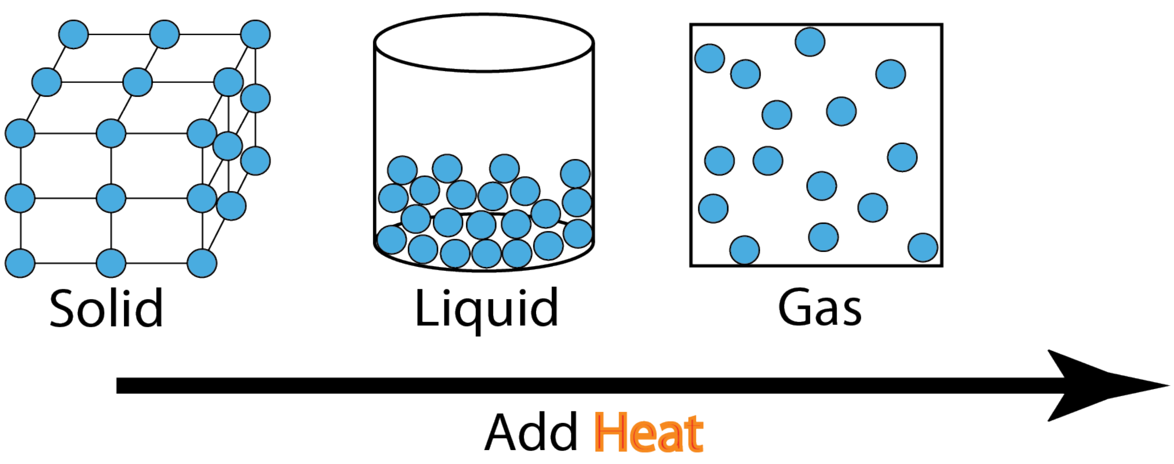
Active Soft Matter

or

the physics of flocking, swarming, crawling, swirling, crowding, and more

What are the **physical principles** that govern the organization of individually driven entities in coordinated motion and function?

States of Matter

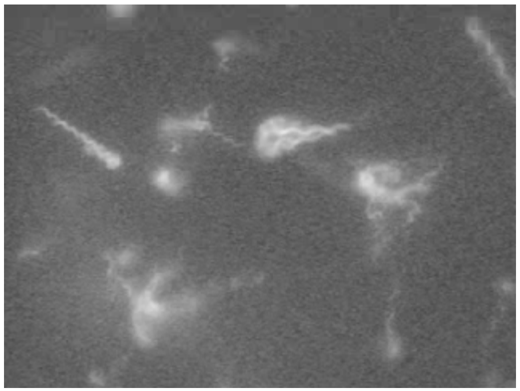


Collectives of interacting, self-propelling entities: bacteria, cells, synthetic swimmers, birds,…
→ Can we think of them as a new kind of `Active Matter'?

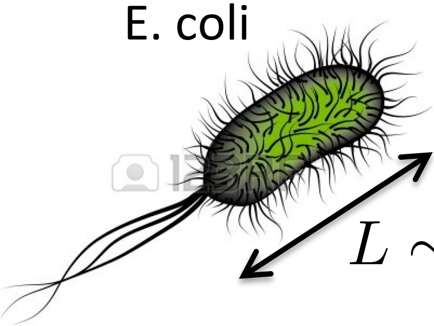
- ❑ What new states are possible and what are their properties?
- ❑ What do we tune to change from one state to another?

Bacteria

One

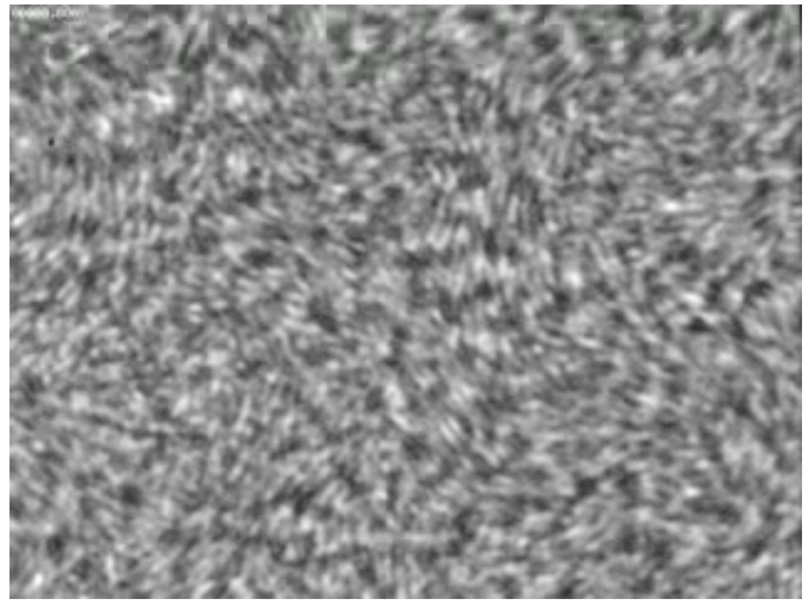


$$\text{speed} \sim 10\mu m/sec$$

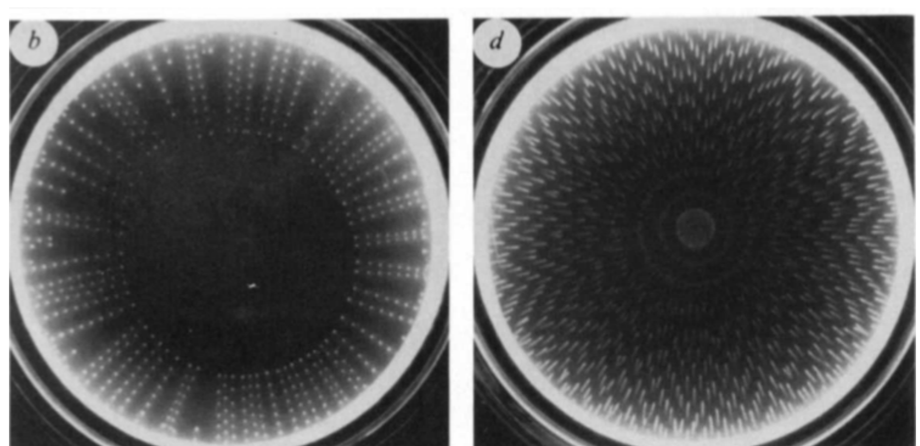


Berg Lab,
Harvard U.

