a), and natural implementation of spatial logic

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and process algebra (Schumann and Adamatzky, 2011). The slime mould's behaviour inspired a range of software implementations of novel approaches towards the design of communication and transport networks (Jones, 2011; Becker, 2011). The *Plasmodium* of *P. polycephalum* can effectively solve several "geographical" problems, such as the evaluation (approximation) of human-made transport networks in several countries. In order to reveal analogies between biological and human-made transport networks and to examine how behavioural traits of biological networks apply onto the development of vehicular transport networks, we conducted a series of experimental laboratory studies on the evaluation and approximation of motorway networks in 14 geographical regions: Africa, Australia, Belgium, Brazil, Canada, China, Germany, Iberia, Italy, Malaysia, Mexico, The Netherlands, U.K., and USA (Adamatzky and Jones, 2010; Adamatzky, 2012b. Adamatzky et al., 2011; Adamatzky and Prokopenko, 2012; Adamatzky and Alonso-Sanz, 2011). Each region was represented with an agar plate where oat flakes marked the major urban sites. The *Plasmodium* of *P. polycephalum* was inoculated in a central site (usually the capital) and the structures of protoplasmic networks were subsequently analysed. What became obvious for all the regions studied in the experiments (Adamatzky, 2012b) was that the networks of the *Plasmodium*'s protoplasmic tubes match/imitate – at least partly – the man-made transport networks. The shape of the country (represented by the agar plate) and the spatial distribution of the urban areas (represented by sources of nutrients) can naturally play a key role in determining the exact structure of the plasmodium network. One obvious deficiency of the experiments (Adamatzky, 2012b) was that the slime mould propagated only on flat substrates (agar plates).

In order to speed up the biological experiments we additionally used a Cellular Automaton (CA) based computational model of the *Plasmodium*'s development. Due to the practical limitations that a living organism (slime mould) presents we introduced a computation analogue of the organism in order to explore the possibilities of a spatially represented computation. Although relatively easy to use and inexpensive the slime mould – as a form of biological computer – is very slow (especially when it is compared to silicon computers). It must also be maintained within strict environmental parameters of temperature, light exposure and humidity. As a result, we tried to reproduce the complex patterning of the slime mould along with the complex interactions it has with its environment by employing computer modelling. Towards this direction we have chosen to use CAs (von Neumann, 1966) as a medium for the computer based implementation of *Physarum*. CAs can be described as the idealized models of physical systems in which space and time are discrete, and the physical quantities take only a finite set of values (Georgoudas et al., 2007). CAs are very effective in simulating physical systems and solving scientific problems (Sirakoulis and Bandini, 2012), because they can capture the essential features of systems where global behaviour arises from the collective effect of simple components which interact locally (Sirakoulis et al., 2005; Tsoutsouras et al., 2012). The presented CA model here mimics the behaviour of the *Plasmodium*. In analogy to the real experiments where the *Plasmodium* is expected to form an efficient network, the CA model propagates from a starting point (SP) towards all existing nutrient sources (NSs) – points of interest – using a foraging strategy similar to the one that the *Plasmodium* uses.

In the following pages we will present our attempt to explore the aforementioned ability of the slime mould in order to approximate the development of an ancient network: the roads that the Romans built in the Balkans during the imperial period (1st century BC–4th century AD), when the political conditions (existence of a single ideologically laden authority based on military power) favored the unification of previously culturally diverse regions. Along with water works and hydraulic engineering the sustainability of this extended network of roads for a long period of time (2nd century BC–3rd century AD) (Chevallier, 1976; Staccioli, 2003) is one of the best manifestations of the prosperity that *pax romana* brought to every corner of the empire (Sitwell, 1981), allowing the free movement of persons, goods and ideas from the distant Britannia to the deserts of North Africa and the Middle East. The Roman road network was chosen as the subject of our experiment as it is a field which is thoroughly documented with new evidence

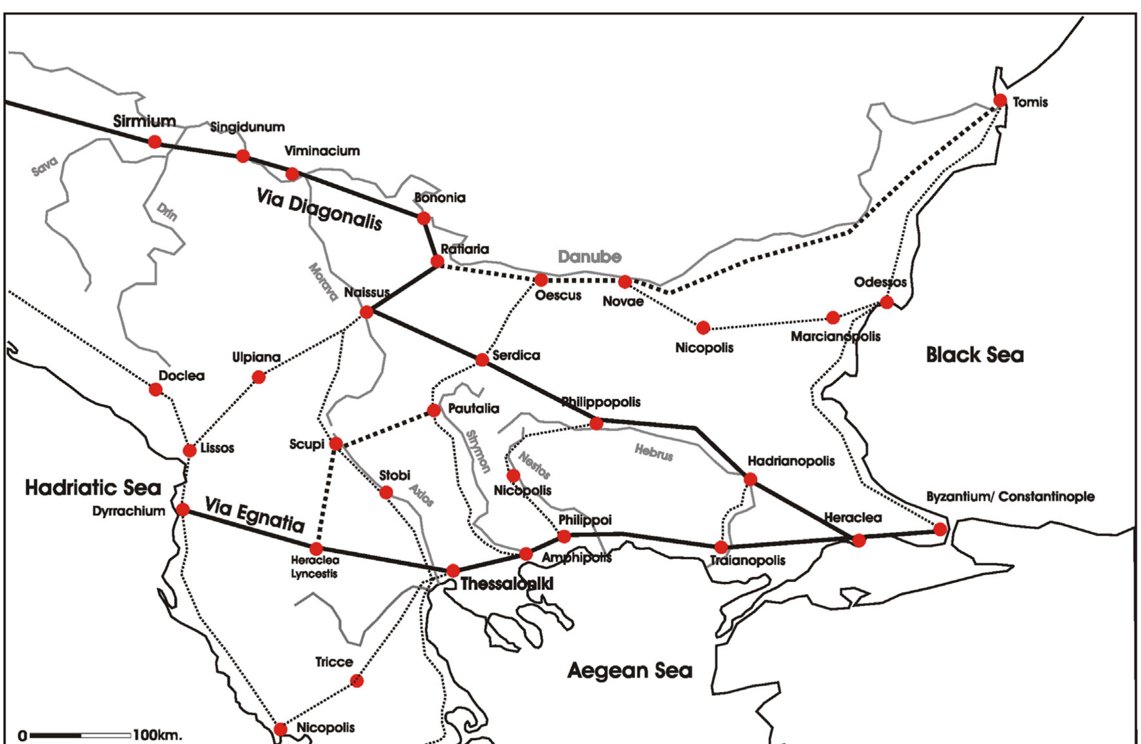

Fig. 1. Network of Roman roads in the Balkans during the imperial period (1st–4th century AD).