The physics of morphogenesis

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One of the main challenges toward a physical framework of a living system is the inherent difficulty in separating any given level of organization from the coupled dynamics at all the other levels, including the environment within which the system is embedded. We will discuss these coupled dynamics in the context of morphogenesis—the emergence of form and function in a developing animal, which is one of the most remarkable examples of pattern formation in nature. The current picture of morphogenesis relies on biochemical patterning. However, as we are going to discuss, morphogenesis involves the integrated symbiotic interplay of three type of processes: biochemical, mechanical and electrical, which span all scales from the molecular to the entire organism. We first briefly discuss our experiments demonstrating the role of mechanics and the integration of mechanical processes with the biochemical ones, utilizing Hydra regeneration as a model. We then discuss our main subject: Hydra regeneration under external electric fields.

The robustness of the morphogenetic process is typically attributed to the presence of a well-defined hierarchy of forward-driven processes, such as threshold-crossing cellular processes and the development of symmetry-breaking fields. Is it possible to modulate the course of morphogenesis in a whole animal and alter its developmental trajectory on demand? We demonstrate that an external electric field can be tuned to drive morphogenesis in Hydra regeneration, backward and forward, around a critical point in a controlled manner. A controlled drive of morphogenesis allows multiple re-initiation of novel developmental trajectories for the same tissue. We next utilize an external electric field to hold the Hydra tissue at the edge of regeneration and study fluctuations and correlations near this critical point. We will discuss the main experimental observations and their implications. Controlled reversal trajectories open a new vista on morphogenesis and suggest a novel approach to study the physics of this fascinating process as a dynamic phase transition.