Life-like Behavior of an Oil Droplet in an Aqueous Surfactant Solution: Comparative Analysis with *Tetrahymena* Movement and Numerical Investigation

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Abstract

We experimentally and numerically delve into the life-like behavior of an oil droplet in an aqueous surfactant solution in response to changes in the volume and composition ratio of the droplet. Much research has been dedicated to investigating living and non-living systems independently, albeit the boundary between the two remains unclear. To address this issue, we conducted experimental observations and identified several types of spontaneous motion exhibited by the oil droplet, which varied depending on its parameters. We then quantified the characteristic motion patterns utilizing analysis from multiple aspects and compared the differences between oil droplets - as an example of non-living material - and *Tetrahymena thermophila* - as a living system. Furthermore, in an attempt to reveal the deterministic or stochastic rule governing each system, a numerical simulation of the Langevin equations was performed.

Introduction

Understanding the boundary between living and non-living things requires an examination of the mechanism of spontaneous motion that is commonly observed in both systems (Hanczyc et al., 2007; Hanczyc and Ikegami, 2010). Thus, it is imperative to quantitatively analyze the similarities and differences in the spontaneous motions of living and non-living systems to identify the requirements for being ”life-itself” (Ikegami et al., 2015). Chemically active self-propelled particles (SPPs) have been extensively studied due to their complex behaviors resulting from nonlinear physicochemical coupling under viscous fluid conditions (e.g., water-in-oil and oil-in-water) (Michelin, 2023). Among the several classes of self-propulsion, Marangoni flow, originating from the inhomogeneous surface tension gradients, triggers self-propulsion. Although these studies have garnered significant attention from various realms, they have primarily been conducted in the context of active matter physics (Suda et al., 2021) independent of Artificial Life research. In this study, we perform a multi-faceted analysis of the spontaneous motions of a single oil droplet as a representative non-living system and *Tetrahymena*, a eukaryotic unicellular organism, as a living organism. Our analysis incorporates examining the trajectory, kinetic energy distribution, embedding dimension, and the Largest Lyapunov exponent (LLE) to characterize differences between both systems. Additionally, we show the numerical simulation of the Langevin equations comprising external forces reproduces the characteristic behavior of an oil droplet as a reference point. Ultimately, by investigating the differences in spontaneous motion between living and non-living systems, we aim to determine whether the rules behind spontaneous motion are stochastic or deterministic and whether fluctuations in motion have different origins for these systems.

Material and method

In the experiment, a single oil droplet consisting of a mixture of ethyl salicylate (ES) and paraffin was placed in a petri dish with an anionic surfactant, Sodium Dodecyl Sulfate (SDS) solution (Tanaka et al., 2015). By changing the volume (5, 10, 20, and 30 μL) and composition ratio (ES: Paraffin (w/w), 5:5, 6:4, 7:3, 8:2, and 9:1) of an oil droplet as parameters, the emerging motion was recorded. *Tetrahymena* was confined in a two-dimensional microculture apparatus and observed under a stereomicroscope with sufficient nutrition.

The time series trajectory data, change in the centroid position of an oil droplet and *Tetrahymena*, experienced analysis of its behavior and kinetic energy distribution. Hence, we estimated the embedding dimension of the time series (Takens, 1980; Sugihara and May, 1990) of the kinetic energy and computed the largest Lyapunov exponent as a nonlinear dynamical systems analysis (Rosenstein et al., 1993). The embedding dimension refers to the system’s complexity as the minimum number of variables necessary to reconstruct the underlying state space. The LLE is an indicator of the sensitivity to the initial condition, which is a requirement of a chaotic dynamical system.

Moreover, based on phenomenological observation, we constructed a numerical simulation of the two-dimensional Langevin equations to reproduce the behavior of an oil droplet.

$$\frac{du}{dt} = -\gamma u + \sqrt{2D}\xi + \hat{f} \tag{1}$$

$$\frac{dv}{dt} = -\gamma v + \sqrt{2D}\xi + \hat{g} \tag{2}$$

Here u and v are x and y directional velocities, respectively, γ is viscosity, and D is diffusion coefficient. The drag forces $\hat{f}$ and $\hat{g}$ are represented as sinusoidal inputs such as $\sin \omega t$ and $\cos \omega t$. The noise term ξ follows an independent Gaussian random number, letting the σ be variance and δ be the delta function. (i.e., $E[\xi(t)] = 0$, $E[\xi(t)\xi(t')] = \sigma\delta(t' - t)$).

