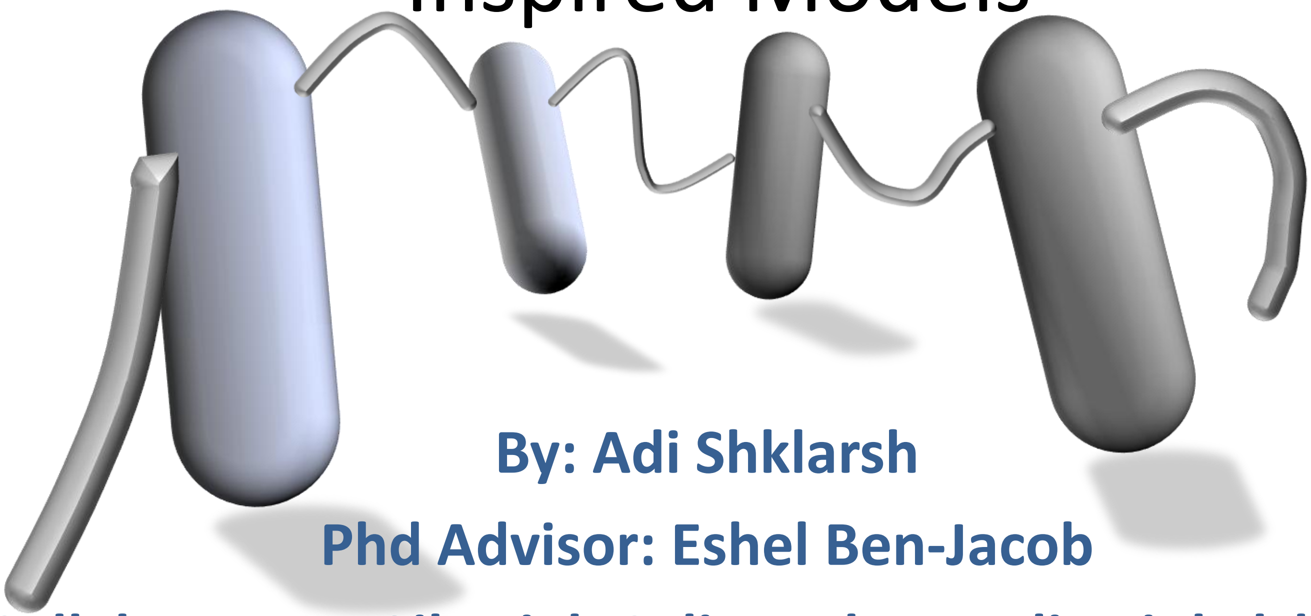
TEL AVIV UNIVERSITY אוניברסיטת תל-אביב

Ki-net – 17.01.13

Complex Collective Navigation in Bacteria-Inspired Models

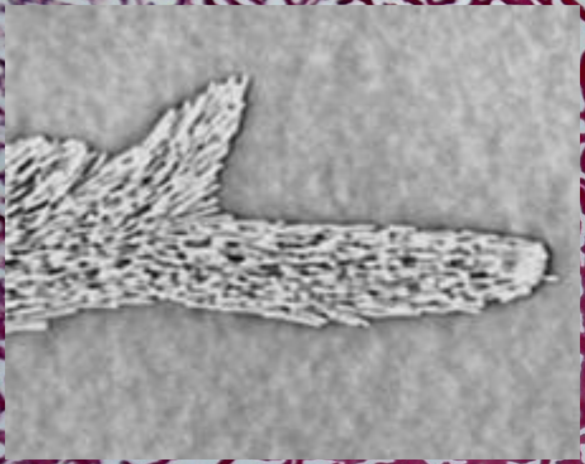


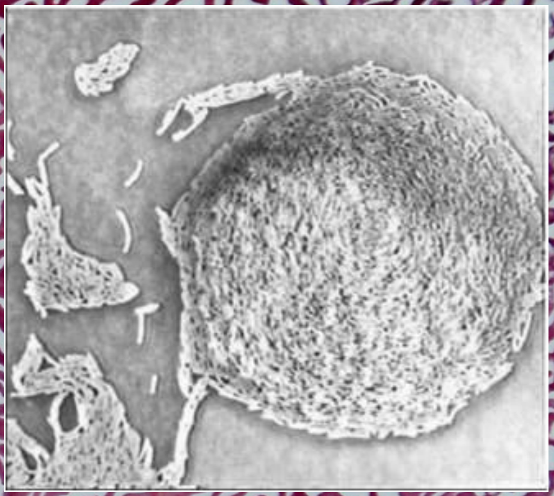
By: Adi Shklarsh

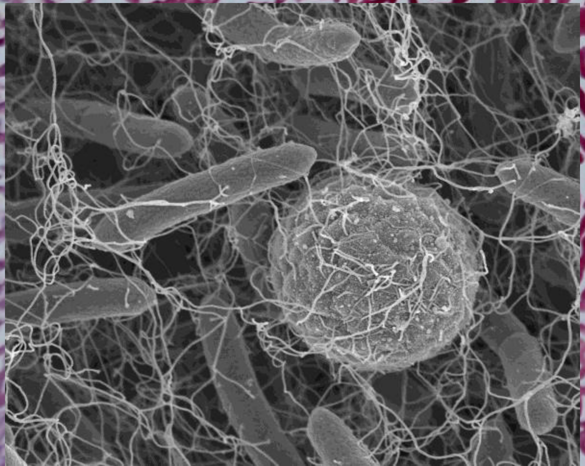
Phd Advisor: Eshel Ben-Jacob

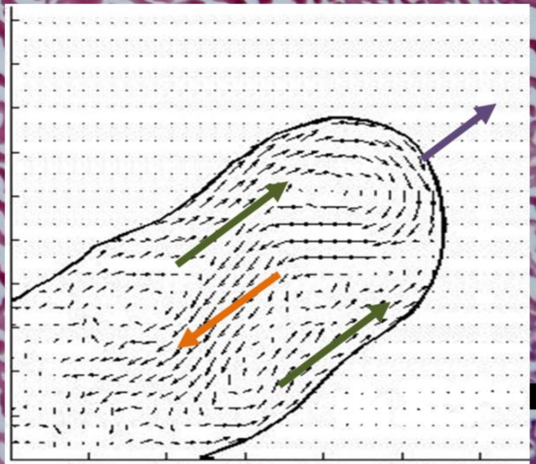
Collaborators: Gil Ariel, Colin Ingham, Alin Finkelshtein

Bacteria collective behavior



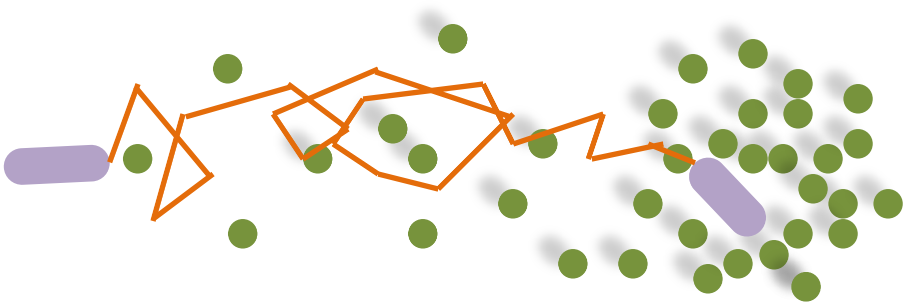




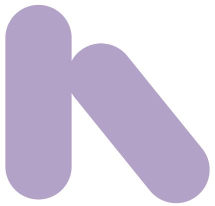


Bacteria tools

- Chemotaxis

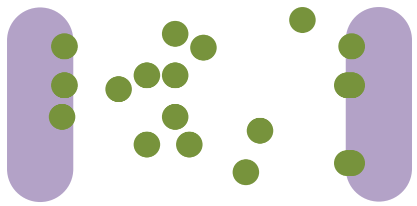


- Physical interactions



- Communication

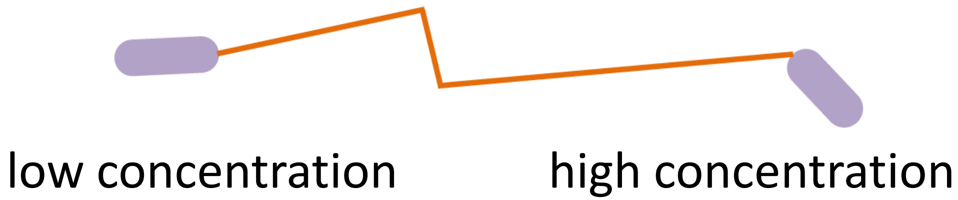
[Miller and Bassler 2001, Annual Reviews Microbiology]



