Swirling Bacteria Linked to the Physics of Phase Transitions

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May 22, 2017

Sitpor.org

Simple models can explain the behavior of thousands of interacting organisms.

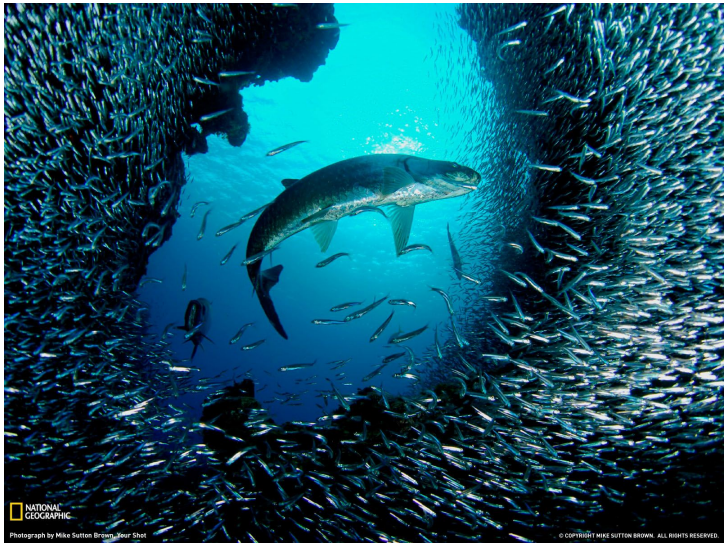
www.ted.com/talks/steven_strogatz_on_sync

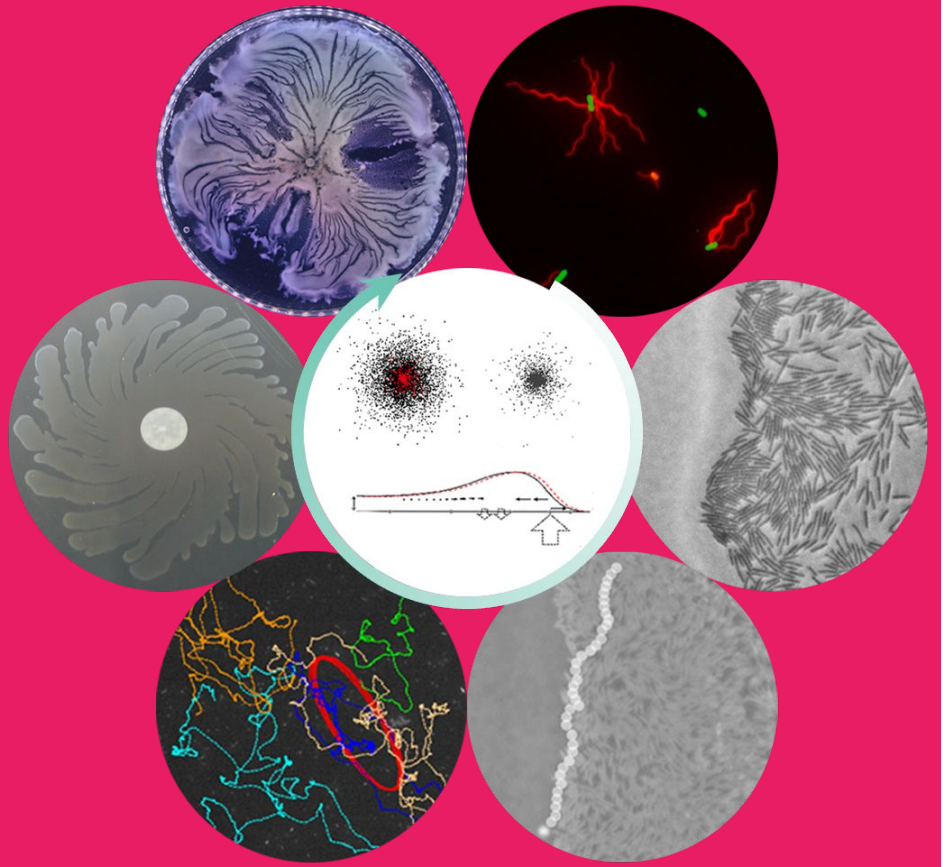
“More”

is

Different

1972





“Physics of Bacterial Behavior”

