Novel type of phase transition in a system of self-driven particles

T. Vicsek et al.

(DOI : 10.1103/PhysRevLett.75.1226)

PHYS 596 Talk Presented By:

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Group 4

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

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(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

Outline

1. Summary and results
2. Comparisons to other relevant work
3. Critical analysis
4. Overall significance and broader impact
5. Citation analysis

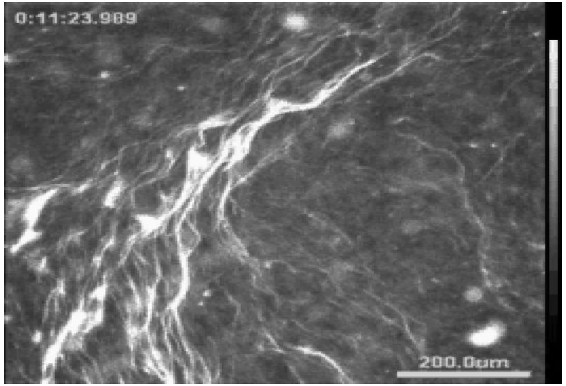
Collective motion in Self-Propelled Particles

[1]

Flocks of
birds

[2]

Schools of
fishes

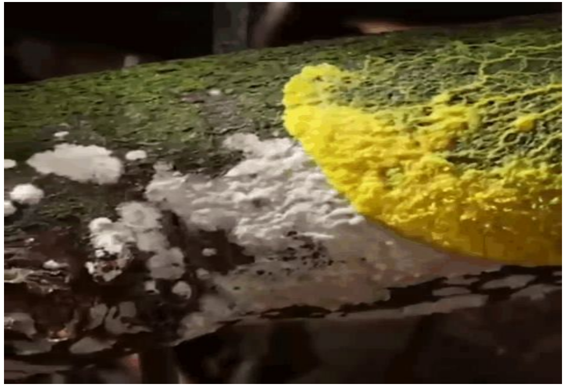


Microtubules
on an active
substrate

[3]

Collective
motion of
slime molds

[4]



What is the Vicsek model?

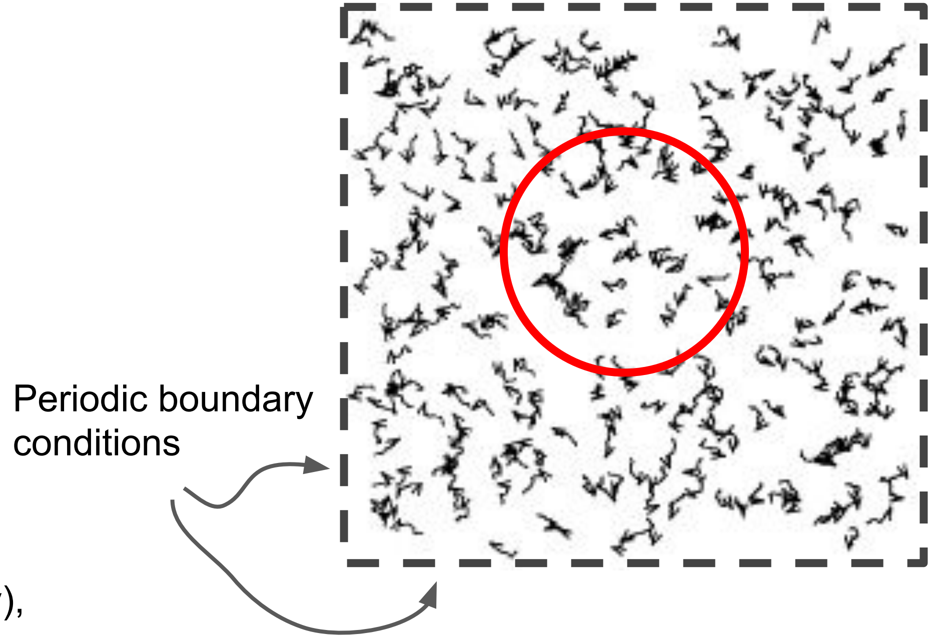
- "Vicsek Particles": non-interacting small arrows always moving with a constant speed
- Update rules:

$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{v}_i(t)\Delta t$$
$$\theta(t+1) = \langle \theta(t) \rangle_r + \Delta\theta$$

- Order parameter:

$$\mathbf{v}_a = \frac{1}{Nv} \left| \sum_{i=1}^{N} \mathbf{v}_i \right|$$

- Control parameters: η (noise), ϱ (density), v (absolute velocity)



What happens in the steady-state?