Modeling Swarms

- Chemotaxis:

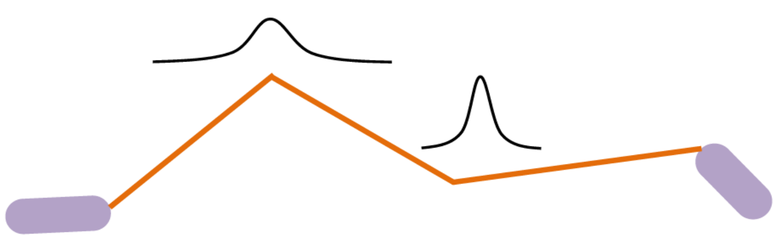
run and tumble



run time is a function of the temporal gradient

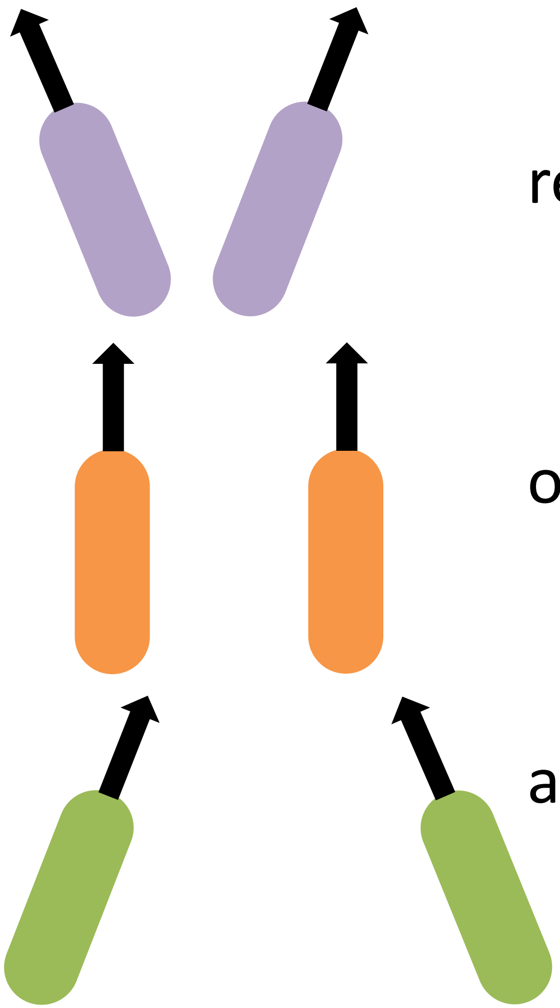
Model:

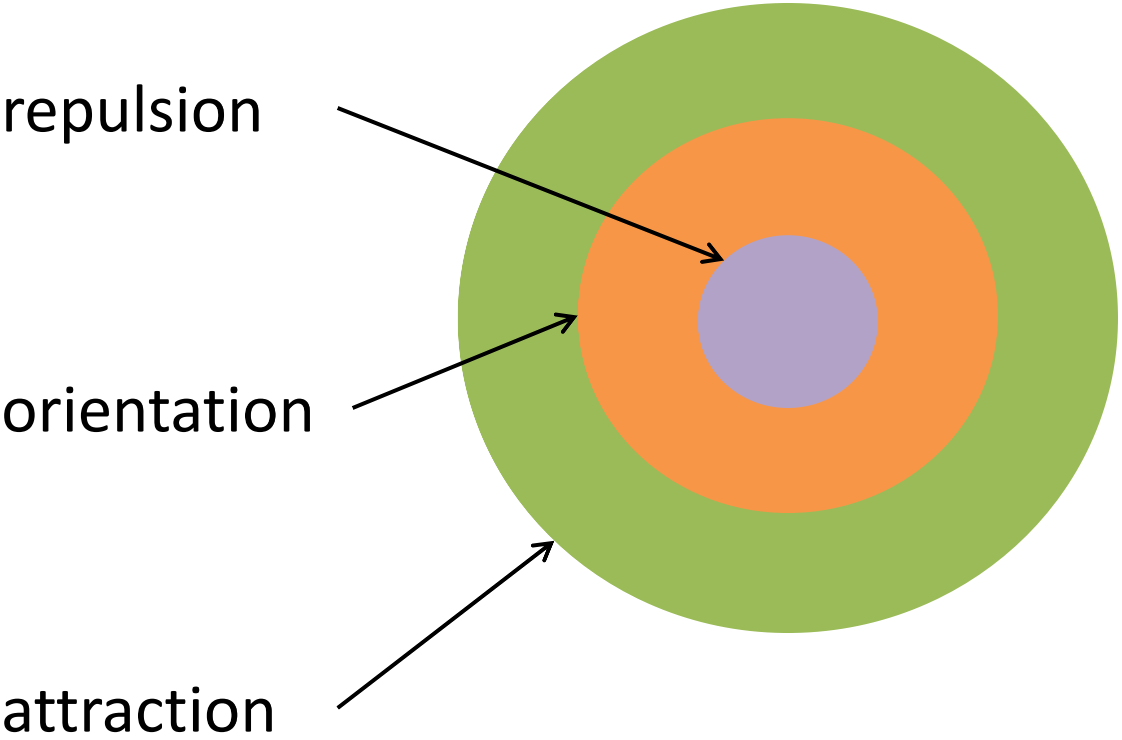
The angle depends on the temporal gradient



Modeling Swarms

Simple interactions

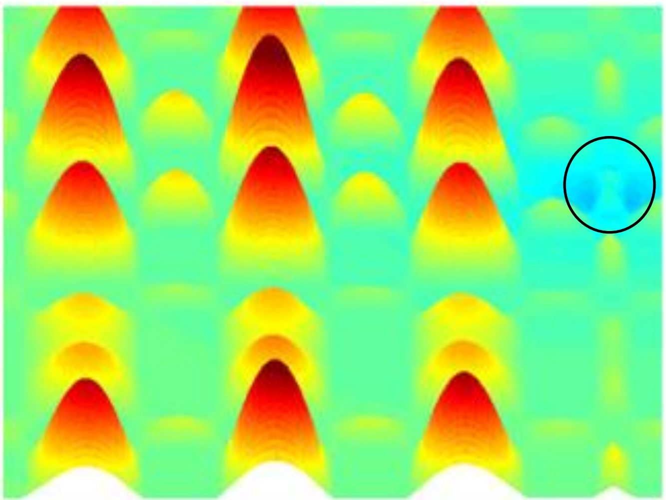




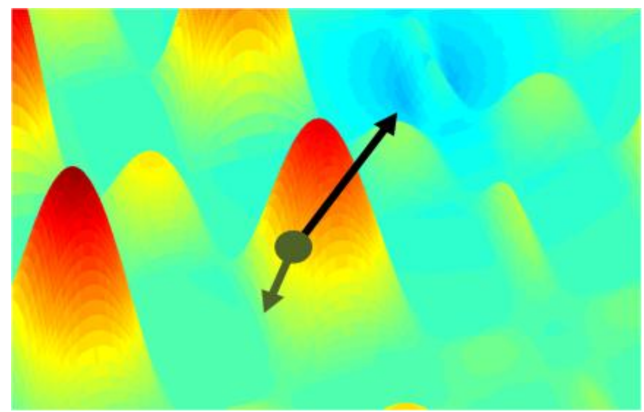
[Vicsek *et al.* 1995, Grunbaum 1998, Couzin *et al.* 2005]

