From Slime to Networks

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The slime mold Physarum plasmodium exhibits some remarkable behavior for a single celled organism. Slime molds can optimize their overall structure to distribute nutrients within themselves in the most efficient manner; essentially solving the Steiner tree problem. In order to minimize the transport distance of nutrients slime molds form tubular networks with shortest total length [1, 3, 7]. Slime molds have been suggested as a good model for studying the transition from single celled organisms to multicellular organisms [4]. This paper will review some current models for how these networks form in slime molds and how people have begun to use these organisms as unconventional computers.

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I. INTRODUCTION

In this paper I will discuss Physarum plasmodium and review various models describing its behavior. The slime mold Physarum plasmodium is a single celled organism with multiple nuclei. Despite being single celled, the slime mold can attain a large size (on the order of 10 to 30 cm across) and is clearly visible with the unaided eye. Physarum plasmodium creates networks that have been used by various authors as unconventional computers. Recently, Andrew Adamatzky showed that it is possible to use Physarum plasmodium to implement an Uspensky machine[2]. Additionally, the networks that Physarum plasmodium creates are robust, have relatively short total length, and have good interconnectivity. Nakagaki and others have taken inspiration from physarum plasmodium to design networks that could be used in real life applications such as power grids, train systems, road networks, and Internet networks.[1] Physarum plasmodium creates these networks with no central command, instead these networks emerge.

The slime mold Physarum polycephalum, also known as the true slime mold exhibits three main phases during its life cycle. It has a vegetative phase called Physarum plasmodium, a dried up hibernation phase called sclerotium, and a fructification phase call sporangia. See Figure 1. This paper will mainly discuss Physarum plasmodium. The Physarum plasmodium looks like a yellowish irregular blob, it grows outward in a thin film and after a sufficient time develops a network of protoplasmic tubes. When multiple food sources are present Physarum plasmodium will grow a network connecting the food sources.

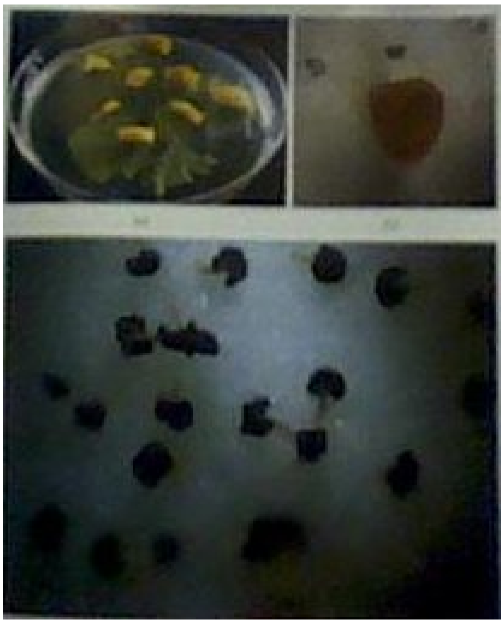

FIG. 1: Three major phases in the life cycle of Physarum. The top left shows the pasmodium, top right sclerotium, and the bottom picture shows sporangia. This figure is taken from reference [2]

The Physarum plasmodium exhibits a contraction cycle with a time scale of two minutes [8]. The tubes connecting the slime mold to food sources vary in diameter dynamically based on the flux of nutrients passing threw them. The plasmodium consists of an outer layer called the ectoplasm and an inner layer called endoplasma. The endoplasma can experience protoplasmic streaming. It has been proposed that the protoplasmic streaming modulates long range pattern formation and the outer ectoplasm dictates short range pattern formation[5]. We will later discuss a reaction diffusion equation that models these two layers separately[5].

