Multiscale modeling and simulation of bacterial colonies

Principle researcher: Gil Ariel

Understanding the evolution of bacterial colonies is of high importance to a wide range of fields ranging from microbiology to drug design. A single colony can involve millions of individuals which are cooperating through secretion and absorption of proteins, pheromones and other chemicals. Hence is a need for simulations, as a mathematical model can assist in identifying the key factors that govern and regulate a colony's dynamics.

The goal of the proposed research is to devise models that can explain and predict experimental results showing the dynamics of colonies grown in a Petri dish. The experiments are performed in collaboration with several experimental groups in Israel, USA and the Netherlands with a particular type of bacteria from the Bacillus family called Paenibacillus. Colonies of these bacteria have been found to develop complicated patterns, with some reproducible global characteristics. In lieu of the experimental results, we would like to show how the bacteria can cooperate and regulate the growth dynamics of an entire bacterial population.

In this research we take a multiscale approach and study the dynamics of the colony across different time and spatial scale. The dynamics inside a bacteria colony occurs on three scales: the smallest is the scale of the individual bacteria. Each cell is an individual that responds to its environment by a complex network of chemical and physical interactions. The intermediate scale is that of the swarm, which is the basic organizational unit. On this scale synchronized movement is observed. Finally, the large, macroscopic scale is that of the entire expanding colony.

Several phenomenological models that attempt to reproduce some of the global characteristics and behaviors that bacteria colonies show such as quorum sensing, chemotaxis and more have been suggested in the literature. We focus on more complicated situations in which collective behavior emerges as organized swarms move collectively, share resources and risks. Furthermore, bacterial swarms carry and transport cargo such as fungi and beads.

Following the hierarchy of scales, the first step in this project is to understand and model the complex dynamics of bacterial swarms, their response to external conditions and the relation between the swarm dynamics and the task at hand. Swarming motility allows microorganisms to move rapidly over surfaces. The bacterium Paenibacillus vortex exhibits advanced cooperative motility on agar plates resulting in intricate colonial patterns with geometries that are highly sensitive to the experimental conditions. These patterns are characterized by aggregates of tens to thousands of cells that move as a coherent unit. The structure and internal organization of the colony is generated by the interplay of many factors including gradients of nutrients and waste products, extracellular polymers and surfactants, cell surface properties, cell death, environmental sensing and intercellular signaling.

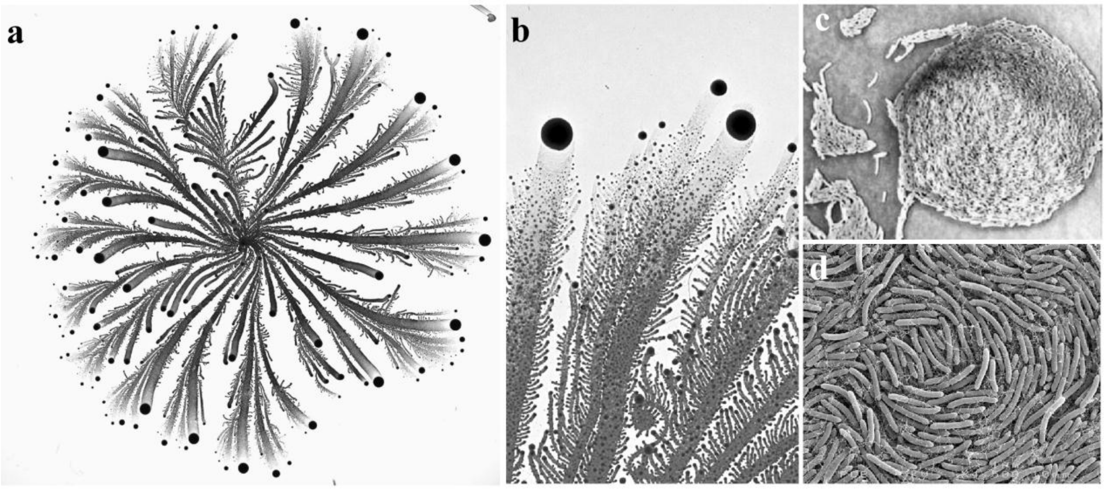

Figure 1: The bacterial colony across different scales. The full colony (a) has a diameter of about 9cm. Individual bacteria (d) are about 5 micrometers long.

