Physarum Itinerae:
Evolution of Roman Roads with Slime Mould

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ABSTRACT
The Roman Empire is renowned for sharp logical design and outstanding building quality of its road system. Many roads built by Romans are still used in continental Europe and UK. The Roman roads were built for military transportations with efficiency in mind, as straight as possible. Thus the roads make an ideal test-bed for developing experimental laboratory techniques for evaluating man-made transport systems using living creatures. The authors imitate development of road networks in Iron Age Italy using slime mould Physarum polycephalum. The authors represent ten Roman cities with oat flakes, inoculate the slime mould in Roma, wait as mould spans all flakes-cities with its network of protoplasmic tubes, and analyse structures of the protoplasmic networks. The authors found that most Roman roads, a part of those linking Placentia to Bononia and Genua to Florenzia are represented in development of Physarum polycephalum. Transport networks developed by Romans and by slime mould show similarities of planar proximity graphs, and particular minimum spanning tree. Based on laboratory experiments the authors reconstructed a speculative sequence of road development in Iron Age Italy.

Keywords: Biological Transport Networks, Physarum Polycephalum, Planar Proximity Graphs, Slime Mould, Unconventional Computing

1. INTRODUCTION
Developing physical, chemical and biological analogies of socio-economic processes are becoming increasingly popular nowadays because they give rise to new metaphors and uncover unique similarities. Successful examples of such cross-disciplinary fertilisation include the theory of fractal cities (Batty & Longley, 1994), leaf-inspired simulation of street network growth (Runions, Fuhrer, Lane, Federl, Rolland-Lagan, & Prusinkiewicz, 2005; Barthelemy & Flammini, 2008), urban theories by Alexander (1964) and Salingaros (2005), approaches relating urban morphology to biological morphogenesis (Mouson, 1997), and indeed the whole branch of socio-physics (Galam, 2012).
Despite the overwhelming success of the bio-inspired simulation and socio-physics, the prevailing majority of publications deal with purely theoretical works and computer simulations. Almost no attempts have been made to undertake experimental laboratory comparisons between very large-scale socio-economic developments and spatio-temporal dynamics of chemical or biological systems. This could be explained by difficulties in finding a suitable experimental substrate which does not require sophisticated laboratory equipment and expensive support. A breakthrough came in 2009 when first experimental results on imitating roads networks in United Kingdom with plasmodium of slime mould *Physarum polycephalum* were published (Adamatzky & Jones, 2010) followed by imitation of rail networks in Japan (Tero et al., 2010).

Plasmodium is a vegetative stage of acellular slime mould *Physarum polycephalum*. This is a single cell with many nuclei. The plasmodium feeds on microscopic particles (Stephenson & Stempen, 2000). During its foraging behaviour the plasmodium spans scattered sources of nutrients with a network of protoplasmic tubes. The protoplasmic network is optimised to cover all sources of food and to provide a robust and speedy transportation of nutrients and metabolites in the plasmodium body. The plasmodium’s foraging behaviour can be interpreted as computation. Data are represented by spatial configurations of attractants and repellents, and results of computation by structures of protoplasmic network formed by the plasmodium on the data sites (Nakagaki, Yamada, & Ueda, 2000; Nakagaki, Yamada, & Toth, 2001; Adamatzky, 2010a). The problems solved by plasmodium of *P. polycephalum* include shortest path (Nakagaki, Yamada, & Ueda, 2000; Nakagaki, Yamada, & Toth, 2001), implementation of storage modification machines (Adamatzky, 2010a), Voronoi diagram (Shirakawa, Adamatzky, Gunji, & Miyake, 2009), Delaunay triangulation (Adamatzky, 2010a) logical computing (Tsuda, Aono, & Gunji, 2004; Adamatzky, 2010b), and process algebra (Schumann & Adamatzky, 2009; see overview in Adamatzky (2010a).

In the pioneering experimental works (Adamatzky & Jones, 2010; Tero et al., 2010), configuration of major cities and boundaries of the countries were physically imitated by distribution of oat flakes (which attract the slime mould) and shape of agar plate (growth substrate). Reasonably good matches between protoplasmic tubes developed by *P. polycephalum* and man-made road networks were detected and experimentally verified. The findings paved a new way towards study of human transportation systems but more work is required to develop deeper conclusions, especially related to urbanization phenomena. Also, a great deal of this research was performed by computer scientists and biologists, who might lack substantial information about cities and the development of urban settlements, which may affect the interpretations of experimental laboratory results in terms of real-world transport networks. In the present paper we aim to bridge this gap and try to evaluate to what extent the emergent behaviour of *P. polycephalum* reflects structure and dynamics of human transportation systems at the macro-scale.

We focus on the well studied and historically understood *Vie Consolari* street system (VC) in the Italian peninsula. VC system is one of the first modern human transportation systems linking cities and certainly the first in Europe. VC is also a modern regional transportation network at the first stage of its development and it is also possible to trace back its evolution to observe that Rome linked all the important primordial principal cities in the Italian Peninsula. This fact is important given that VC is a transportation network that is not affected by the complex amount of changes derived by technological evolutions in transportation systems and — more generally — by the stratification of historical facts like wars, demography dynamics and natural hazards. It is derived by a top-down and self organized local organization given the complete absence of bottom-up technologies in regional planning.
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