Nature, doi:10.1038/nature20817

Hugues Chaté

*“Seemingly **uncoordinated** motions of individual bacteria can add up to **synchronized oscillations** at large scales!”*

Wu Lab: www.phy.cuhk.edu.hk/ylwu/

Active Matter

Simple mathematical rules governing interactions between **individual units**, each **harnessing energy** and **moving on its own**, can give rise to **large-scale order**!

www.brandeis.edu/departments/physics/hagan/research/images/starlings.jpg

Active Matter

- To An early 20th-century **biologist:**
  - the birds might share some sort of “**group soul**.”

- To **physicists:**

  - such collective behavior evokes not souls but **phase transitions**

Wait a second!

Nature: May, 16, 2017

"Although traditional academic labs have been and continue to be very productive, research institutions should look critically and creatively at their staffing."

nature

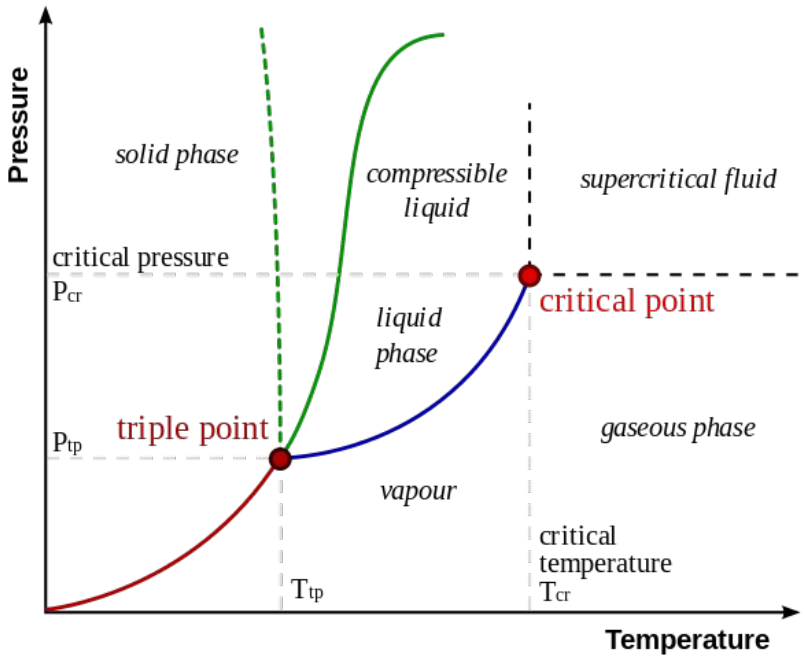
Staff scientist Stacey Gabriel co-authored 25 of the most highly cited papers worldwide in 2015.

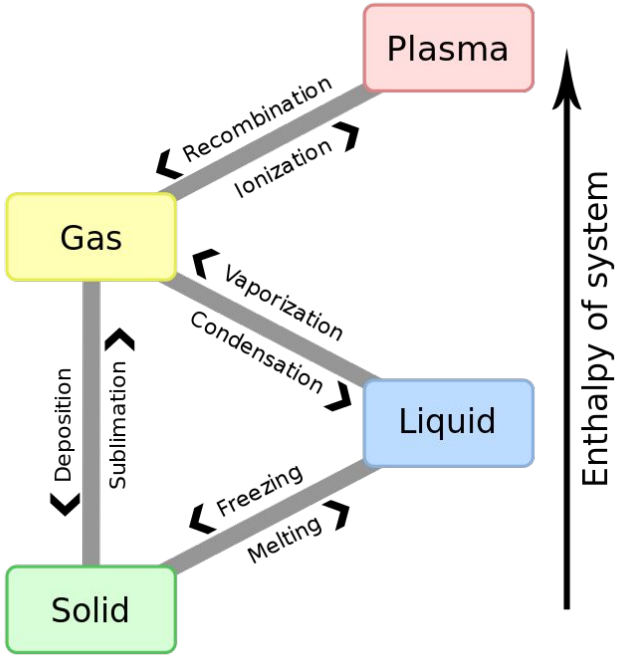
Biology needs more staff scientists

Independent professionals advance science in ways faculty-run labs cannot, and such positions keep talented people in research, argues **Steven Hyman**.