Many: ``turbulent'' fluid

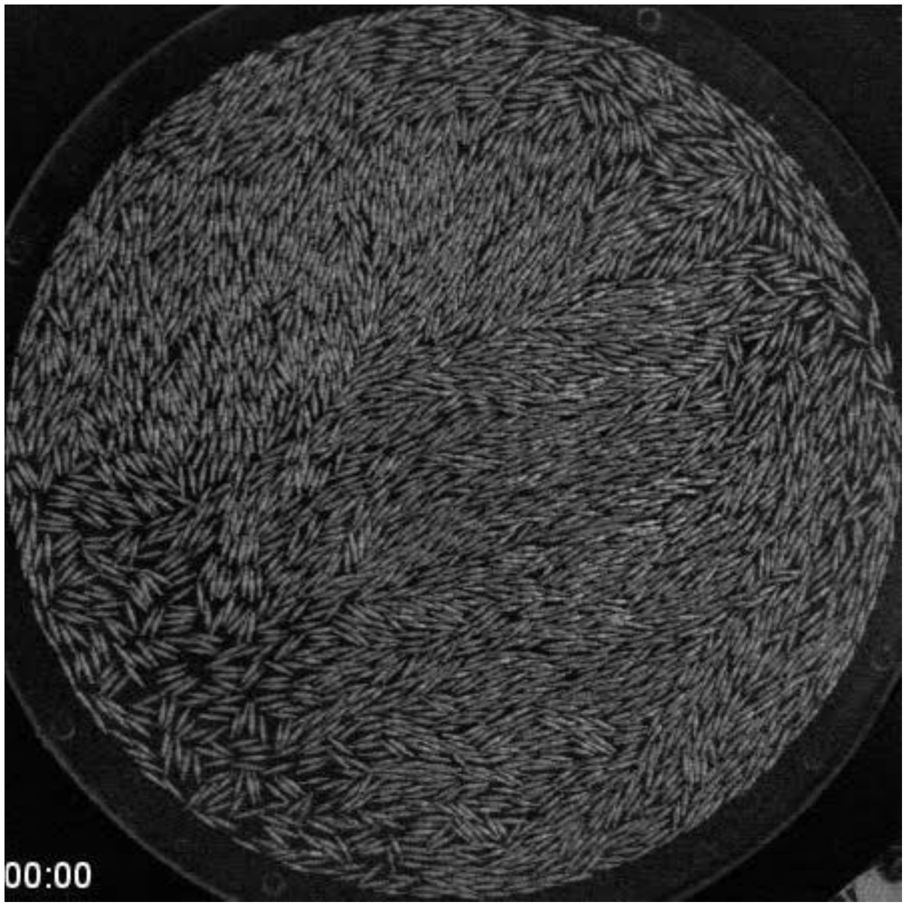


also complex patterns



Layer of rods on a vertically vibrated surface

13cm

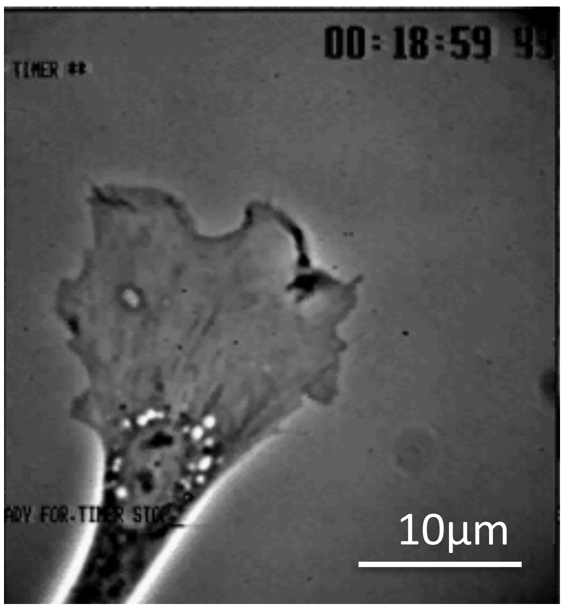


2820 rods
L=5mm

Narayan et al Science 2007,
IISc Bangalore, India

Cells

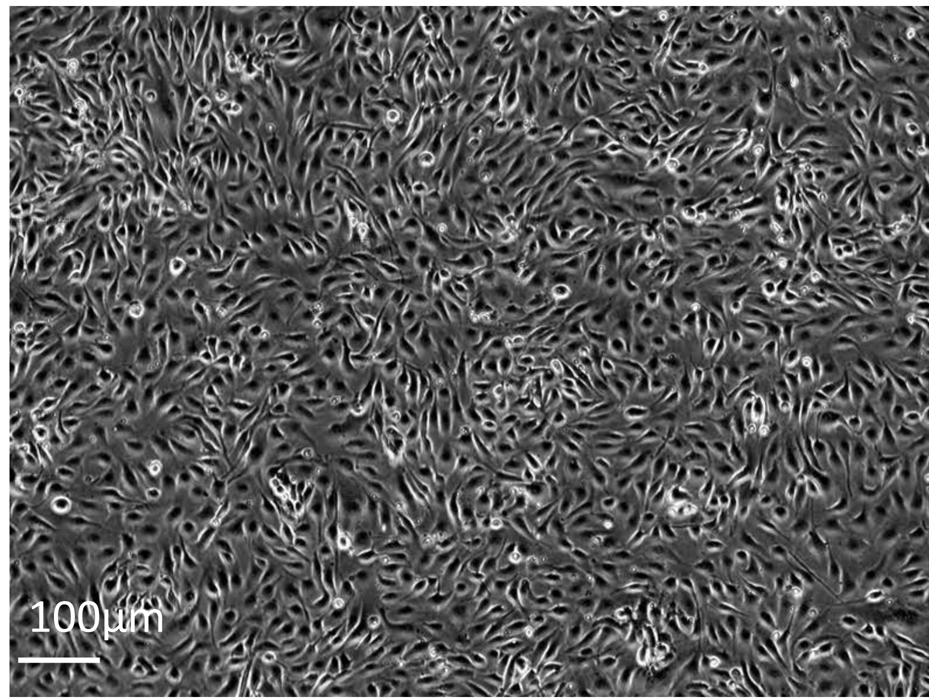
Individual cell



chick fibroblasts (2h)

Small Lab
Vienna

Tissue: liquid or solid?



Endothelial cells v=35µm/h

Czirok, 2010
U. Kansas

Starlings in a flock move in unison like a fluid

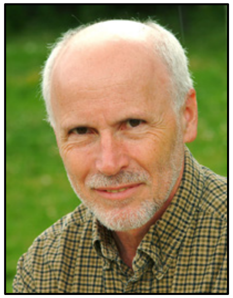
STARFLAG Collaboration, Rome

200-50,000 starlings

How can physics help understand this complex organization?