Navigation in complex terrain

The environment is constant in time and spatially noisy

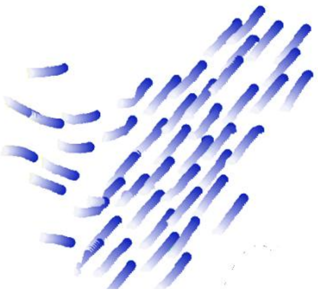


$$\cos(\omega_1 x + \varphi_1) \cdot \cos(\omega_2 x + \varphi_2)$$



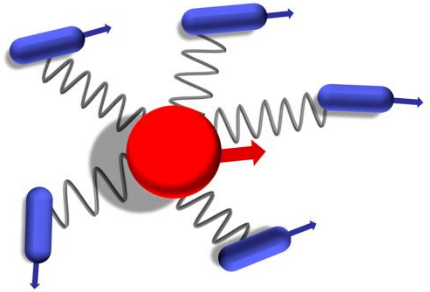
Bacteria-Inspired Models

- Adaptable Interactions



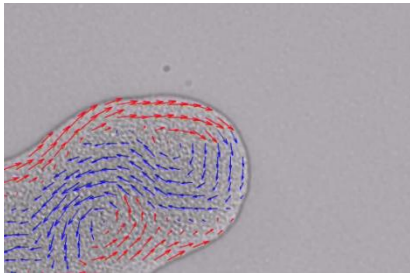
[Shklarsh el al. 2011, Plos Computational Biology]
Elad Schneidman, Gil Ariel, Eshel Ben-Jacob

- Cargo Carrying Swarms



[Shklarsh el al. 2012, Interface Focus]
Alin Finkelshtein, Gil Ariel, Oren Kalisman, Colin Ingham, Eshel Ben-Jacob

- Collective Dynamics



Gil Ariel, Adi Shklarsh, Oren Kalisman, Colin Ingham, Eshel Ben-Jacob

Modeling Bacteria Swarms

positions: $\vec{r}_i(t)$
velocity directions: $\vec{v}_i(t)$, $|\vec{v}_i(t)|=1$

run

$$\vec{v}_i(t+\Delta t)=\vec{d}_i(t)+w\cdot\vec{v}_i(t)$$

velocity direction

group influence

weight

previous velocity direction

$$\vec{d}_i(t)=-\sum_{j\in RR_i(t)} \frac{\vec{r}_j\, t)-\vec{r}_i(t)}{|\vec{r}_j(t)-\vec{r}_i(t)|}$$

repulsion

or

$$\vec{d}_i(t) = \sum_{j\in RO_i(t)} \vec{v}_j(t) \quad + \quad \sum_{j\in RA_i(t)} \frac{\vec{r}_j(t)-\vec{r}_i(t)}{|\vec{r}_j(t)-\vec{r}_i(t)|}$$

orientation attraction

Modeling Bacteria Swarms

positions: $\vec{r}_i(t)$
velocity directions: $\vec{v}_i(t)$, $|\vec{v}_i(t)|=1$
chemical concentration: $c(x)$

run

$$\vec{v}_i(t+\Delta t)=\vec{d}_i(t)+w\cdot\vec{v}_i(t)$$

velocity direction

group influence

weight

previous velocity direction

tumble

$$\text{gaussian noise}(c(\vec{r}(t))-c(\vec{r}(t-\tau)))$$

constant measurement interval

Adaptable interactions

$$\vec{v}_i(t+\Delta t)=\vec{d}_i(t)+w_i(t)\cdot\vec{v}_i(t)$$

adaptable weights

$$w_i(t)=\begin{cases} 1 & \text{sign}(grad_i)>0 \\ 0 & \text{else} \end{cases}$$

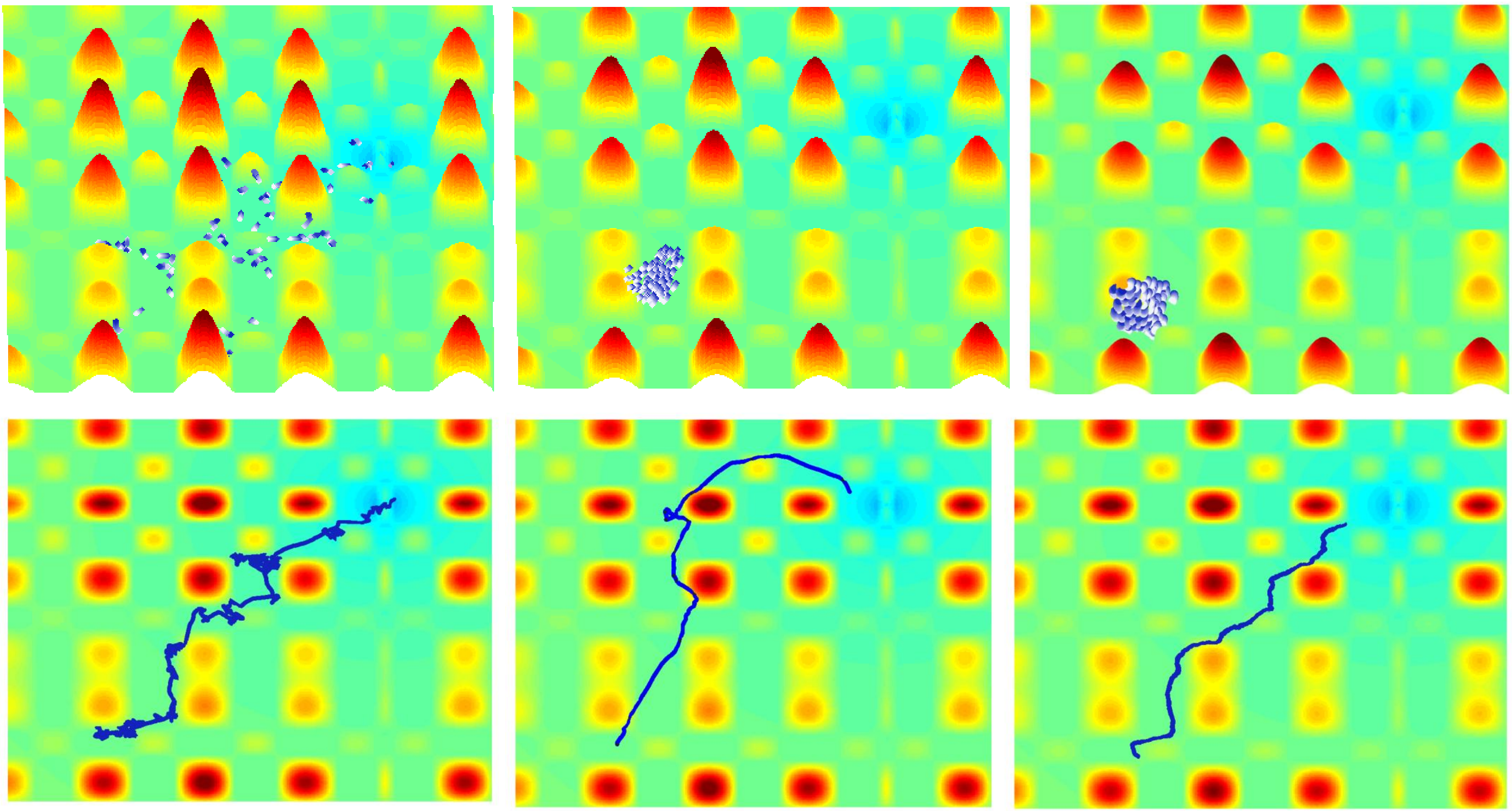
We consider adaptable interactions as a biologically-inspired design principle that will dynamically modify the behavior of the system in response to changes in the environment.

