Ethology and rheology of an amoeboid cell

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Abstract

We will show that ability of information processing in an amoeboid organism is higher than we had thought. The model organism is the plasmodium of *Physarum polycephalum* (true slime mold), which is a large aggregate of protoplasm with many nuclei. The organism found the optimal path when it obtained the multiple locations of food. A simple mathematical model for the path finding was proposed in terms of differential equations. As well as the path-finding ability, the organism was able to anticipate the next timing of periodic climate change after experienced some periodic changes of climate, and to show a kind of behaviors that seemed to be ‘ indicisive ’ when it encountered the presence of a chemical repellent, quinine. We indicated that simple dynamics was enough to reproduce these observed behaviors. Mathematical modeling is helpful to understand the mechanism of behavioral smartness in slime mold. The behavioral smartness can be based on motion of viscoelastic body, so we discuss rheological description of smart behavior.

1 Introduction

Cells are the elementary units of all organisms and the simplest living systems. They sense the surrounding conditions and take a suitable action in response. Studies of single-celled organisms in contradictory situations have revealed smart behavior.

Two basic questions are posed regarding the smart behavior at the cell level: (1) What is the extent of this capacity? (2) What is the equation of motion used? In this presentation, we shed light on a few types of smart behaviors and mathematical model of motion in the good model organism of *Physarum* plasmodium. Plasmodium is a large aggregate of protoplasmic sol and gel. This organism just looks like a blob of slimy material but it is alive and behaves in a smart way. The third question may arise then: (3) What is the material basis that realizes the smartness? We hope to discuss some rheological aspects of the mathematical models[1, 2, 3, 4, 5].

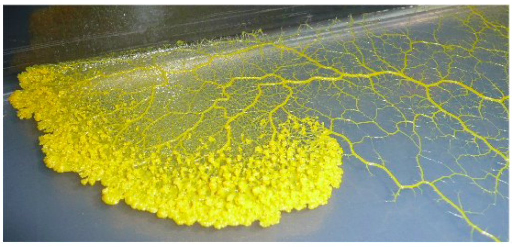

Figure 1: Picture of the plasmodium of *Physarum polycephalum*, which migrates on the agar plate. Scale bar: 1 cm.

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2 Amoebal design for multi-functional network[7]

Design principle for communication networks including traffic transportation, information highway and power cable is needed in modern industrial world. A public transportation network, for instance, is required to meet the multiple requirements: short total length of network and tolerance of accidental breakdown of connecting lines. But it is in principle difficult to obtain a good solution because of exponential explosion of computational time in a combinatorial optimization problem of this kind. We report here that a well-designed network of railway transportation is simulated by an amoeboid organism of true slime mold *Physarum polycephalum*. When many small food sources were presented at various positions corresponding to geographical locations of cities, the plasmodium made a tube network among the food sources, which satisfies all of the requirements. Comparing the real railway network with *Physarum* network, functional similarity was found between them even though they were totally different systems. The *Physarum* networks showed a rich variety over a wide range of total length and included the railway network as one of them. A common mechanism of development should be noticed. That is adaptability: each path is more likely to grow as more traffic flows through it. A simple mathematical model reveals a core mechanism of self-organization of multifunctional network through the adaptability.

3 Amoebae anticipate periodic events[6]

Anticipating and recalling events are higher functions performed by the brains of higher animals. But their evolutionary origin and the way in which they are self-organized remain open questions. We show that an amoeboid organism can anticipate the timing of periodic events. The *Physarum* plasmodium moves rapidly under favorable conditions, but stops moving when transferred to less-favorable conditions. Plasmodia exposed to unfavorable conditions, presented in three consecutive pulses at constant intervals, reduced their locomotive speed in response to each episode. When subsequently subjected to favorable conditions, the plasmodia spontaneously reduced their locomotive speed at the time point when the next unfavorable episode would have occurred. This implied anticipation of impending environmental change. After this behavior had been evoked several times, the locomotion of the plasmodia returned to normal; however, the anticipatory response could subsequently be induced by a single unfavorable pulse, implying recall of the memorized periodicity. We explored the mechanisms underlying these behaviors from a dynamical systems perspective. Our results hint at the cellular origins of primitive intelligence and imply that simple dynamics might be sufficient to explain its emergence.

4 Contemplative behavior when encountering a toxin[8, 9]

It has recently been reported that even single-celled organisms appear to be “ indecisive ” or “ contemplative ” when confronted with an obstacle. When the amoeboid organism *Physarum* plasmodium encounters the chemical repellent quinine during migration along a narrow agar lane, it stops for a period of time (typically several hours) and then suddenly begins to move again. When movement resumes, three distinct types of behavior are observed: The plasmodium continues forward, turns back, or migrates in both directions simultaneously. Here, we develop a continuum mathematical model of the cell dynamics of contemplative amoeboid movement. Our model incorporates the dynamics of the mass flow of the protoplasmic sol, in relation to the generation of pressure based on the autocatalytic kinetics of pseudopod formation and retraction (mainly, sol-gel conversion accompanying actin-myosin dynamics). The biological justification of the model is tested by comparing with experimentally measured spatiotemporal profiles of the cell thickness. The experimentally observed types of behavior are reproduced in simulations based on our model, and the core logic of the modeled behavior is clarified by means of nonlinear dynamics. An on-off transition between the refractory and activated states of the chemical reactivity that takes place at the leading edge of the plasmodium plays a key role in the emergence of contemplative behavior.

5 Concluding remarks[10]

The behavioral smartness at the cell level was described. A mathematical model was proposed and reproduced the main features of the observed behavior. The study of the rheology of mixtures of sol and gel will be challenging in the future in relation to self-organization of the ability of smart behavior or ethological intelligence at the cell level.

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