Three examples:

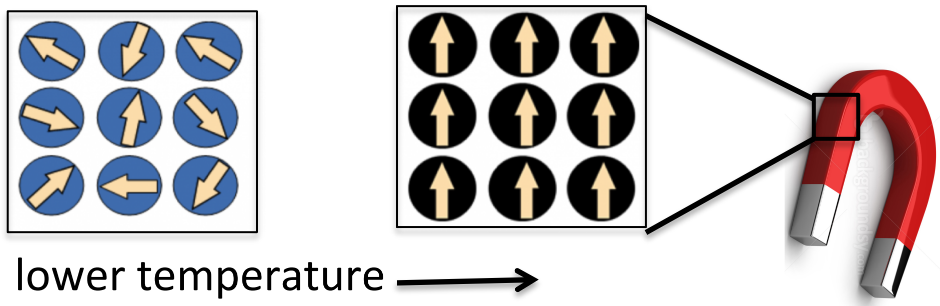
- Vicsek model of flocking
- Inside the cell: active liquid crystals
- The peculiar properties of an active gas



Vicsek Model of Flocking

T. Vicsek et al, 1995; C. Reynolds, SIGGRAPH '87 Conference Proc.

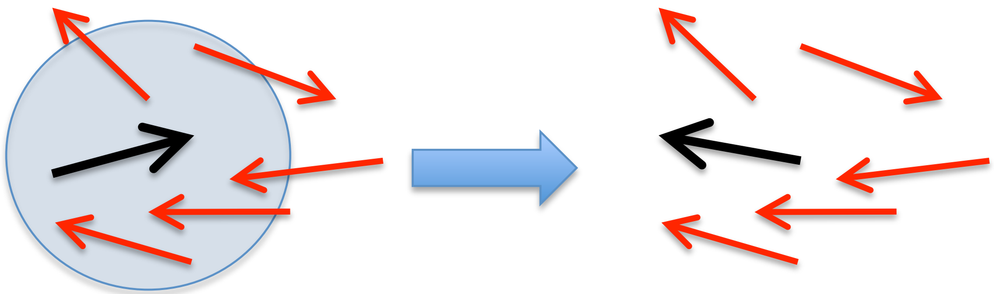
Inspired by magnetism



Bird modeled as a ``magnet'' flying at speed v_0

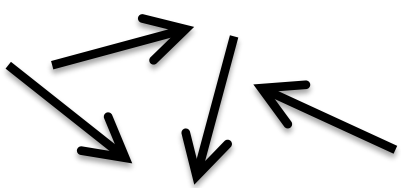
What are the interaction rules?

- At every step, each bird aligns with neighbors contained within a circle of fixed radius

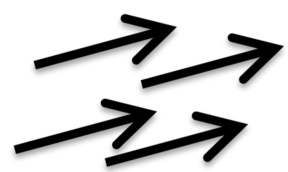


- Birds make mistakes → noise like a ``temperature''

large mistakes/noise
disordered state



small mistakes/noise
ordered state

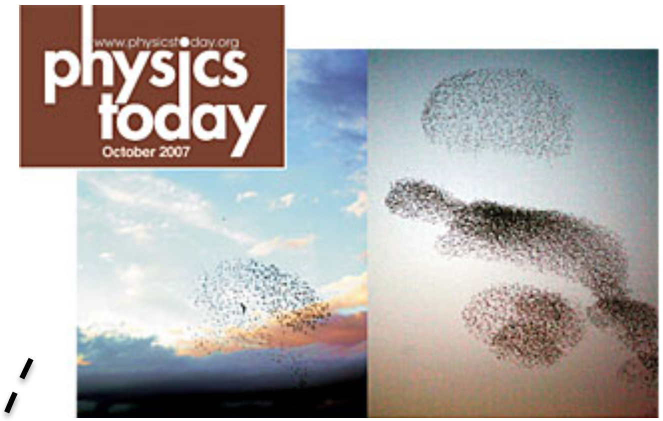


http://www.stthomas.edu/physics/research/Computation/vicsek.html

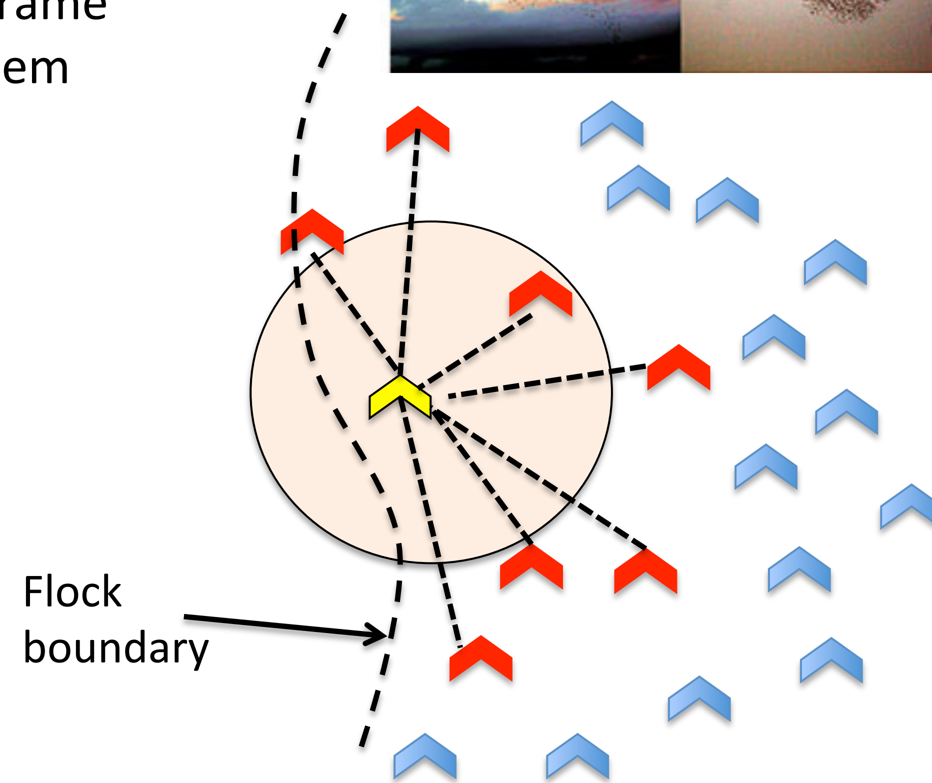
Flocks of Starlings → a surprise

Rome-based STARFLAG collaboration collected 3-dim data on flocks of 200-50,000 starlings.