Simulations

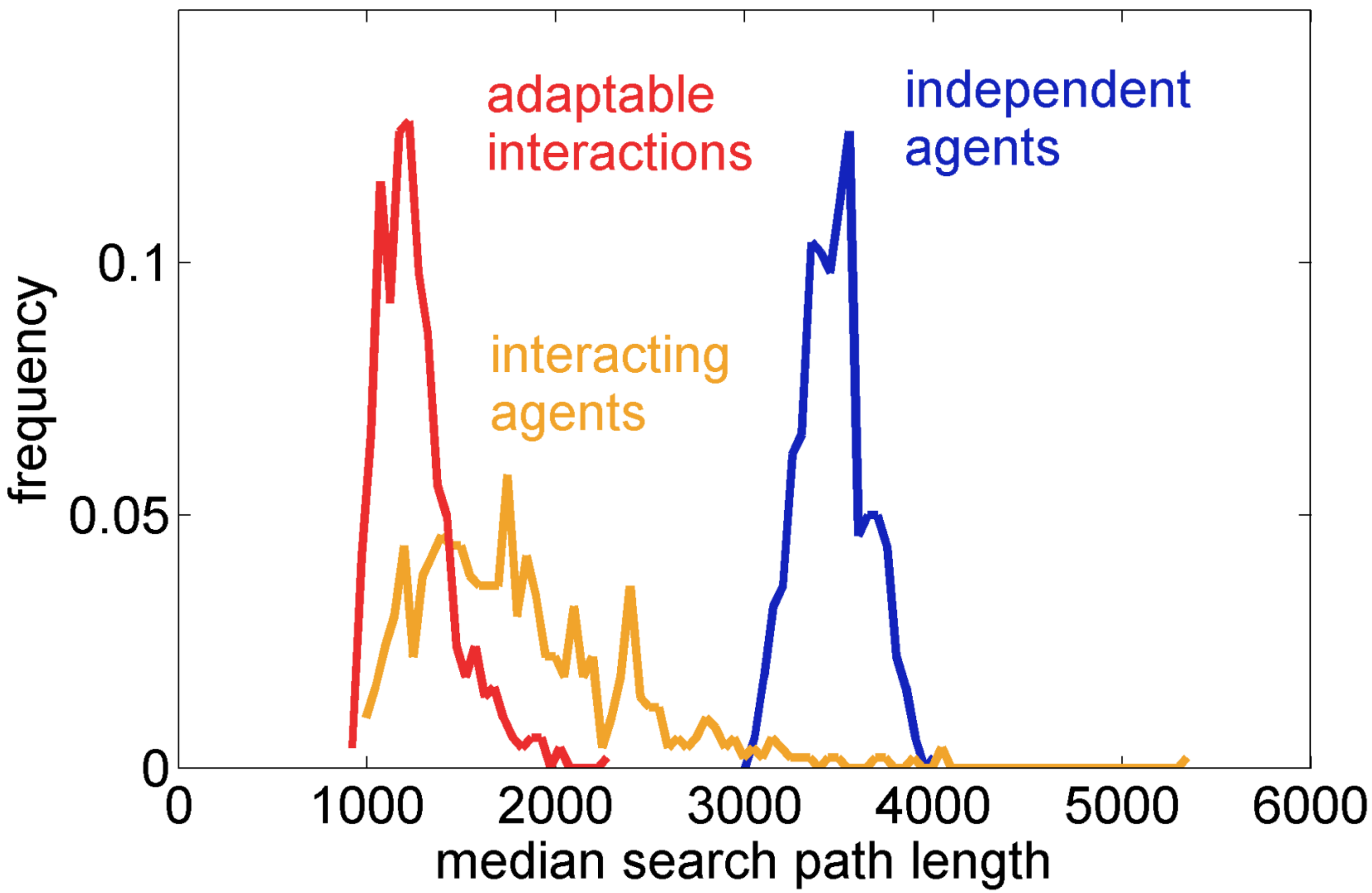
independent agents

interacting agents

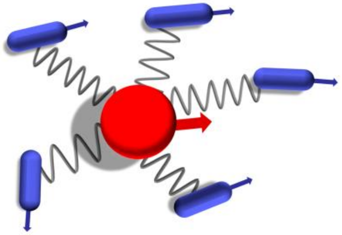
adaptable interactions

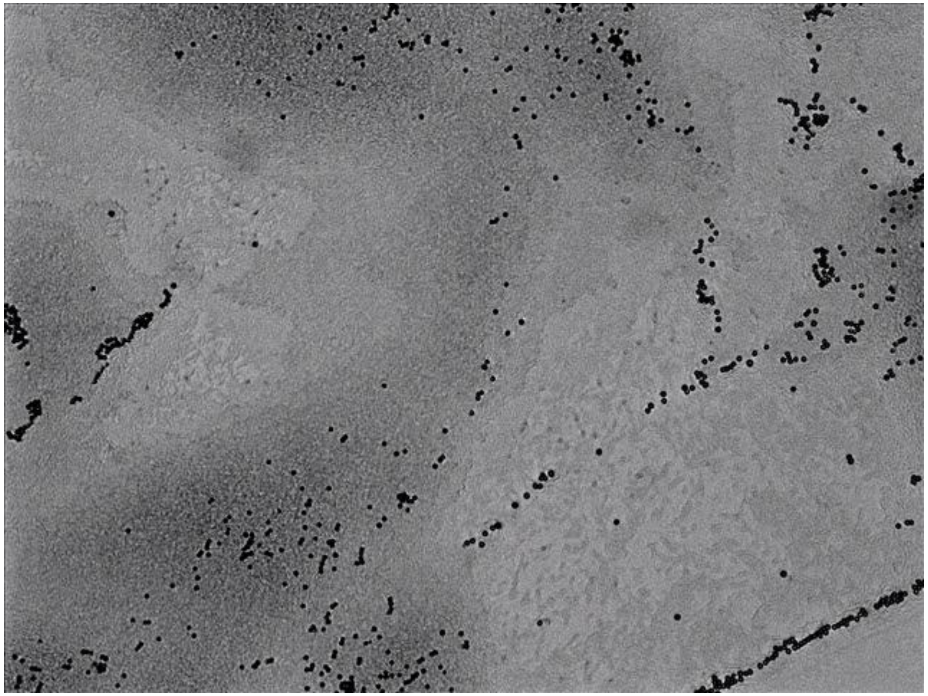


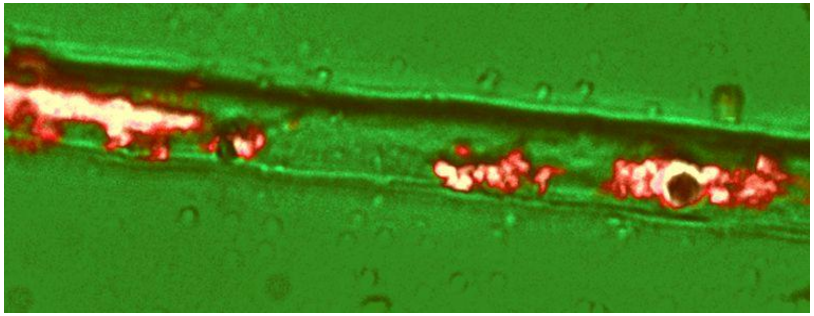
Distribution of search paths



Cargo Carrying Swarms

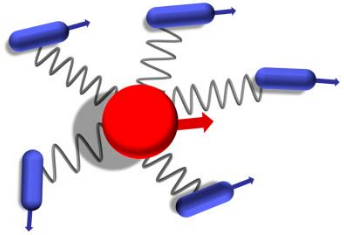




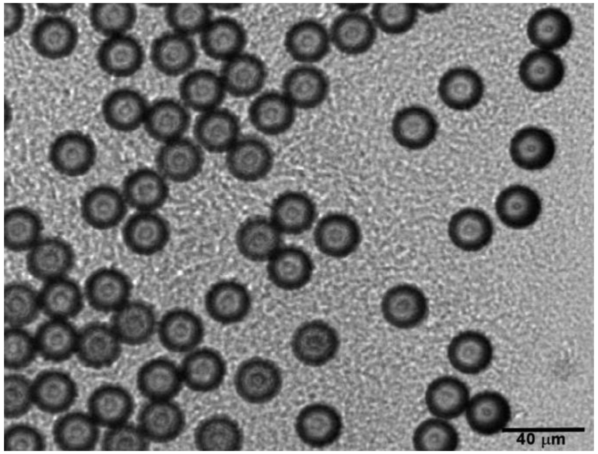


[Ingham *et al.* 2011, PNAS]