The sclerotium phase occurs when Physarum becomes dehydrated. The Physarum plasmodium will dry up into a hard brownish-yellow lump. When the sclerotium is put back into a moist environment it will revert back to the plasmodium. If the Physarum plasmodium is exposed to environmental stress such as light, it will change into the sporangia phase. In this phase it grows a stalk with a globule top from which it will release spores. [2]

The Physarum plasmodium phase is perhaps the most interesting phase to examine because it forms networks. Networks are found everywhere from the Internet to our transportation systems. Recently there have been some major failures of some networks because these networks lacked sufficient robustness to withstand various perturbations. These failures lead to situations such as blackouts in power grids and traffic on our road system. Conventional networks are often planned in order to minimize total cost. Since cost is proportional total length, most network architects attempt to minimize network length. Networks with minimum length are called minimum spanning trees. Minimum spanning trees are often not as robust and average length of inter-node travel is long. Physarum balances these three factors much better than a minimum spanning tree. It does this by adding extra edges to its network. Though these edges increase the total length this effect is counterbalanced by the improvement of robustness and the decrease in average travel distance between nodes. We therefore see that Physarum can be used as a model to build more robust networks and networks with shorter travel time between nodes.

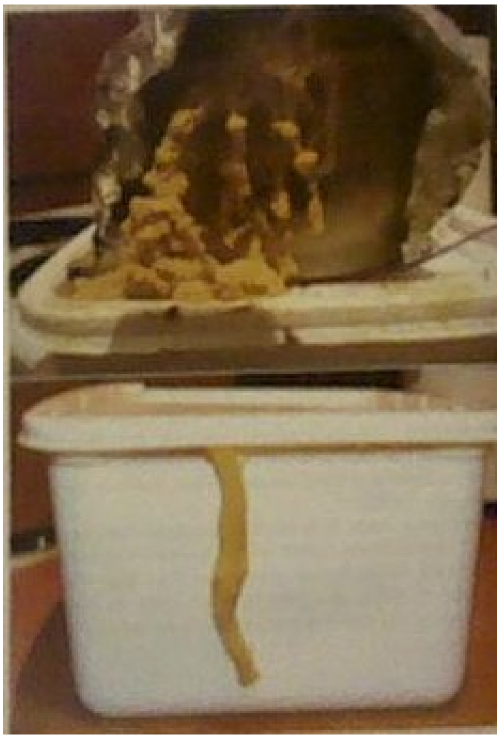

FIG. 2: Physarum growing in a pot. This figure is taken from reference [2]

Physarum plasmodium is also interesting in that it is cheap and easy to grow. In fact, if you are lucky you can find Physarum plasmodium in a damp forest for free. Physarum plasmodium requires very little maintenance. Slime molds grow on porous material such as paper towels and napkins. Traditionally slime molds are fed with oak flakes. The relative ease of acquiring and maintaining a Physarum plasmodium makes it an ideal organism for nontraditional computing.

II. EXPERIMENTS AND MODELS

A. Maze Experiment

One of the first experiments to highlight Physarum plasmodium's computing power was conducted by Toshiyuki Nakagaki[3]. In this experiment Nakagaki demonstrated that a Physarum plasmodium can find the shortest path in a maze. The slime mold was cut up into chunks and distributed throughout the maze. Food sources were placed at the beginning and end of the maze. Physarum plasmodium initially expanded linking up all its parts to create one organism that spanned the entire maze. As time progressed, the plasmodium contracted from dead ends leaving only the shortest or nearly the shortest path between the two food sources linked. Near food sources the plasmodium had a higher contraction frequency and plasmodial tubes parallel to this periodic contraction were reinforced. [3] In this particular maze there were multiple branches that the Physarum could choose. In one case, one path was 22% shorter than the other; in this situation the plasmodium always picked the shorter path. In another case where the two path lengths differed by 2% tubes formed in equal amounts in both branches. This shows that Physarum plasmodium will attempt to pick the shortest path but has some fluctuations in how it does so.