Challenge: track birds from one frame to the next → optimization problem



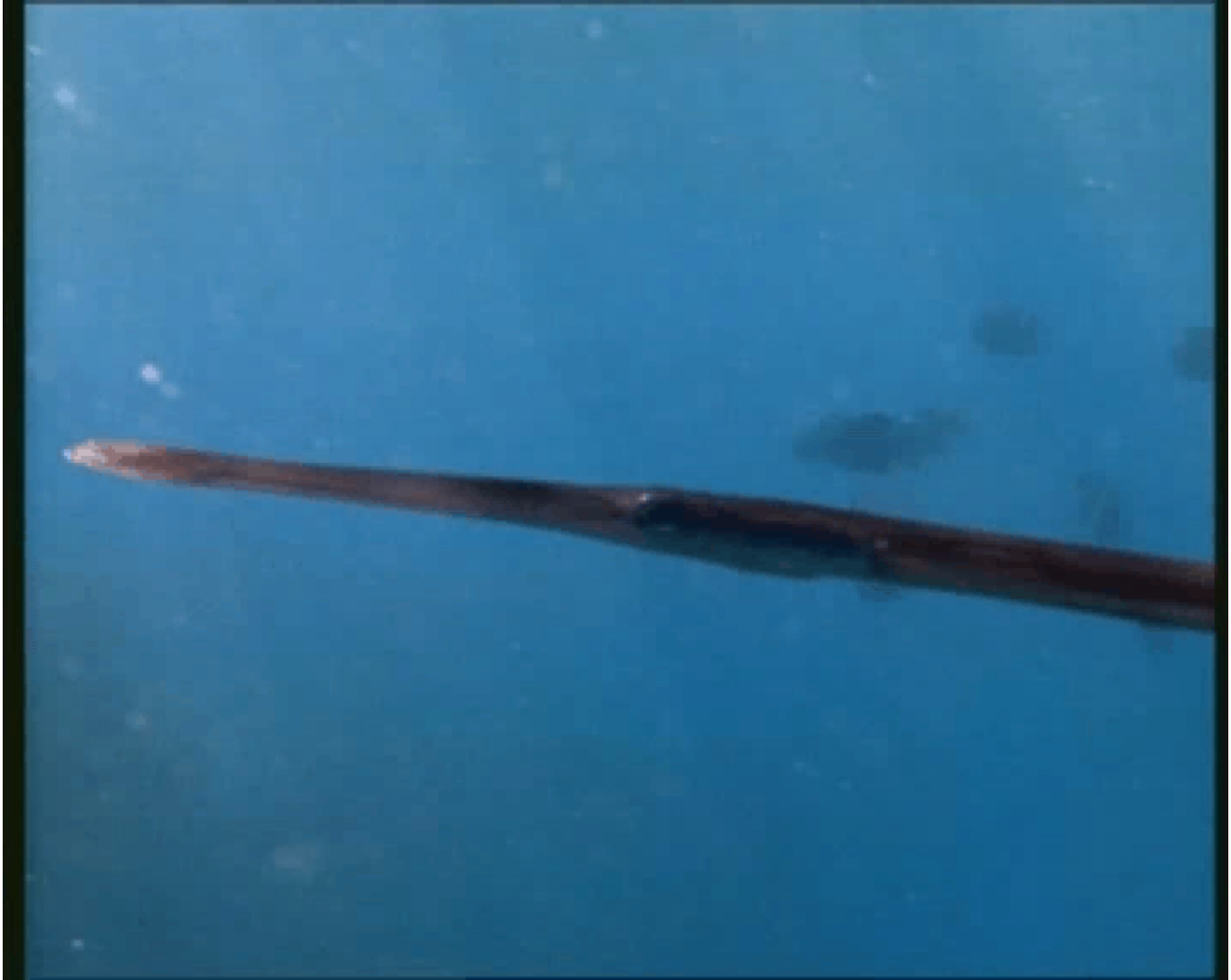
Each bird interacts not with birds at a fixed distance, but with 6-7 closest neighbors



Interaction with fixed # neighbors matters when the density changes, e.g. under attack.

→ Provides robustness to the flock

Next slide: video by Iain Couzin, Princeton

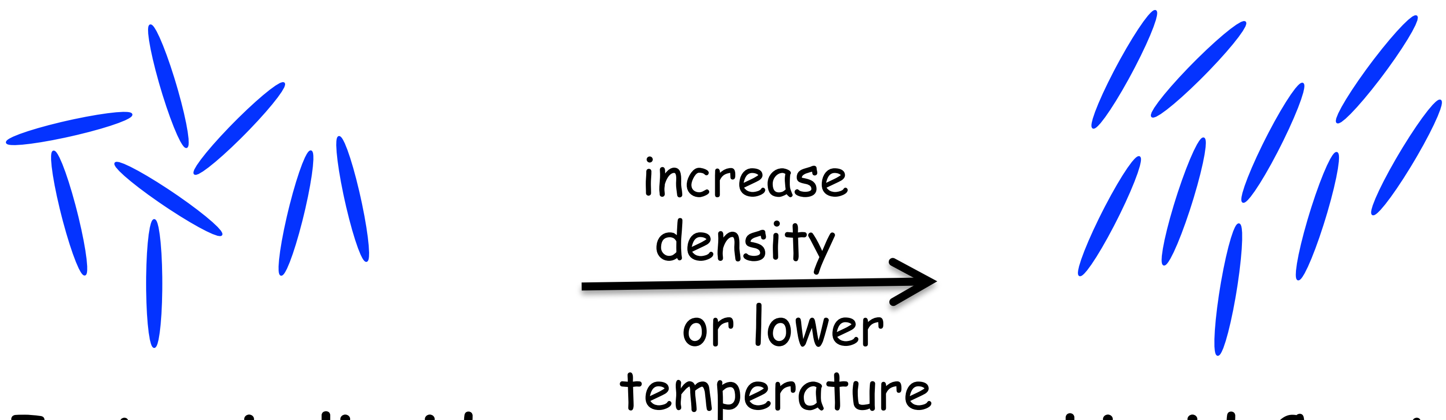


Inside the cell:

Active Liquid Crystals

Liquid Crystals

A liquid or rod-like molecules that order upon increasing density or decreasing temperature