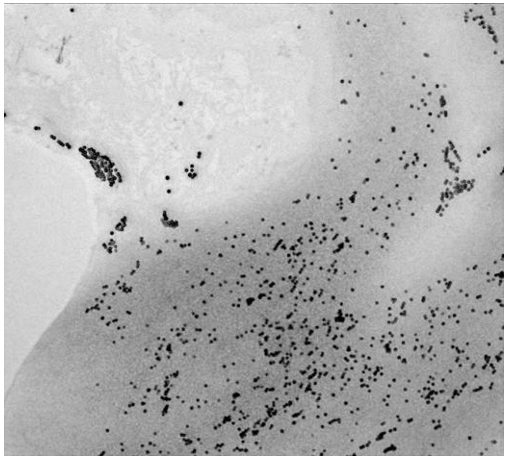
Cargo Carrying Swarms



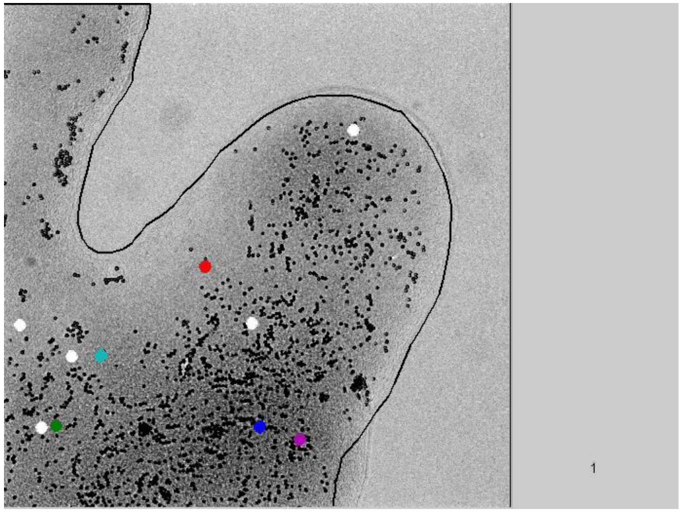
Beads



Conidia

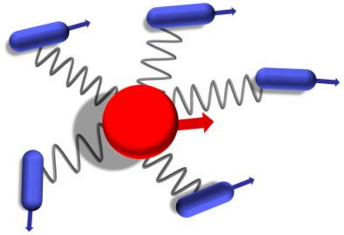


Bacteria swarms carry cargo and react to external forces

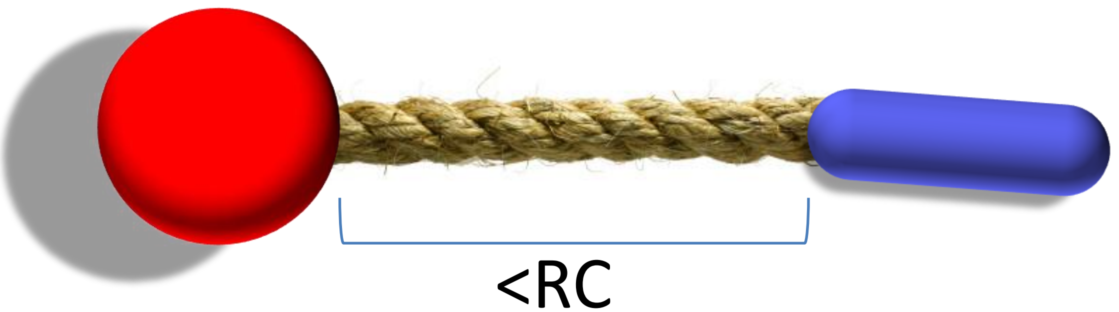


[Ingham *et al.* 2011, PNAS]

Cargo Carrying Swarms



Rope Model:



$$\vec{v}_c(t+\Delta t)=\sum_{i\in RC_c(t)} \vec{b}_{ic}(t)\cdot k+w\cdot\vec{v}_c(t)$$

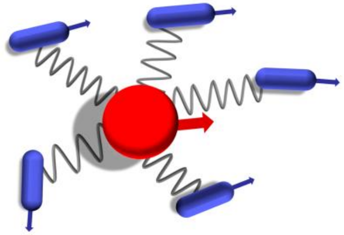
agent-cargo bond

previous velocity direction

velocity direction

constant force

Cargo Carrying Swarms



Rope Model:

$$\vec{v}_i(t+\Delta t) = d_i(t) + \vec{b}_{ci}(t) \cdot k + w \cdot \vec{v}_i(t)$$

group influence

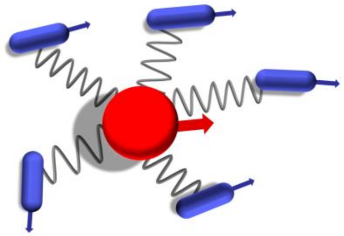
agent-cargo bond

previous velocity direction

velocity direction

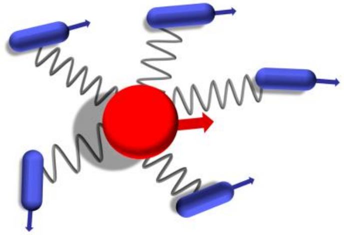
constant force

Cargo Carrying Swarms

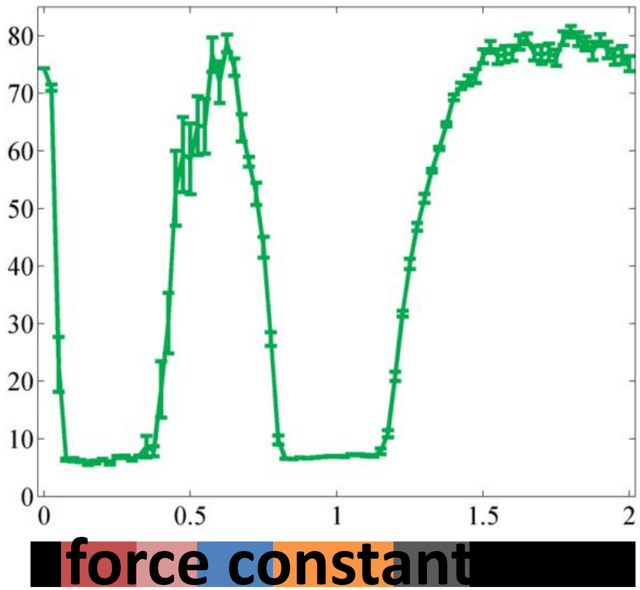


Simulation of the rope model

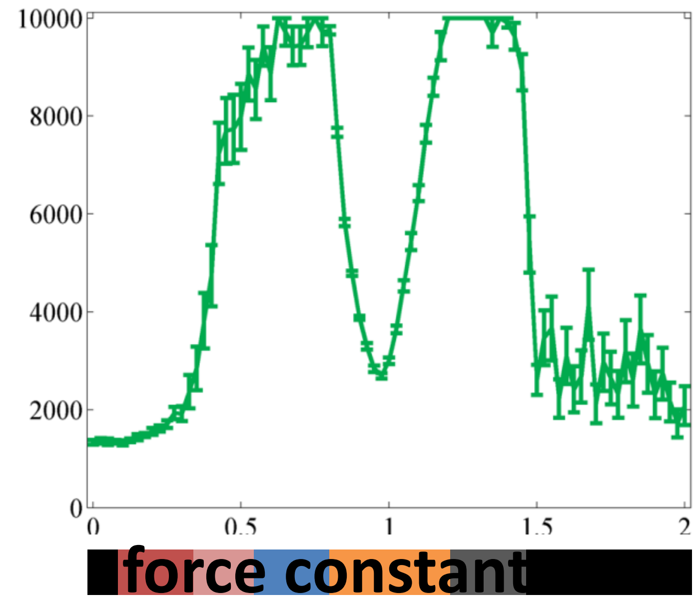
Cargo Carrying Swarms



Cargo distance from target



Group path length



cargo drops

successful aligned group

group splits

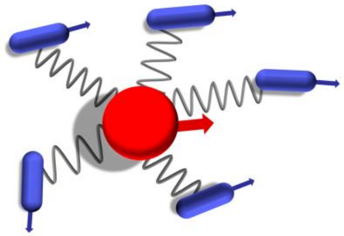
Splitting cohesive unaligned static group