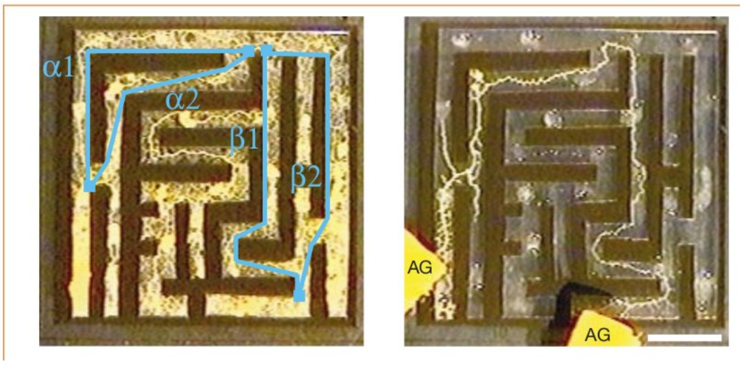

FIG. 3: Physarum plasmodium solving a maze. This figure is taken from reference [3]

B. Tokyo Railway Experiment

Another experiment conducted by Toshiyuki Nakagaki involved placing food at nodes in a transportation network and letting Physarum grow outward from a central hub and examining the resulting network[1]. For this particular experiment they used Physarum to simulate the Tokyo railway system. The experiment consisted of 36 food sources placed in such a way as to represent cities in the Tokyo area. Initially the Physarum expanded out in a uniform way but as it came upon food sources it refined its network to thick tubes carrying the majority of the nutrients. Toshiyuki Nakagaki characterized these networks by calculating their total length, fault tolerance (robustness), and average minimum distance between food sources. He normalized all these results to that of a minimum spanning tree. The results he found for Physarum plasmodium were total length: 1.75 ± 0.30 as compared to the real train network value of 1.8. The mean minimum distance between nodes was 0.85 ± 0.04 for the plasmodium and .85 for the train network. He also characterized the fault tolerance for plasmodium by finding the percentage of the time that deleting an edge would isolate one part of the network. He found that the fault tolerance for plasmoidum was $14\% \pm 4\%$ and 4% for the rail network.[1] Thus we see that the plasmodium did just as well as human engineers in designing a network for transportation and distribution.

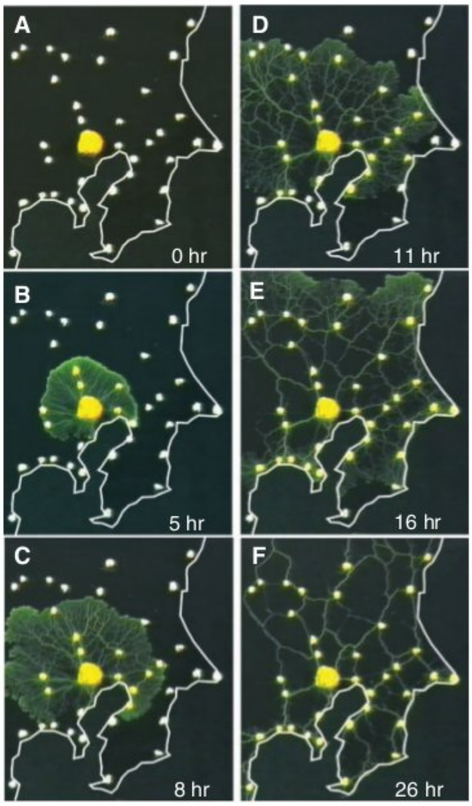

FIG. 4: This time series of photographs shows how Physarum plasmodium grows outward from “Tokyo” slowly colonizing other cities ie food sources. Each panel is 17cm in width. This figure is taken from reference [1]

C. Phenomenological Model of Tokyo Experiment

Nagakaki came up with a phenomenologically inspired model of Physarum plasmodium. As was noted earlier, when the plasmodium grows it first grows outward in a thin film, essential its conducting foraging or exploration. Once the plasmodium has found a food sources it gradual increases the size of the tubes connecting the food and its main body. All other tubes slowly die out. The same idea is now used in a mathematical model. First tessellate all of space with a fine network of tubes of radius r. Now construct a feedback loop such that tubes with higher rates of flow will become thicker and all other tubes will become thinner. Suppose the pressure at nodes i and j are p_i and p_j and that the nodes are connected by length L_{ij} and radius r_{ij}. Also assume flow is laminar and thus follows the Hagen-Poiseuille equation for flux through a cylindrical tube. The flux Q_{ij} is proportional to the pressure difference, the conductivity $D_{ij} = \pi r^4 \eta$, and inversely proportional to the length of the tube.