http://www.nature.com/news/biology-needs-more-staff-scientists-1.21991?WT.mc_id=TWT_NatureNews&sf79459703=1&sf80096092=1

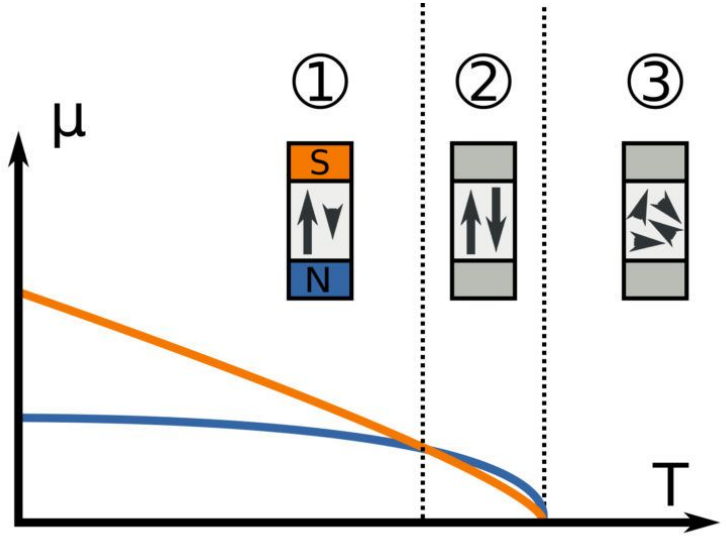
the Physics of Phase Transitions





This diagram shows the nomenclature for the different phase transitions.
@wikipedia

the Physics of Phase Transitions



@wikipedia

① Below the magnetization compensation point, ferrimagnetic material is magnetic.

② At the compensation point, the magnetic components cancel each other and the total magnetic moment is zero.

③ Above the Curie point, the material loses magnetism.

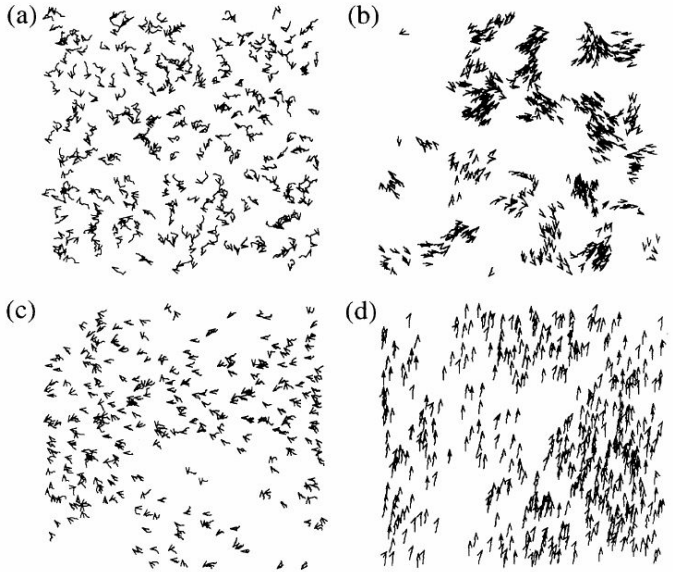
Active VS Passive matter

“On the surface of Earth, almost everything is nonequilibrium, You just cannot solve them without computers.” Tamás Vicsek

hal.elte.hu/~vicsek/

Vicsek Model for “flocking” 1995

VOLUME 75, NUMBER 6 PHYSICAL REVIEW LETTERS 7 AUGUST 1995



Novel Type of Phase Transition in a System of Self-Driven Particles

Tamás Vicsek,[1,2] András Czirók,[1] Eshel Ben-Jacob,[3] Inon Cohen,[3] and Ofer Shochet[3]
[1]*Department of Atomic Physics, Eötvös University, Budapest, Puskin u 5-7, 1088 Hungary*
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[3]*School of Physics, Tel-Aviv University, 69978 Tel-Aviv, Israel*
(Received 25 April 1994)