successful unaligned groups

cohesive unaligned static group

cargo drops

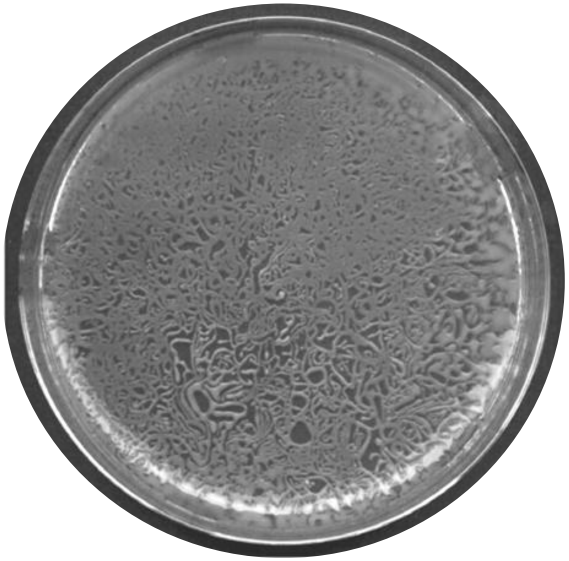
Cargo Carrying Swarms

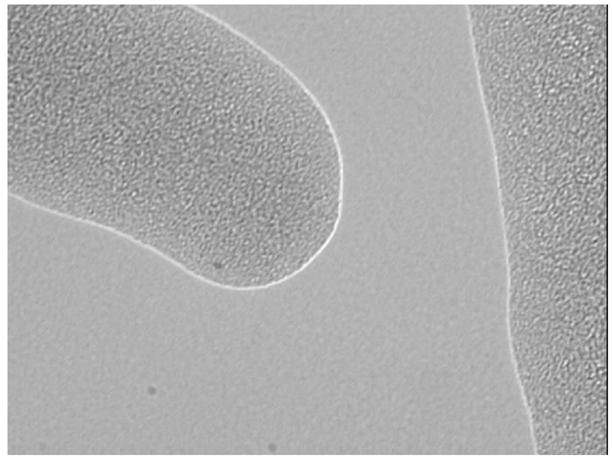


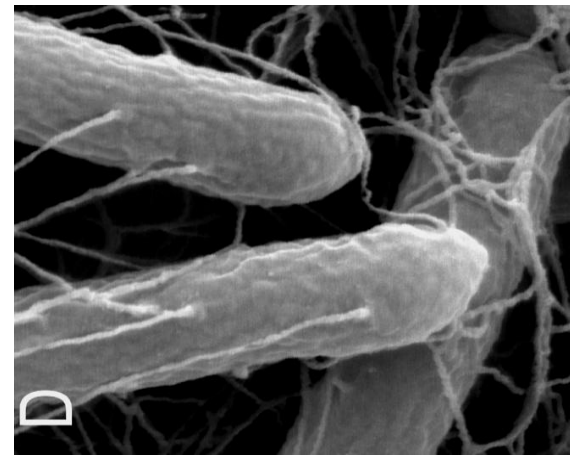
Simulation of the extended model

Lubricating fluid edge is modeled as a discrete dual phase field
Edge blocks motion of agents
Enough close agents move the edge

Bacteria movement dynamics



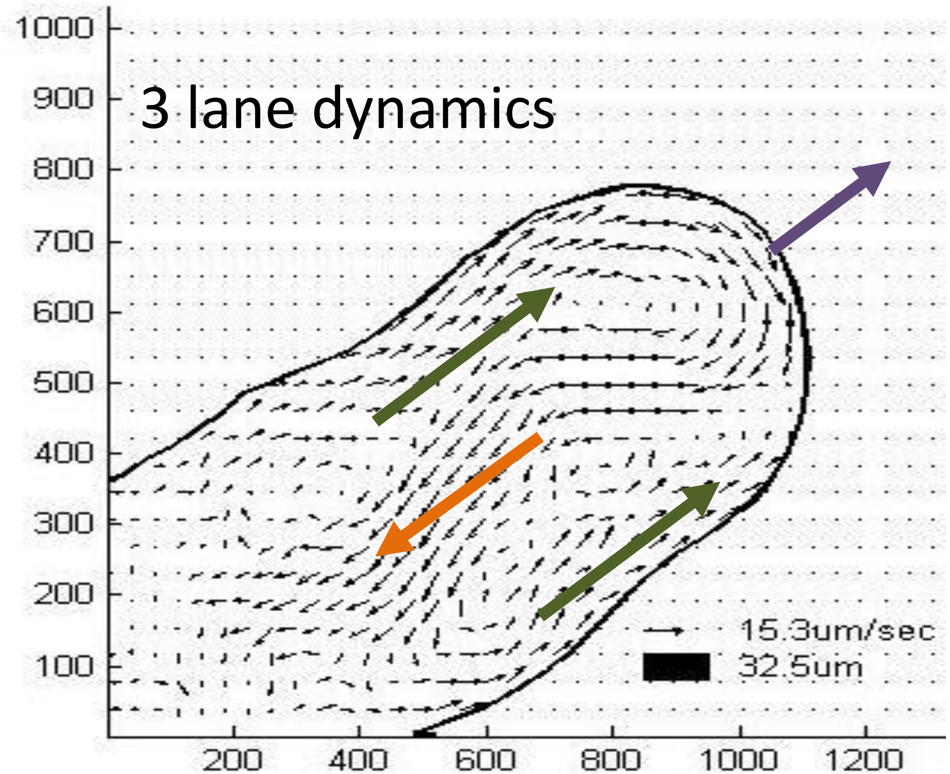




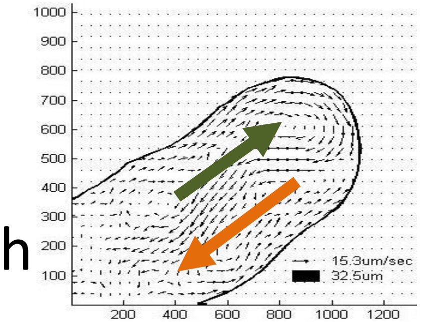
Intermediate level: movement dynamics of a group of lubricating bacteria in an envelope

[pictures by Ingham and Ben-Jacob]

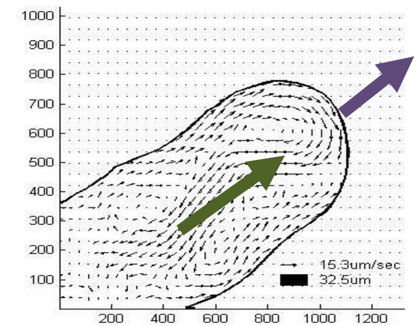
Bacteria dynamics in a branch



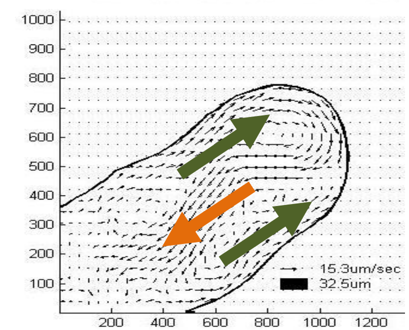
2 lane dynamics – static branch



1 lane dynamics



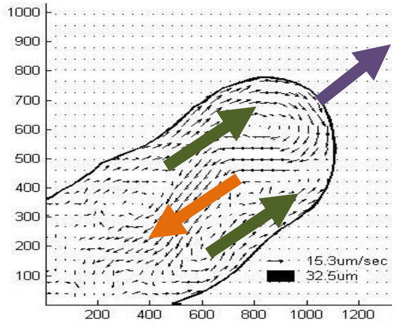
complex motion



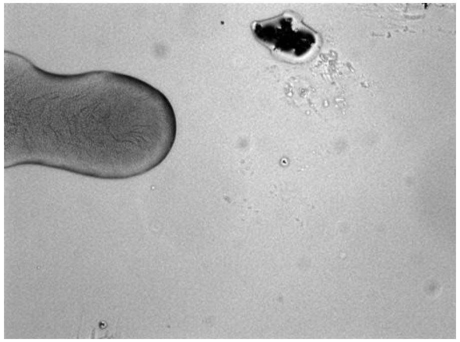
$$v_{branch} \approx \frac{3}{4} \cdot v_{bacteria}$$