$$Q_{ij} = \frac{\pi r^4 (p_i - p_j)}{8 \eta L_{ij}} = \frac{D_{ij}(p_i - p_j)}{L_{ij}} \tag{1}$$

The plasmodium adapts the size of the tubes based on flow. Thus the conductivity of a tube can be modeled by the following differential equation:

$$\frac{dD_{ij}}{dt} = f(|Q_{ij}|) - D_{ij} = \frac{|Q_{ij}|^\gamma}{(1 + |Q_{ij}|^\gamma)} - D_{ij} \tag{2}$$

The first term represents growth in response to amount of flow and the second term is a constant rate of shrinkage. Thus in the absence of flow a tube will disappear. A similar model to the one currently being presented was considered by Bonifaci but he changed this equation to $\frac{dD_{ij}}{dt} = |Q_{ij}| - D_{ij}$. In the case considered by Bonifaci he proved that this choice leads to convergence to a minimum spanning tree [7].

Finally we note that current is conserved at each node. What goes in must come out:

$$\sum_j Q_{ij} = 0 \tag{3}$$

At each time step two food nodes are chosen at random; one to act as source I_0 and the other one to act as a sink $-I_0$. By selecting the proper combination of parameters I_0 and γ it is possible to get a network close to that formed by the slime mold or one closer to the actual rail network. A choice of $I_0 = 2.0$ and $\gamma = 1.8$ gives networks similar to those created by Physarum.

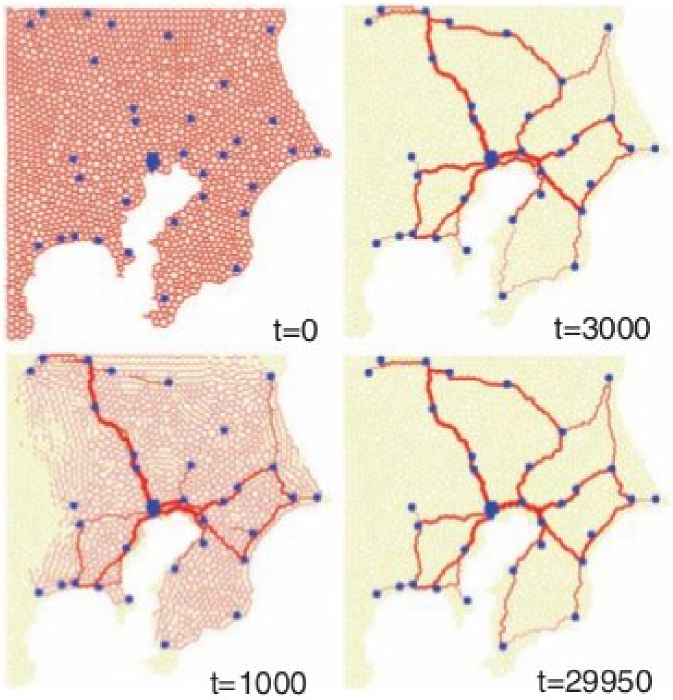

FIG. 5: Results from fluid model of network growth in Physarum plasmodium. Initially all edges have equal strength but as time progresses the most used edges gain in weight while the least used edges shrink. This figure is taken from [1]

D. Reaction Diffusion Model

In this section I will briefly review a bottom up approach proposed by Yamada et al using reaction diffusion equations to model the propagation of slime molds.[5]. As mentioned earlier, slime molds consist of two parts; an endoplasma and an ectoplasma. The ectoplasma is where the contractions occur. Thus there must be some sort of the chemical oscillations in the ectoplasma that serve as clock for these contractions (These chemical oscillations could be in Ca or in ATP). The endoplasma equation includes the effects of streaming. Let h be the thickness of the endoplasma and $\vec{v}$ be the average endoplasma velocity. Let $\mathbf{u}_{gel}$ be the chemical components in the ectoplasma and $\mathbf{u}_{sol}$ be the chemical components of the endoplasma. Let D be the various diffusion constants and F be the reaction kinetics.