A simple model with a novel type of dynamics is introduced in order to investigate the emergence of self-ordered motion in systems of particles with biologically motivated interaction. In our model particles are driven with a constant absolute velocity and at each time step assume the average direction of motion of the particles in their neighborhood with some random perturbation (η) added. We present numerical evidence that this model results in a kinetic phase transition from no transport (zero average velocity, $|\mathbf{v}_a| = 0$) to finite net transport through spontaneous symmetry breaking of the rotational symmetry. The transition is continuous, since $|\mathbf{v}_a|$ is found to scale as $(\eta_c - \eta)^\beta$ with $\beta \simeq 0.45$.

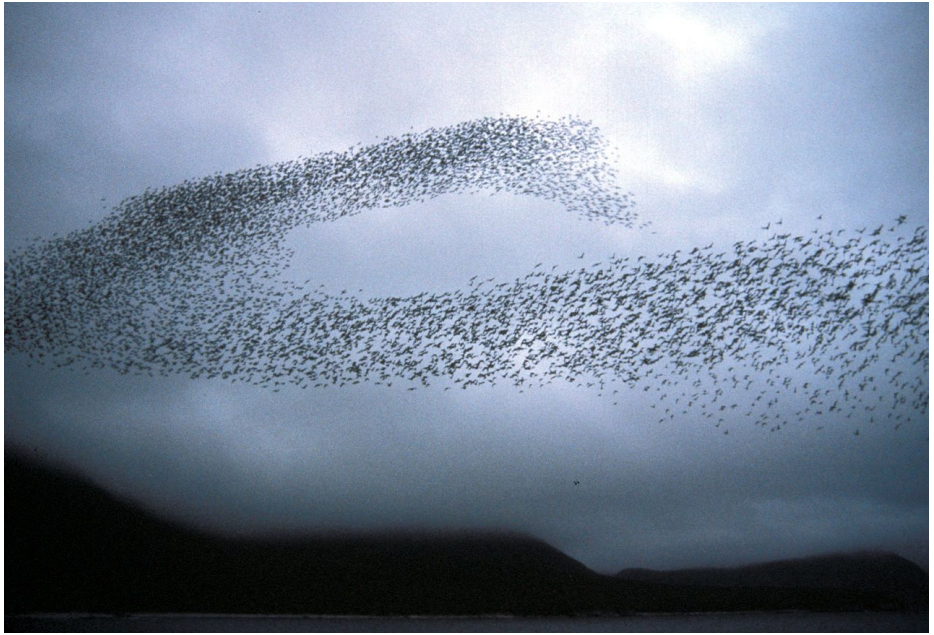
PACS numbers: 87.10.+e, 64.60.–i

Vicsek Model for “flocking” 1995

Flocking is due to the combination of **any** kind of **self propulsion** and of **effective alignment.**

$$\Theta_i(t+\Delta t) = \langle \Theta_j \rangle_{|r_i - r_j| < r} + \eta_i(t)$$

$$\mathbf{r}_i(t+\Delta t) = \mathbf{r}_i(t) + v\Delta t \begin{pmatrix} \cos\Theta_i(t) \\ \sin\Theta_i(t) \end{pmatrix}$$



en.wikipedia.org/wiki/Vicsek_model

Model for “flocking” 1996

Swirls & **colonies:**
“a few natural extensions”:

1. **Bacterial chemistry**
2. **Bacteria reproduce**

en.wikipedia.org/wiki/Vicsek_model

Formation of complex bacterial colonies via self-generated vortices

András Czirók,[1] Eshel Ben-Jacob,[2] Inon Cohen,[2] and Tamás Vicsek[1,3]
[1]*Department of Atomic Physics, Eötvös University, Puskin u. 5-7, 1088 Budapest, Hungary*
[2]*School of Physics, Tel-Aviv University, 69978 Tel-Aviv, Israel*
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(Received 23 October 1995; revised manuscript received 29 March 1996)