Isotropic liquid **Liquid Crystal**

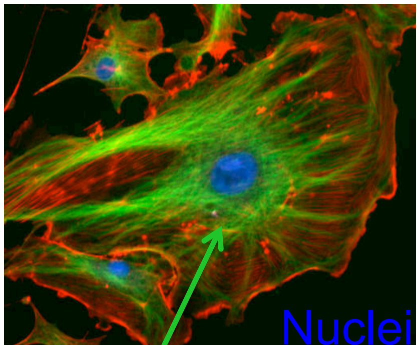
Order is never perfect

Kemi River,
Finland, 1949

Topological
defects

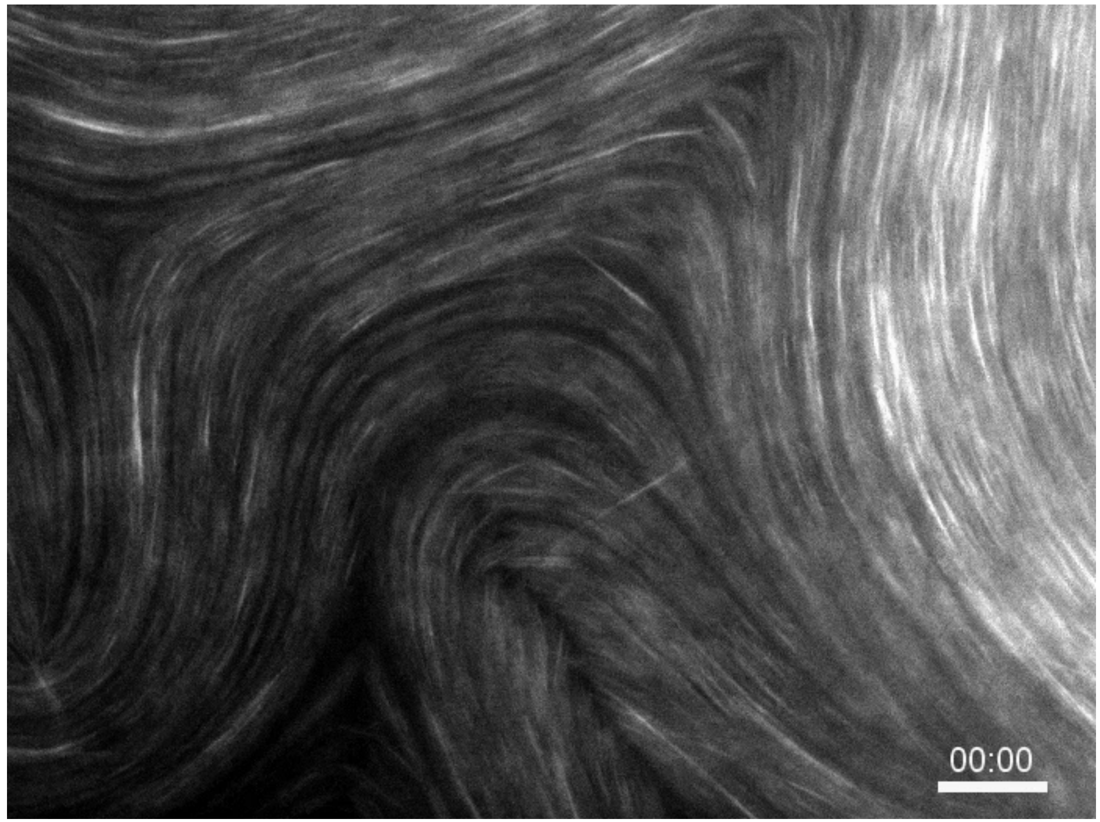
An Active Liquid Crystal

built from polymer and proteins extracted from living cells

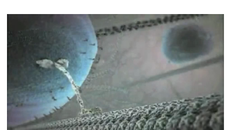


Microtubules
+ motor proteins
+ chemical ``fuel''

Motor proteins are molecular machines that transform chemical energy into mechanical work to remodel the polymer network