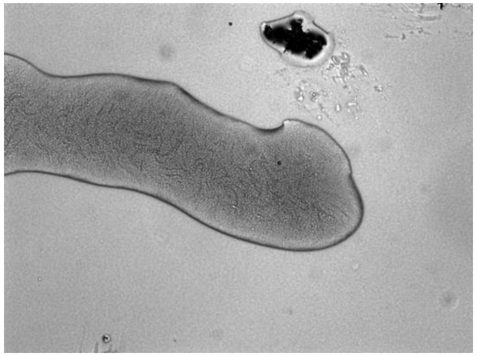
constant branch width

3 lane dynamics

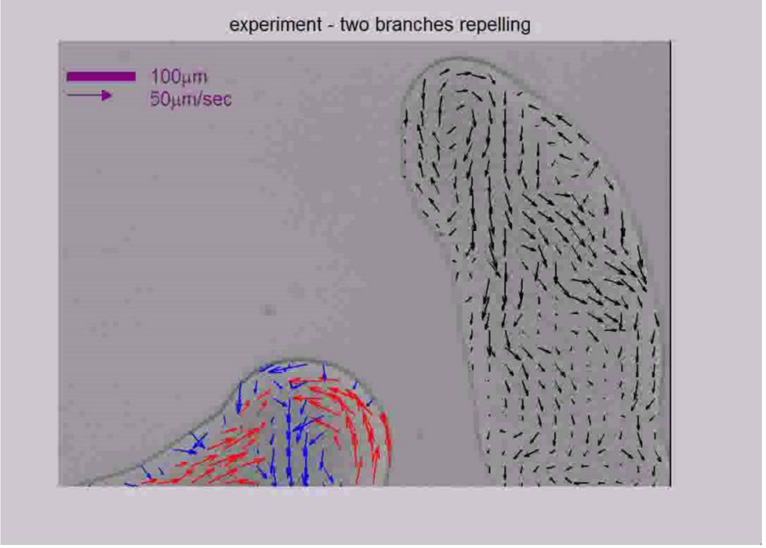


collective chemotaxis





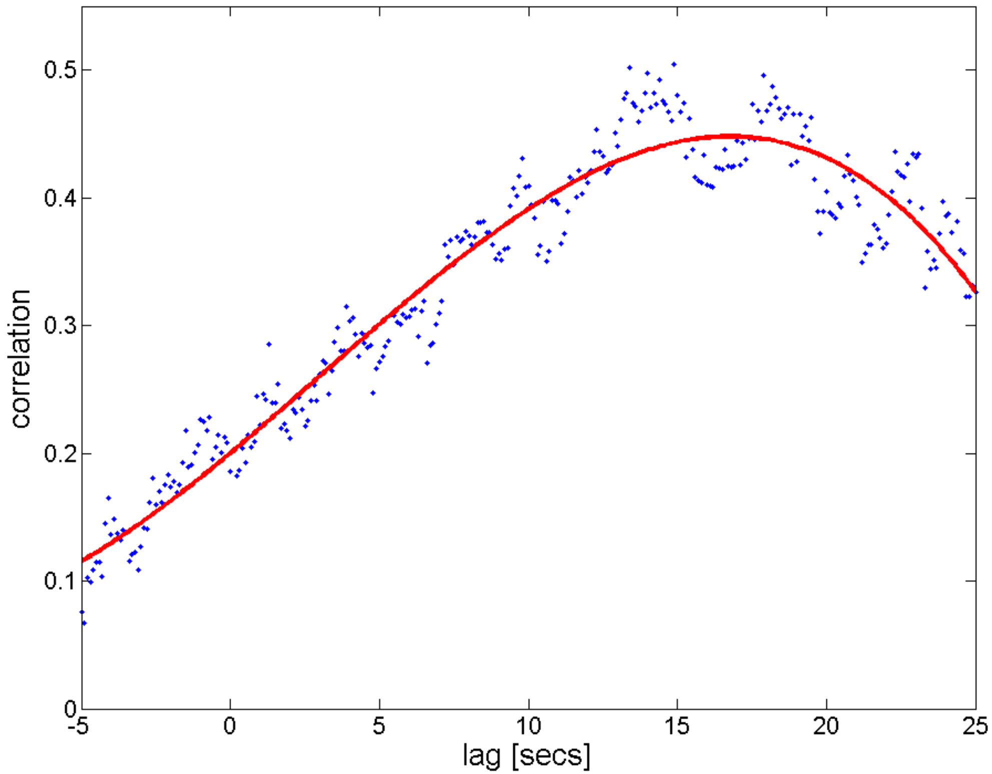
branch repulsion



[movie by Gil Ariel]

Group navigation by collective organization

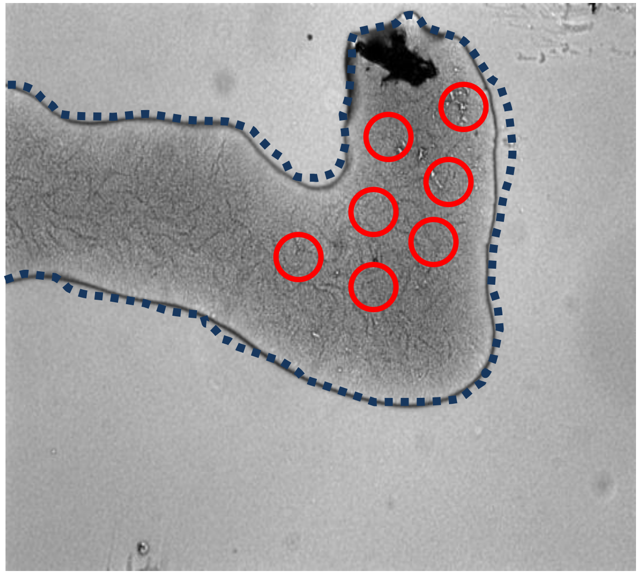
The point of return predicts the direction

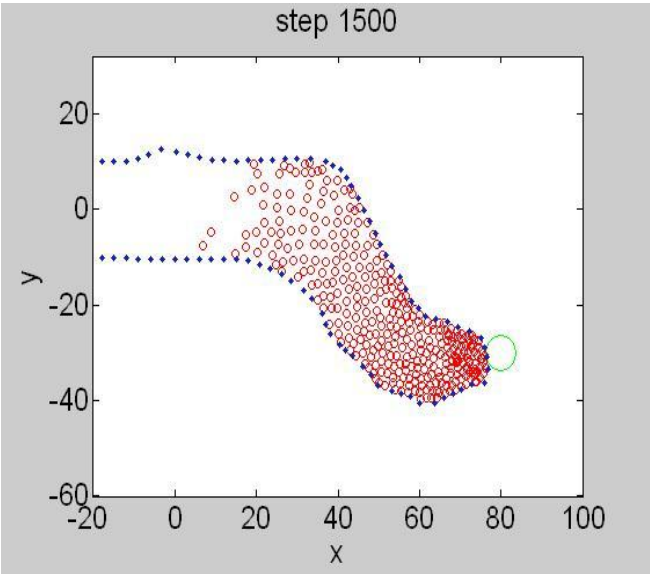


[figure by Gil Ariel]

Modeling branch dynamics

Identifying the key mechanisms underlying the dynamics



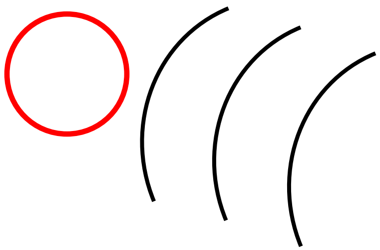


represents local cluster of bacteria -

coarse graining of bacteria branch

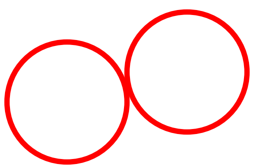
a dynamic boundary represents lubricating fluid limit