Depending on the environmental conditions bacterial colonies growing on agar surfaces can exhibit *complex colony formation* and various types of *collective motion*. Experimental results are presented concerning the hydrodynamics (vortices, migration of bacteria in clusters) and colony formation of a morphotype of *Bacillus subtilis*. Some of these features are not specific to this morphotype but also have been observed in several other bacterial strains, suggesting the presence of universal effects. A simple model of self-propelled particles is proposed, which is capable of describing the hydrodynamics on the intermediate level, including the experimentally observed rotating disks of bacteria. The colony formation is captured by a complex generic model taking into account nutrient diffusion, reproduction, and sporulation of bacteria, extracellular slime deposition, chemoregulation, and inhomogeneous population. Our model also sheds light on some possible biological benefits of this ‘‘multicellular behavior.’’ [S1063-651X(96)04408-X]

PACS number(s): 87.10.+e, 87.22.−q, 05.60+w

Model for “flocking” 1996

Swirls & **colonies:**
“a few natural extensions”:

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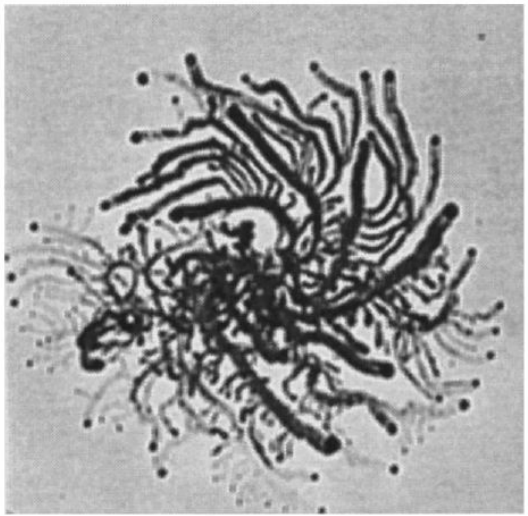
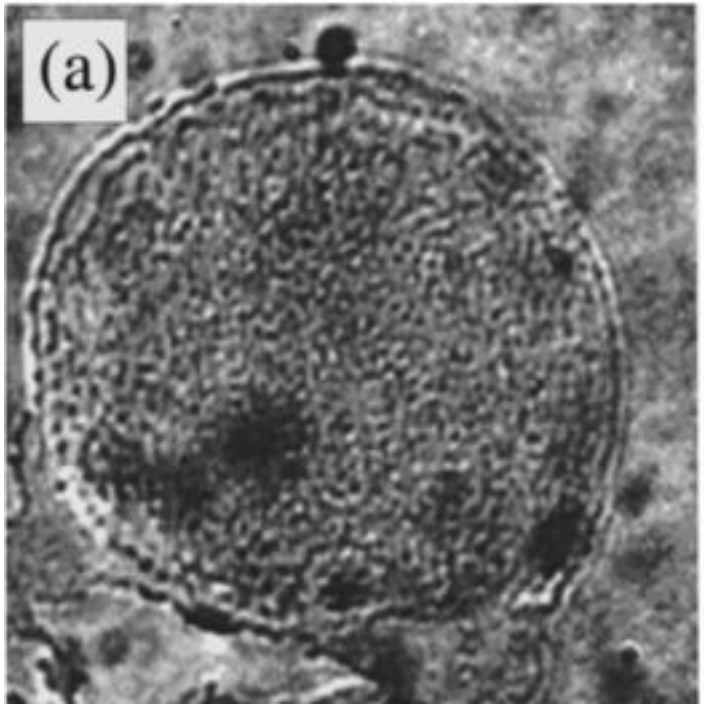


FIG. 1. A typical colony formed by the *vortex* morphotype. Each branch is formed by a rotating droplet of many bacteria moving together in a correlated manner at the tips of the branches.