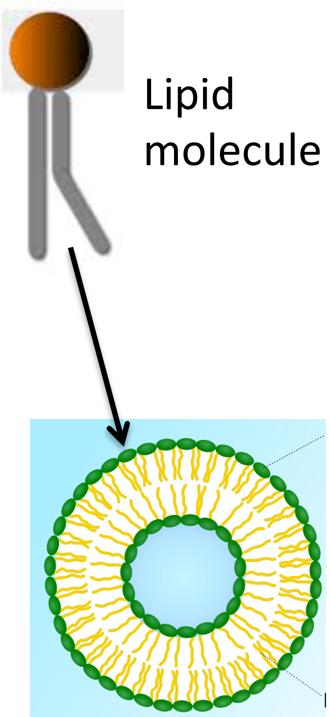


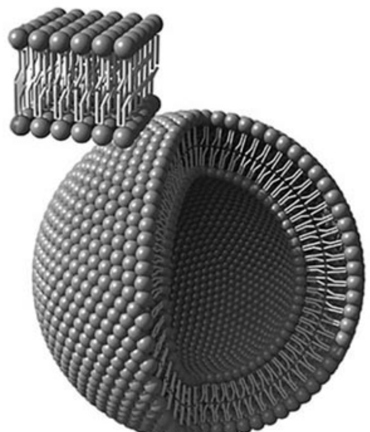
45µm

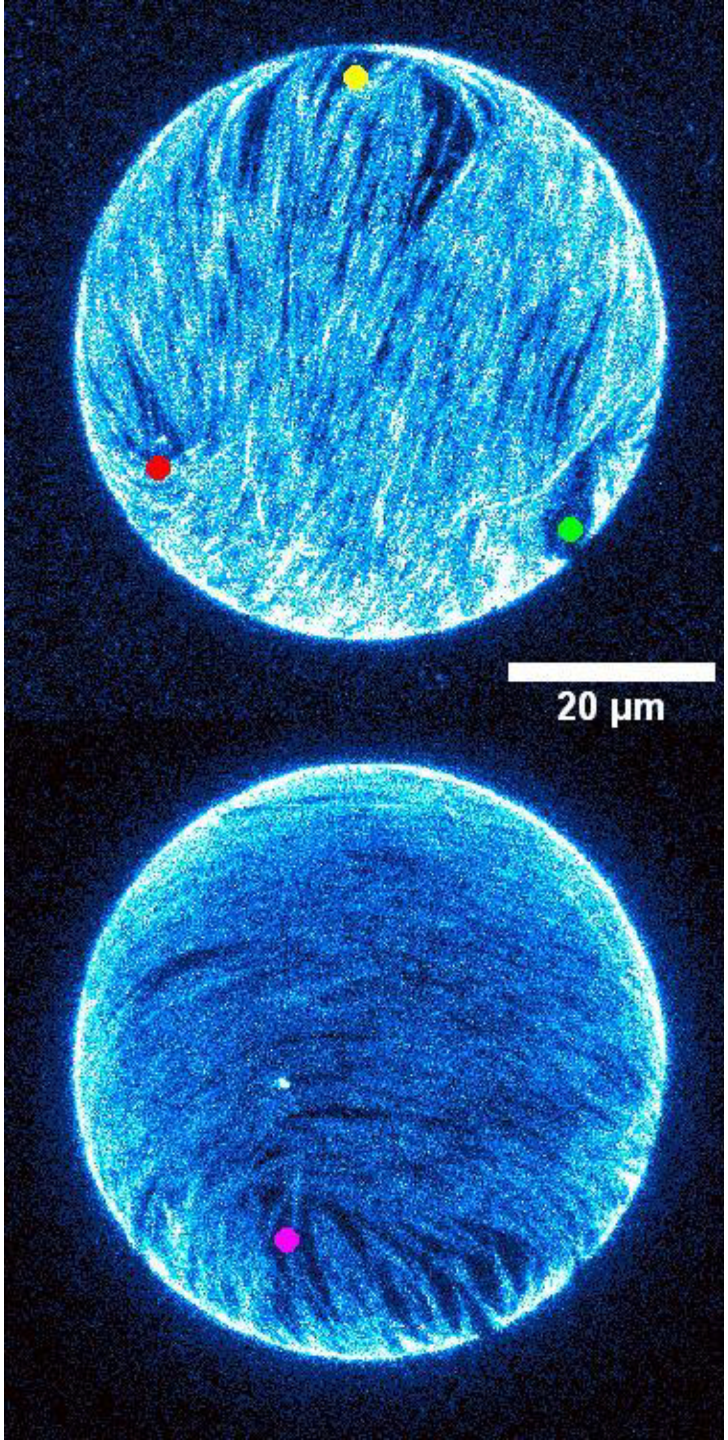


Sanchez et al 2012
Dogic Lab, Brandeis U

Active Liquid Crystal confined to the surface of a vesicle

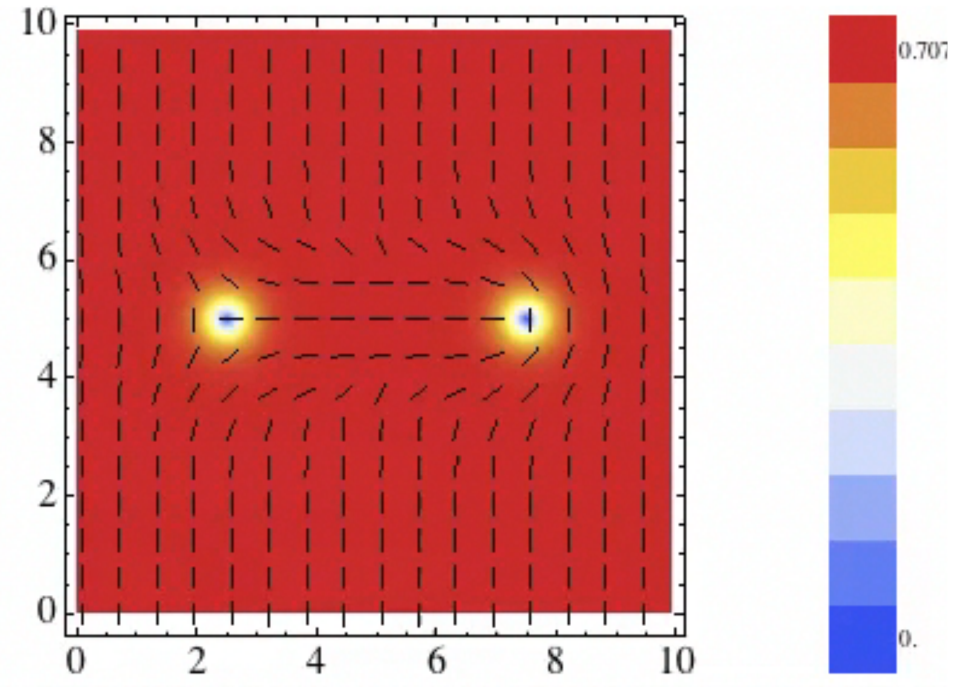






Keber et al, 2014
Bausch(TU Munich) & Dogic (Brandeis) Labs

We can describe the complex self-sustained flows seen in active liquid crystals using equations of fluid dynamics, augmented by new terms that model the energy input by the motor proteins

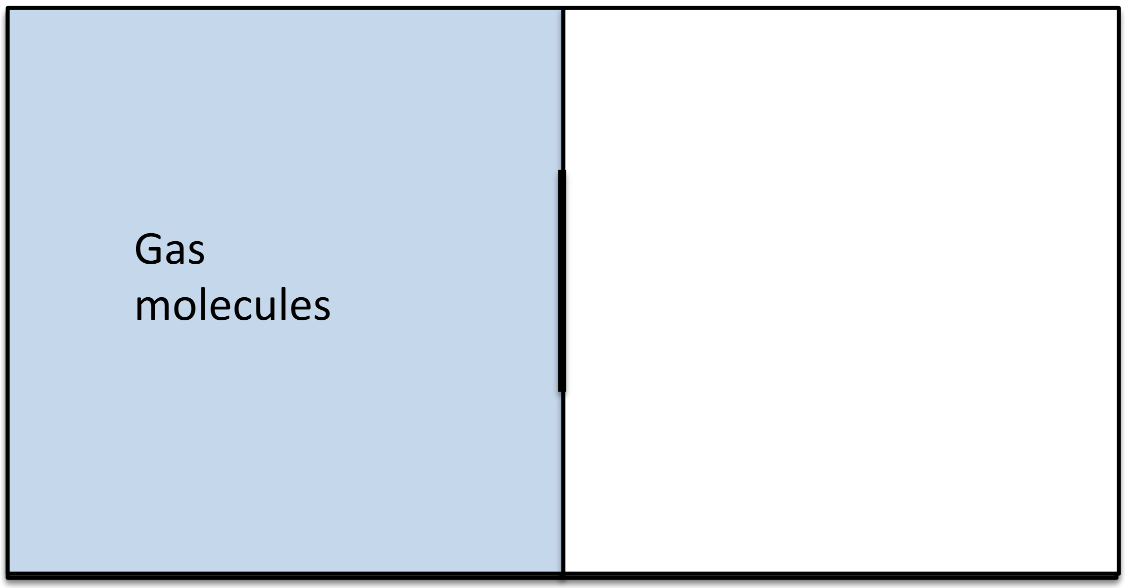


Towards a quantitative understanding of *in vitro* systems that mimic some functions of living systems