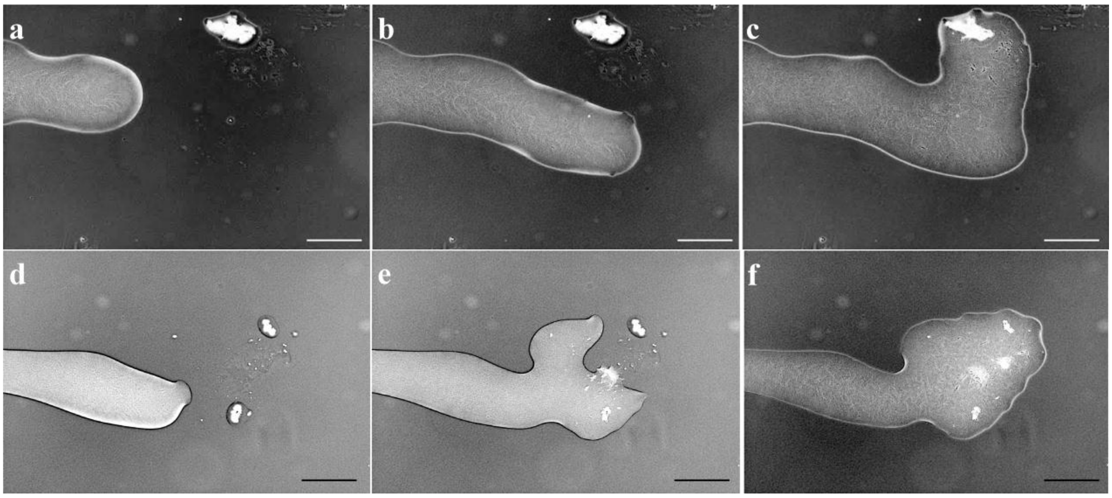

Figure 2: A swarm of bacteria moving toward a source of food. The bar is approximately 100 micrometers.