$$
\begin{aligned}
&\frac{\partial h}{\partial t} + \vec{\nabla} \cdot (h\vec{v}) = 0 \\
&\frac{\partial \mathbf{u}_{gel}}{\partial t} = \mathbf{F}_{gel}(h, \mathbf{u}) + \vec{\nabla} \cdot (D_{gel} \vec{\nabla} \mathbf{u}_{gel}) \\
&\frac{\partial \mathbf{u}_{sol}}{\partial t} + \vec{v} \cdot \vec{\nabla} \mathbf{u}_{sol} = \mathbf{F}_{sol}(h, \mathbf{u}) + \frac{1}{h} \vec{\nabla} \cdot (D_{sol} \vec{\nabla} \mathbf{u}_{sol})
\end{aligned} \tag{4}
$$

After considering low Reynolds number flow and ignoring sol-gel conversion, it is possible to expand the inter-cellular pressure about the homogeneous static state. Using these simplifications it is possible to rewrite the previous equations 4 as a reaction diffusion advection equation

$$\frac{\partial \mathbf{u}}{\partial t} + M\vec{\nabla}\mathbf{u} \cdot \vec{\nabla}\mathbf{u} = \mathbf{F}(\mathbf{u};\mu) + D\vec{\nabla}^2\mathbf{u} \quad (5)$$

Here **F** is reaction kinetics, M is a tensor of advection current coefficients caused by the endoplasmic flow, and D is a matrix of diffusion constants.

By analyzing these equations it is possible with weak nonlinear analysis to find that the envelope obeys the complex Ginzburg-Landau equation. [5]. Also these equations model a self-determined flow. Further analysis also gives evidence that neighboring oscillators become in step with one another and thus indicates that phase difference in contraction must be a important mechanism in pattern formation in Physarum plasmodium [5].

III. CONCLUSION

Of the models presented, the simple phenomenological model is perhaps the easiest to understand and has powerful results. By varying the parameters I_0 and γ it is possible to produce networks which range in properties from extremely fault resistant and interconnected to minimum spanning trees. This simple phenomenological model can explain how Physarum plasmodium can create such sophisticated networks with a simple feedback loop mechanism. The algorithm as presented already encapsulates a lot of Physarum plasmodium's behaviors but it still has room for improvment. The algorithm could be changed so tessellation happens incrementally (in a more evelotiunary process) slowly growing outward from a central node as would happen in real life. The model would still retain its ability to refine an exhisting mesh but it would also be able to explore and find new food sources in the absence of a prexisting network. Additionally, I think instead of making the total amount of nutrients in the network constant, the network itself should consume nutrients (ie when it is creating new paths) and all food sources should act as sources. The emergence of networks is a truly remarkable feature of Physarum plasmodium.

[1] Toshiyuki Nakagaki, et. al, "Rules for Biologically Inspired Adaptive Network Design" Science 22 January 2010: 327 (5964), 439-442. [DOI:10.1126/science.1177894]

[2] Andrew Adamatzky. "Physarum Machines; Computers from Slime Mould" World Scientific, 2010.

[3] T. Nakagaki, H. Yamada, A. Toth, "Intelligence: Maze-solving by an amoeboid organism", Nature 407, 470 (2000).

[4] Graeme J. Ackland, Richard D.L.Hanes, Morrel H. Cohen. "Self assembly of a model multicellular organism resembling the Dictyostelium slime molds" arXiv:0705.0227

[5] H. Yamada, T. Nakagaki, M. Ito. "Pattern formation of reaction-diffusion system having self-determined flow in the amoeboid organism of Physarum plasmodium" arXiv:patt-sol/9805004

[6] Robert D. Guy, Toshiyuki Nakagaki, and Grady B. Wright, "Flow-induced channel formation in the cytoplasm of motile cells," Physical review. E, Statistical, nonlinear, and soft matter physics 84 (1 Pt 2), 016310 (2011).

[7] Vincenzo Bonifaci, Kurt Mehlhorn, Girish Varma. "Physarum Can Compute Shortest Paths" arXiv:1106.0423

[8] Yuki Kagawa, Atsuko Takamatsu. "Collective behavior in coupled dynamical systems on two-dimensional weighted networks: A step toward understanding adaptive behavior of true slime mold" arXiv:0904.1456