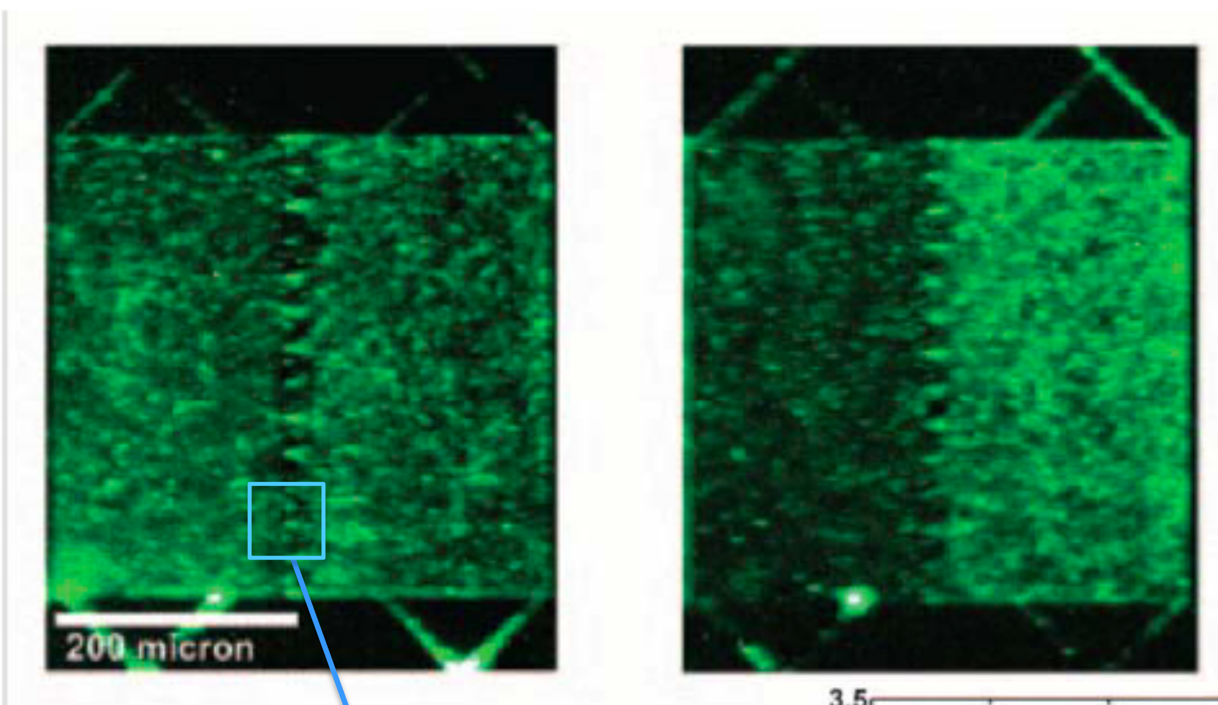
Giomi, Bowick, Ma & MCM, 2013

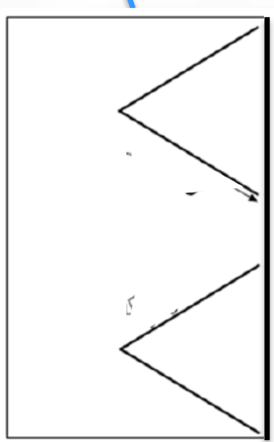
Bacteria do not know thermodynamics
or
The peculiar properties of an active gas

A gas fills the container regardless of the shape of the opening

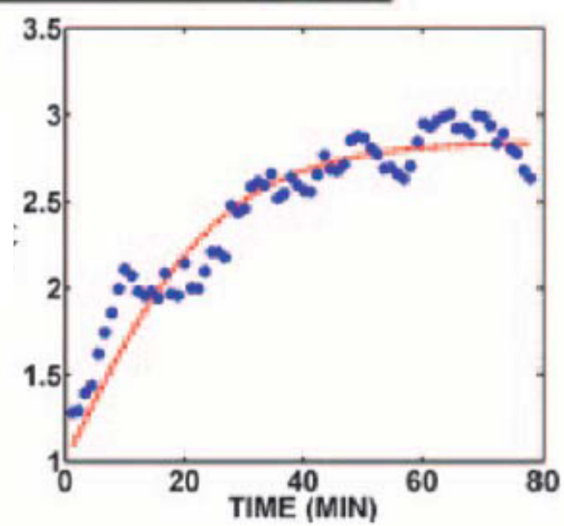


E. Coli concentrates on one side of the container



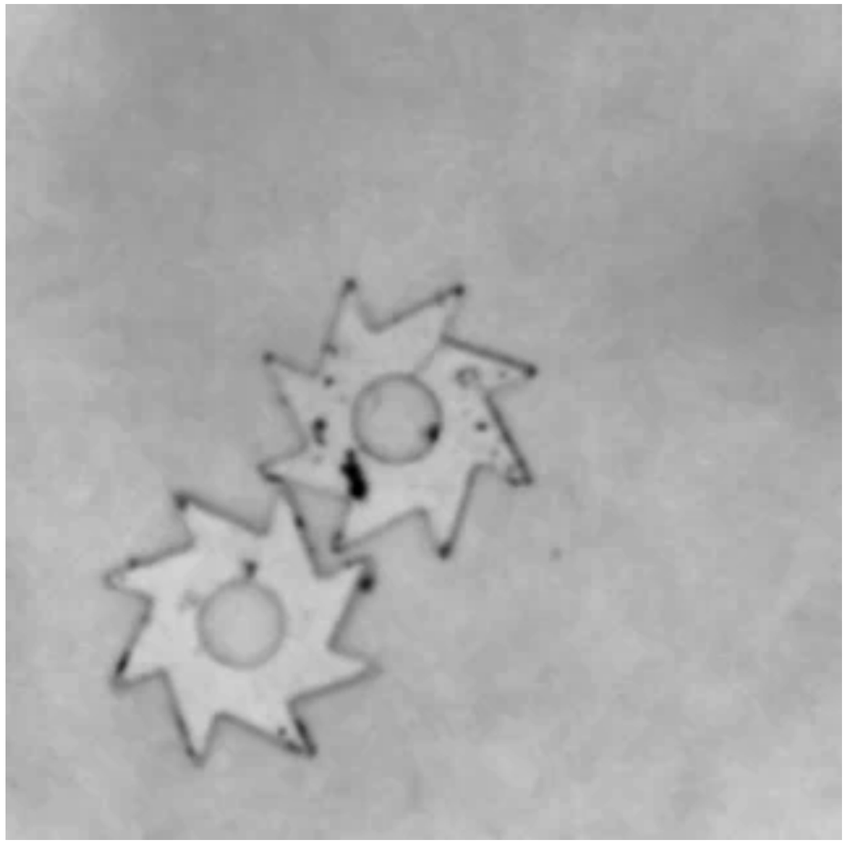


Density in right chamber



Galajda et al, 2008
Austin Lab, Princeton

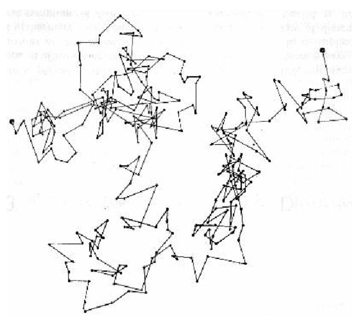
Bacteria power microgears



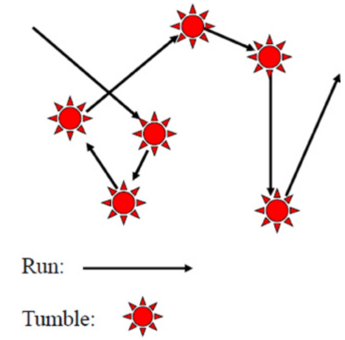
Sokolov et al, 2010, Argonne Nat Lab
gears diameter 380μm, 6 x real time

Brownian motion vs Active motion

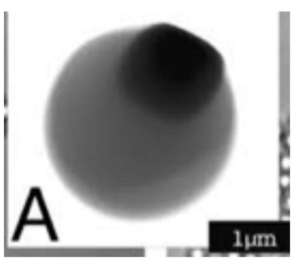
Robert Brown, 1827: incessant random motion of pollen grains in water