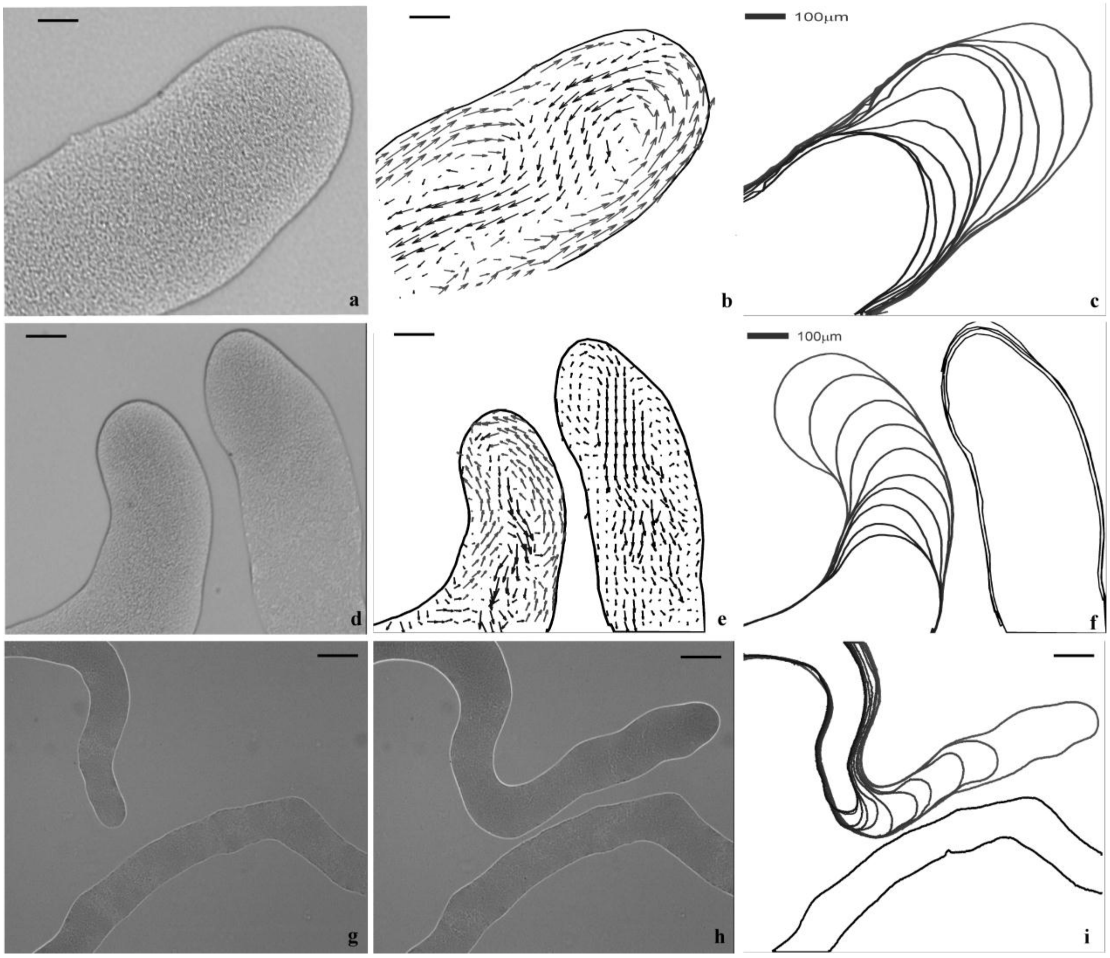

Figure 3: Bacterial swarms interacting. Subplots show the bacterial swarm and the flow pattern as analyzed by tracking and optical flow algorithms. The bar is approximately 100 micrometers.

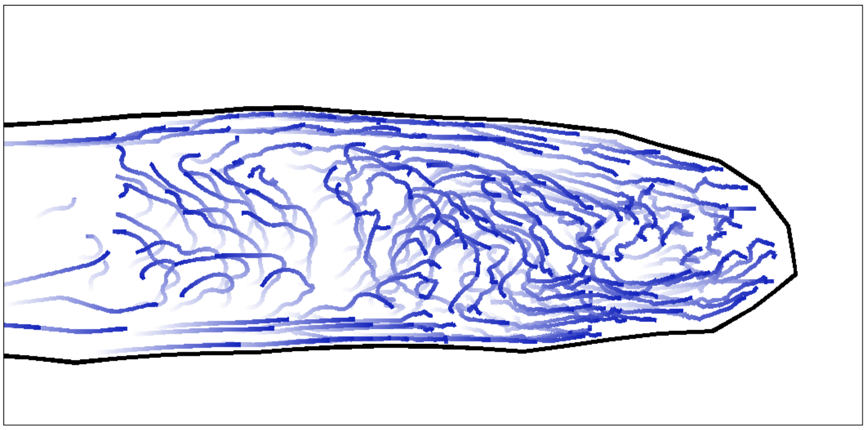

Figure 4: A snapshot showing a swarming group of agents following biologically realistic interactions.

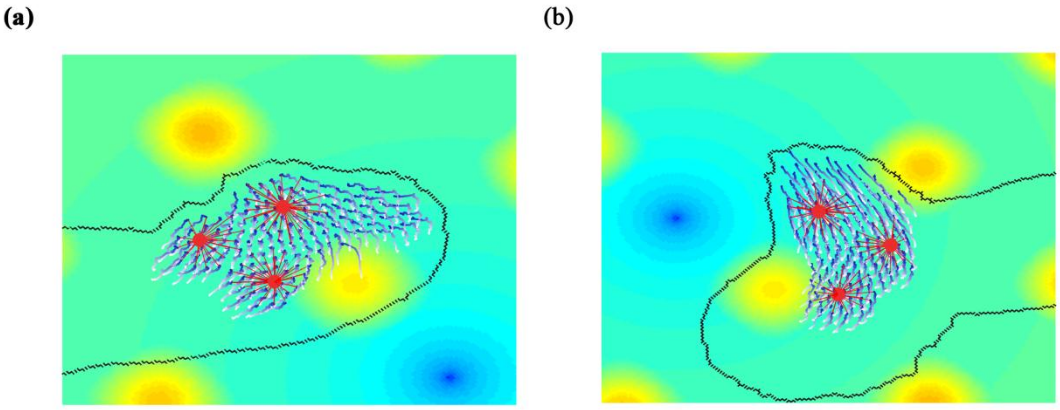

Figure 5: simulation of bacteria carrying cargo