Self propelled agents



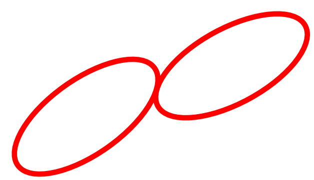
acceleration depends

on attractant

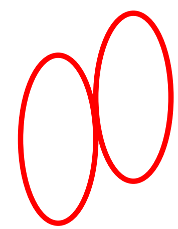


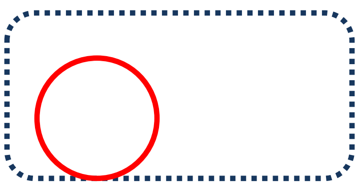
agent-agent
interactions

Inelastic
collisions



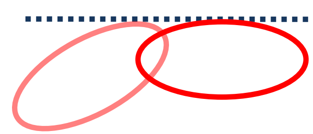
orientations



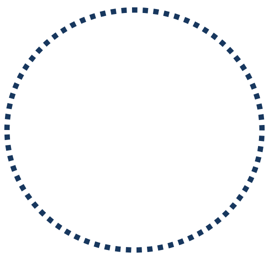


agent-envelope
interactions

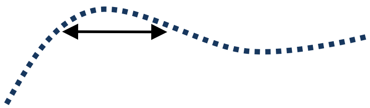
alignment

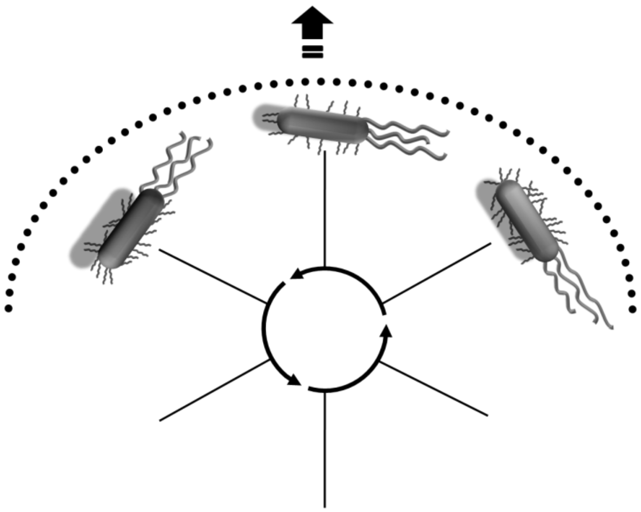


Dynamic envelope



surface
tension



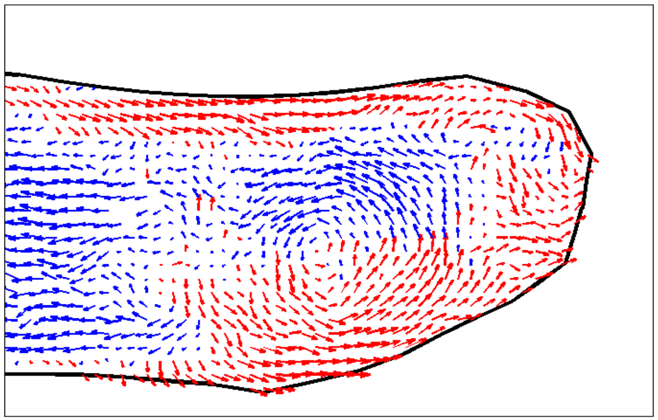


A phenomenological expression to the speed of the boundary

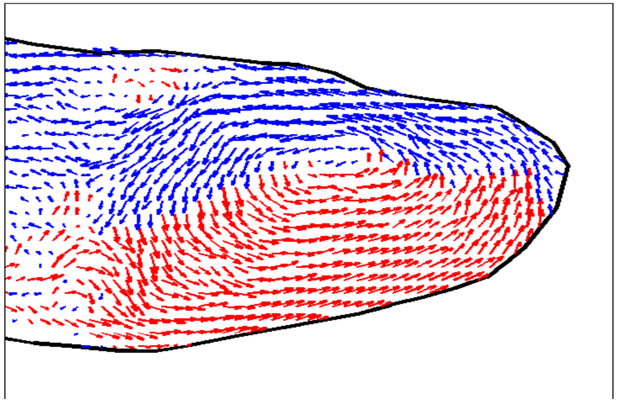
$$\frac{d\gamma_n(s)}{dt} \simeq \hat{v}_i \times v_i \times \nabla n$$

Simulation

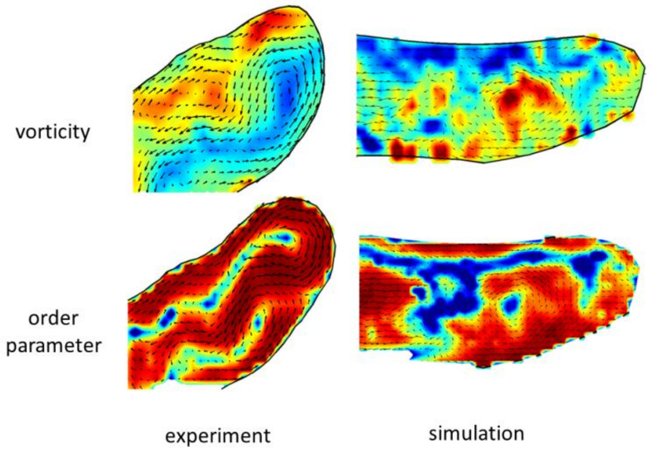
Moving branch with three lanes



Static branch with two lanes



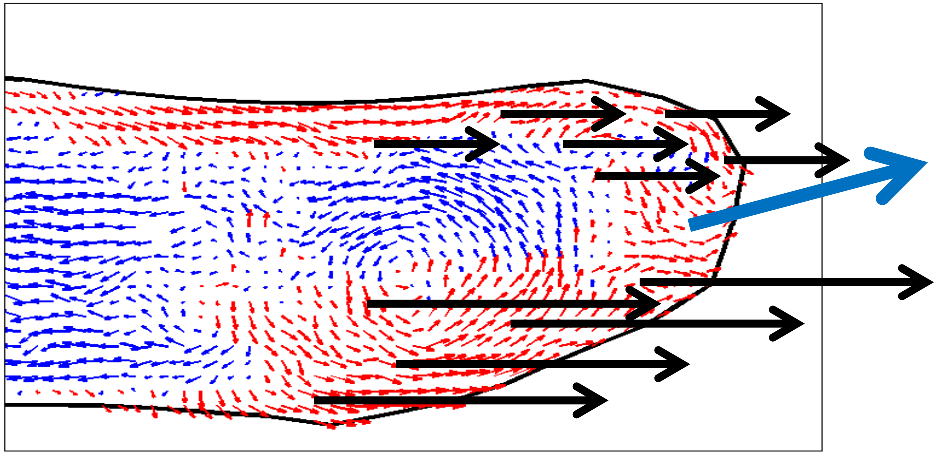
Agreement with experiments – velocity, vorticity, and order parameter



How can local interaction rules control the direction of the branch?

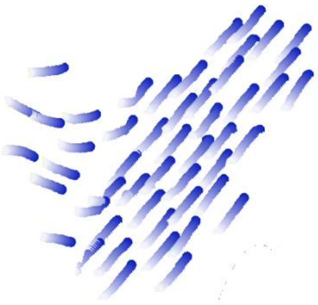
agents which become closer to the food source increase their speed

An uneven accumulation of cells on the side of the branch tip closer to the food source results in shifting of the tip to the other side

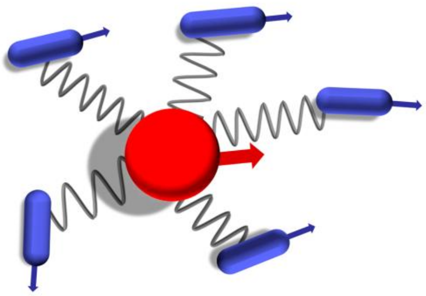


Summary

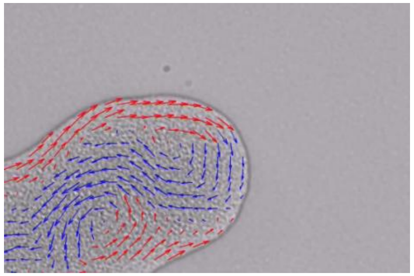
- Adaptable interactions improve efficiency in a navigation task



- Complex behavior in cargo carrying swarms



- Navigation by self organization in bacteria branches



Links:

- https://sites.google.com/site/adishklarsh/
- "Smart Swarms of Bacteria-Inspired Agents with Performance Adaptable Interactions"
Shklarsh *et al.* PLoS Computational Biology
- "Collective Navigation of Cargo-Carrying Swarms"
Shklarsh *et al.* Interface Focus