Run-and-tumble of E. coli



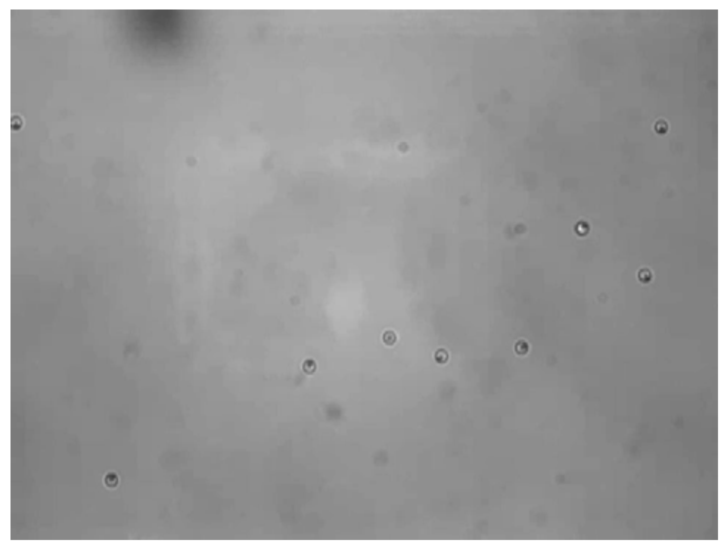
Light-activated colloids



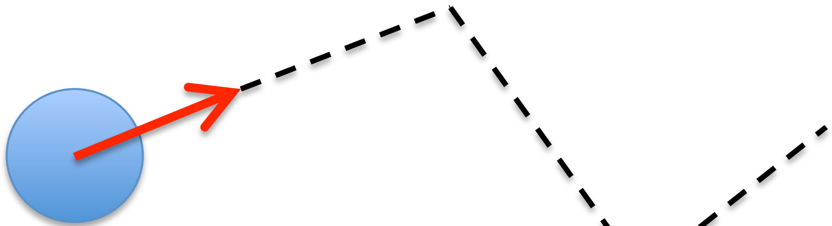
Palacci et al, 2013
NYU

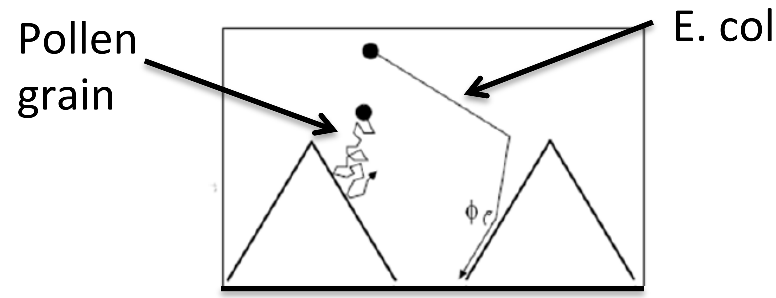
$$D = 600 nm$$

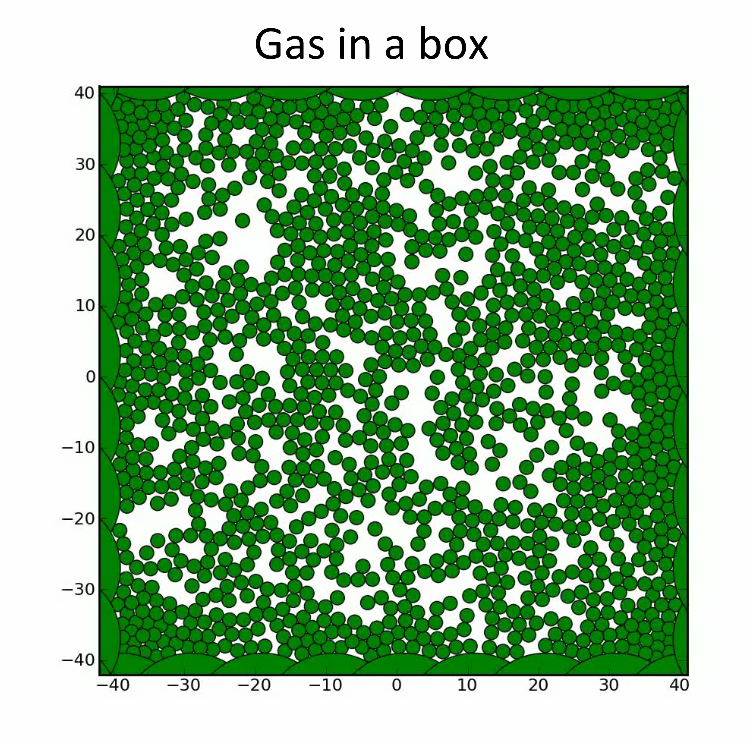
$$v_0 = 15 \mu m / s$$

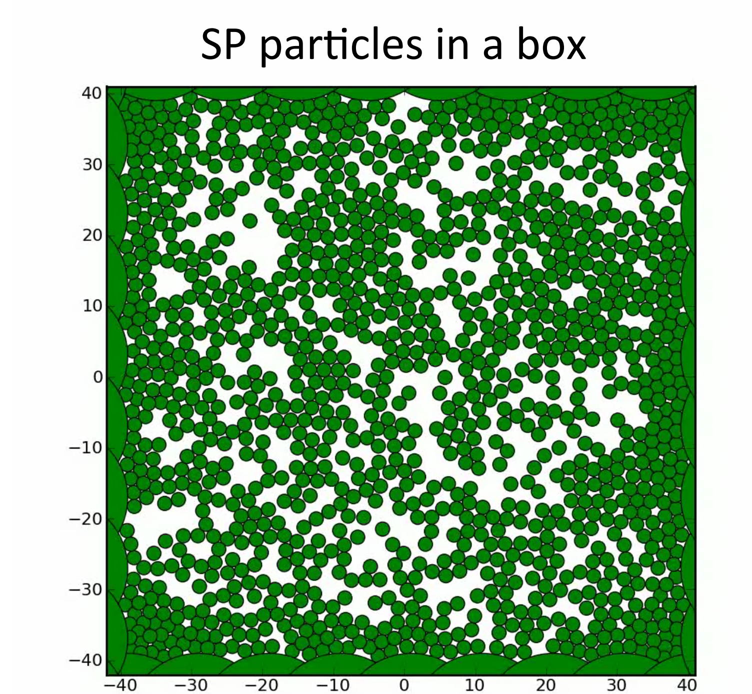


``Self-Propelled'' billiard balls that travel in a straight line for some time before changing direction are ``attracted'' to walls









Yang, Manning & MCM, 2014

Questions

- How does nature organize individual active units to create coherent motion and function at the large scale?
- Can we use these organizing principles to make novel biomimetic materials and micromachines?
- What can we learn from synthetic active systems? What can this knowledge teach us about how living systems work?