Model for “flocking” 1996



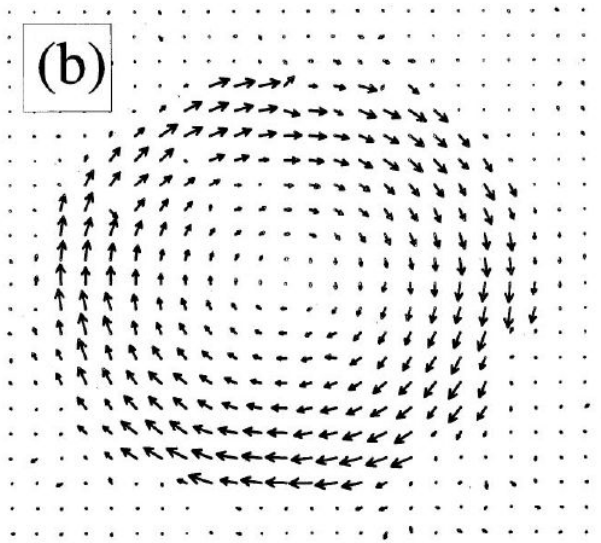


FIG. 2. Bright field micrograph of a single rotating droplet with a magnification of 500× (a) and the corresponding velocity field obtained by digitizing our video recordings (b).

Model for “flocking” 2004

Raymond Goldstein
Sriram Ramaswamy

Bacteria in 3d droplet

- **Jets**
- **Swirls**

- Solution?

“Fluid dynamics + Vicsek’s model”

Self-Concentration and Large-Scale Coherence in Bacterial Dynamics

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[2]*Program in Applied Mathematics, University of Arizona, Tucson, Arizona 85721, USA*
(Received 23 December 2003; published 24 August 2004)

Suspensions of aerobic bacteria often develop flows from the interplay of chemotaxis and buoyancy. We find in sessile drops that flows related to those in the Boycott effect of sedimentation carry bioconvective plumes down the slanted meniscus and concentrate cells at the drop edge, while in pendant drops such self-concentration occurs at the bottom. On scales much larger than a cell, concentrated regions in both geometries exhibit transient, reconstituting, high-speed jets straddled by vortex streets. A mechanism for large-scale coherence is proposed based on hydrodynamic interactions between swimming cells.

DOI: 10.1103/PhysRevLett.93.098103 PACS numbers: 87.18.Ed, 05.65.+b, 47.20.–k, 47.54.+r

Model for “flocking” 2010

Collective motion and density fluctuations in bacterial colonies

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Edited by Raymond E. Goldstein, University of Cambridge, Cambridge, United Kingdom, and accepted by the Editorial Board June 23, 2010 (received for review February 18, 2010)

Model for “flocking” 2013

PAPER

Directed collective motion of bacteria under channel confinement

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Keywords: bacteria, confinement, collective behaviour

Why Bacteria Team Up?

Do they help bacteria **survive** and **reproduce**, or are they mere **byproducts** of bacteria's basic biology, rather like magnetism, which could be considered a byproduct of quantum mechanics?

Why do collective behaviors exist at all?

Evolution's handiwork:

"Since the laws of physics allow you to essentially get patterns for free, it's attractive to think that biology could take advantage of this.It seems like in some instances or maybe even many instances, they are at least partially **taking advantage** of it."

Joshua Shaevitz, a biophysicist at Princeton University who studies myxobacteria.

Why do collective behaviors exist at all?

Evolution's handiwork:

Vicsek, 1996:

- Swirls could help bacteria **concentrate nutrients.**

Goldstein's group:

- **Biofilms**: large groups of bacteria can transition from free-swimming individuals to a much less mobile collective state. **(The analogy to a phase transition is almost irresistible.)**

Why do collective behaviors exist at all?

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Joshua Shaevitz, a biophysicist at Princeton University who studies myxobacteria.

Why do collective behaviors exist at all?

“It’s up to the physicists to show that there is something here that biologists should pay more attention to. Whenever we see a **pattern**, we’re intrigued by patterns, and we immediately assign some kind of **meaning** … but that doesn’t necessarily mean that it’s something **functional**.”

Gürol Süel, a molecular biologist at the University of California, San Diego

Let's think again;

What is Science?
What is Physics?
Who is a wise policy maker?!

Thank You :D

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