Result

The parameter of an oil droplet, such as the volume and composition ratio, has fulfilled a critical role in its emerging behaviors. As shown in Fig.1, in response to the parameter change, an oil droplet exhibited different characteristic motion patterns (e.g., rotational, circular, chaotic, and reciprocal). In contrast, *Tetrahymena* showed far more random and complex motion in the culture medium.

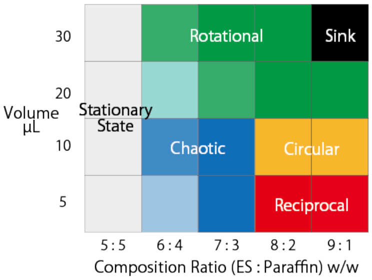

Figure 1: Phase diagram of the motion depending on the composition ratio and volume of an oil droplet. Motions were qualitatively classified into five categories: rotational, circular, chaotic, reciprocal, and stationary state.

The analysis of the kinetic energy distribution revealed that the oil droplet motion is described by mostly constant velocity and the oscillation around it. Subsequently, the distribution followed the Gaussian and exponential distributions depending on the parameter. In comparison, Thetrahymena exhibited Maxwell Boltzmann distribution and deviations from it.

According to the estimation of the embedding dimension, the motions of an oil droplet, which are sensitive to external tension fields generated by chemical gradients, are successfully embedded into a relatively low dimensional state space (Fig.2). Also, it indicates a positive LLE and implies partially chaotic motions. While since the motion of *Tetrahymena* is dominated by noise (or higher dimensional chaos), the embedding dimension and the LLE were not uniquely identified.

Finally, we performed numerical simulations of the two-dimensional Langevin equations with external forces eq.(1) and (2). We found that the behavior of an oil droplet can be described comparatively well by the Langevin equations.

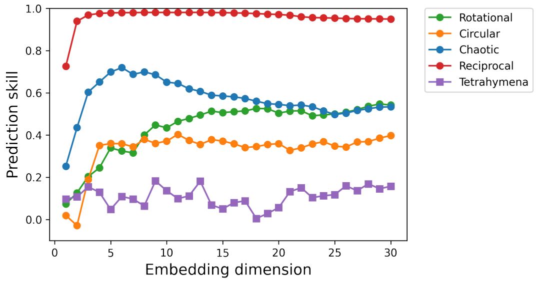

Figure 2: An example of the estimation of the embedding dimension of *Tetrahymena* and an oil droplet according to each characteristic motion pattern.

Discussion and Conclusion

We reported the experimental observation and quantitative analysis of the life-like behaviors of an oil droplet through the comparison with *Tetrahymena* and the Langevin equation as a reference. To sum up, we found the followings:

1. The spontaneous movement of an oil droplet exhibits characteristic patterns in response to the volume and composition ratio change.
2. Kinetic energy distribution manifests the qualitative difference in the behavior of oil droplets (well-organized) and *Tetrahymena* (random).
3. Evaluation of the embedding dimension and the LLE quantified the degree of noise contribution in both systems.

These results suggest that the origin of fluctuation in the motion of non-living as an oil droplet and living as *Tetrahymena* is different. This difference can be attributed to the increased degrees of freedom of droplet deformation with the parameter change (Tarama and Ohta, 2016). On the other hand, *Tetrahymena* behaved in a more stochastic manner. In this study, we simplified the trajectory of the oil droplet as the trace of the centroid. Hence, the role of the deformation in triggering spontaneous symmetry breaking and in giving rise to complex motion has remained in question.

We will discuss whether the rules governing each system are deterministic or stochastic and whether fluctuations in the motion of non-living and living systems are originally different. Furthermore, if we can observe biological ”autonomy” in spontaneous motion, does *Tetrahymena* have ”free will” as a manifestation in the form of noise? These focal points provide insights into the nature of life-like behavior.

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