Growth pattern of *Physarum polycephalum* during starvation

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ABSTRACT
Physarum polycephalum typically grows as a network from microplasmodia. We describe a new growth pattern where globular moving fragments are formed instead of networks. This work was presented at PhysNet 2015.

Categories and Subject Descriptors
J.3. [**Computer Applications**]: Life and Medical Sciences-*Biology and Genetics*

Keywords
Physarum polycephalum, foraging

1. INTRODUCTION
Physarum polycephalum is a unicellular organism, but houses many nuclei in one cell in its vegetative state. The multinucleate form, called plasmodium, is able to grow up to hundreds of square centimeters. The network constructed by *Physarum* is likely optimized through evolution to maximize the survival of the organism. Studies show that *Physarum* networks can have better transport efficiency and are more resistant to disruption than man-made networks [1].

All organisms employ a different set of foraging strategies with a common goal of ensuring their survival. These strategies are also likely to be optimized through natural selection to be efficient in finding new resources [2]. Depending on the capabilities of the organism (e.g., memory, cognition) and the surrounding environment (e.g., distribution of food), the optimal strategies for foraging will differ.

One way of improving the efficiency of foraging is to minimize the re-visiting of previously surveyed area. A systematic search pattern where the organism follows a set path in order to forage, or remembering the visited sites both fall in this category [3]. These strategies are optimal when an organism knows the food is nearby [4].

However, when there is no information present regarding the resources, organisms perform random searches [5]. For example, many organisms, both prokaryotes and eukaryotes, employ a movement called a Levy walk, where random movement is coupled with long period of directed movement [6]. These special movements maximize the chance of encountering a food source in an unknown environment [5].

Dictyostelium, a close relative of *Physarum*, performs a correlated random walk during foraging [4], where the organism is more likely to maintain the direction of movement. Moreover, *Dictyostelium* appears to utilize an adaptive strategy of 'win-stay/lose-shift'. The organism turns frequently to stay in one place in the presence of food, and performs directed movement without turns in the absence of food

Generally, *Physarum* forages as a network with extended veins and growth fronts. With this organization *Physarum* can survey a larger area with minimal biomass. The organism is capable of selecting the ideal ratio of proteins and carbohydrates for their growth by connecting appropriate food sources with veins [7]. *Physarum* also distinguishes and selects the nutrient source with a higher concentration, and behaves similar to higher-cognitive organisms under stress [8]. Lastly, *Physarum* utilizes extracellular slime as an external memory [3, 9], and is capable of anticipating periodic events [10]; somewhat unexpected from an unicellular organism.

While investigating the network properties of *Physarum*, we have discovered a different growth mode that does not depend on the formation of an external network. We describe the general progression of growth, and discuss the possible responses and mechanisms that lead to this new pattern.

2. EXPERIMENTAL PROCEDURE
Physarum polycephalum was grown in liquid culture and maintained as microplasmodia. Microplasmodia are harvested, centrifuged, and resuspended to a desired concentration. A fixed volume of the resuspension was placed on an agar plate dropwise to produce a circular patch with defined area.

In order to identify a growth pattern that is specifically associated with a starvation response, microplasmodia were grown and harvested shortly before spherulation. These aged microplasmodia were inoculated on a low nutrient agar.

3. RESULTS
3.1 A new growth pattern
Most of the time, microplasmodia harvested from the liquid culture plated on agar plates fused together and formed networks, as described in [11].

However, microplasmodia with advanced age aggregate locally and produce fragments that propagate radially away from the patch of inoculum (See Fig. 1). We term the alternative growth

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progression 'search pattern', and the motile fragments of *Physarum* 'satellites'.

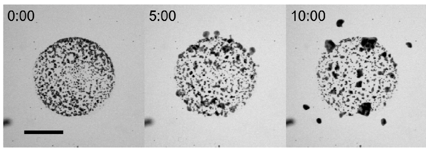

Figure 1. A specific search pattern of *Physarum*. When microplasmodia of advanced age are inoculated, they form local aggregates and fuse together to produce a moving body that radiates away from the inoculum. Time of observation is indicated as hh:mm. The scale bar represents 5 mm.

3.2 Qualitative assessment

During our observation of the new growth pattern of *Physarum*, the number and the size of satellites varied across the experiments. In general, the density of the microplasmodia seems to play a role in satellite production. We found a tendency that larger satellites are produced from higher density patches, and smaller satellites are formed from low density patches (See Fig. 2).

Despite the difference in size, morphology and numbers produced, all satellites eventually transitioned into networks after translocation.

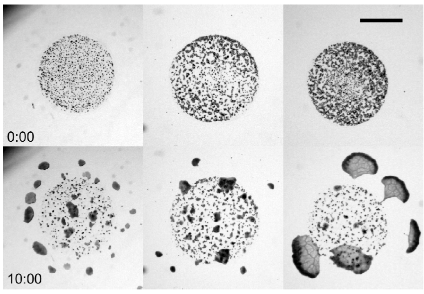

Figure 2. Variations of search patterns. Microplasmodia form small but numerous satellites in lower density (left, 21% of the area occupied) versus larger and fewer satellites in higher densities (middle, 40%; right, 62%). Time of observation is indicated as hh:mm. The scale bar represents 5 mm.

4. DISCUSSION

The new growth pattern of *Physarum* only occurred from old microplasmodia in a low nutrient environment. Since the satellites turned into networks after the locomotion, it is likely an emergency mechanism of the organism in response to adverse conditions, and not a primary mode of growth.

The satellites, although disconnected, showed correlated behavior. Most satellites traveled in a straight line, radially away from the center of the patch. They are formed, protrude from the patch, and stop at about the same time. This behavior may suggest that the pattern is a concerted effort as an organism, rather than the individual behavior of microplasmodia.

Our experimental setup allows us to investigate the decision-making process of *Physarum*. Initially, all microplasmodia are disconnected, subjected to different environments (i.e. middle of the patch vs. edge of the patch). The information is collected from different microplasmodia during the fusion into a single body, and based on these information, satellites appear to determine the direction of movement. Although originating from the same plasmodium, microplasmodia demonstrate heterogeneity – some microplasmodia fuse and move, some fuse and stay, and do not participate in the fusion. These differences are likely reflected at the gene expression level.

There is a short delay between the satellite movement and the inoculation. It is possible that *Physarum* expresses proteins for locomotion during this delay. Satellite locomotion may also share the same machinery required for network growth, and *Physarum* simply needs to alternate the organization of these proteins. Determining how this search pattern is regulated, and what components are required for locomotion would give better insights on how *Physarum* perceives information from the environment and make decisions accordingly, especially during conditions that may be detrimental to the organism.

Based on other foraging strategies described in other organisms, as well as the previously described behavior of *Physarum*, the search pattern is likely an optimized process to maximize the chance of survival in a starvation condition.

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