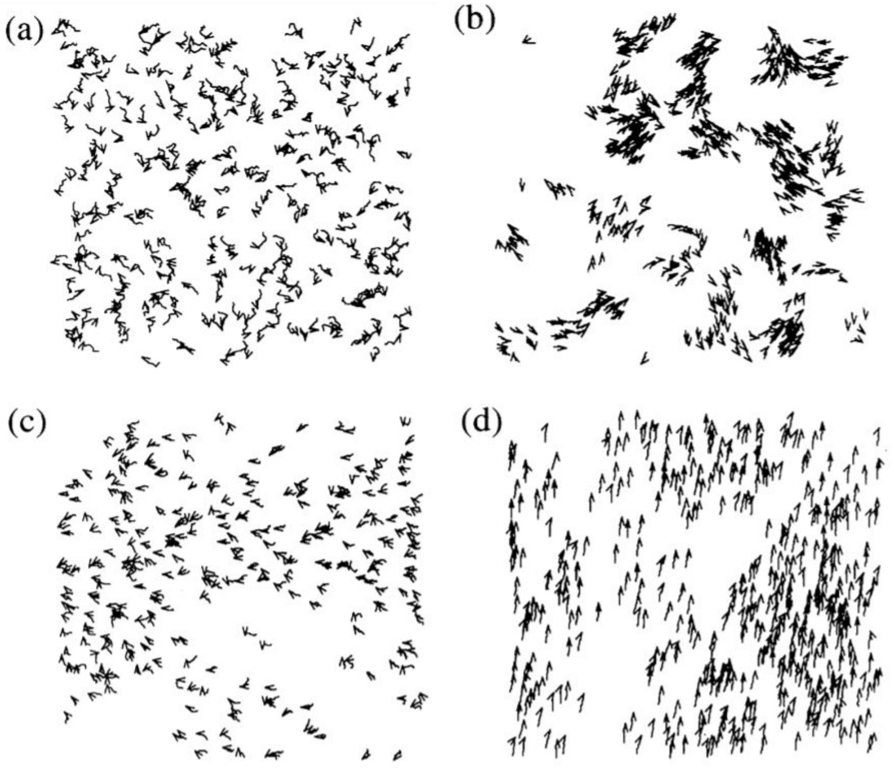
(a) Initial configuration : $$\mathbf{v}_a = \frac{1}{Nv}\left|\sum_{i=1}^{N}\mathbf{v}_i\right| = 0$$

(b) Steady-state for low noise and low density

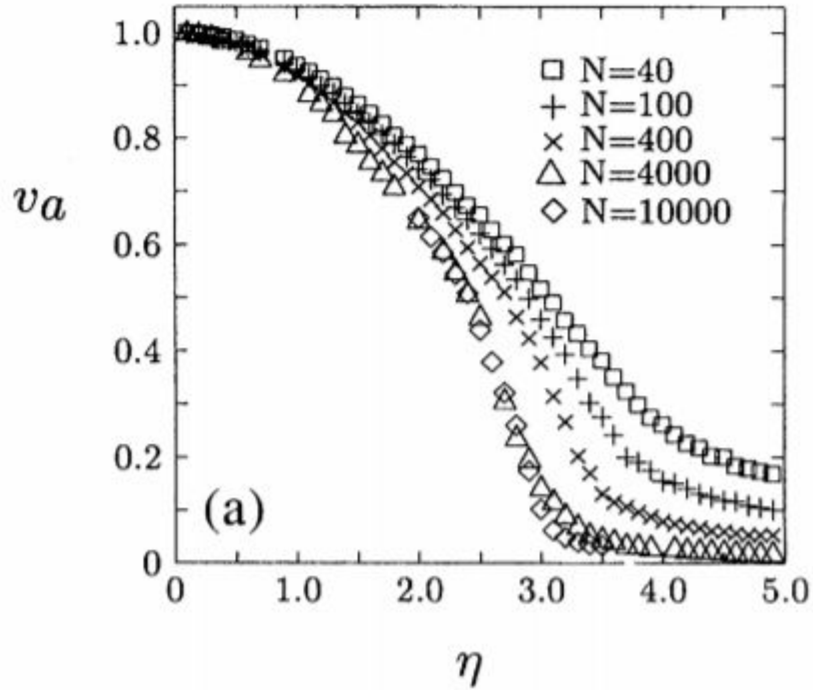
(c) Steady-state for high noise and high density

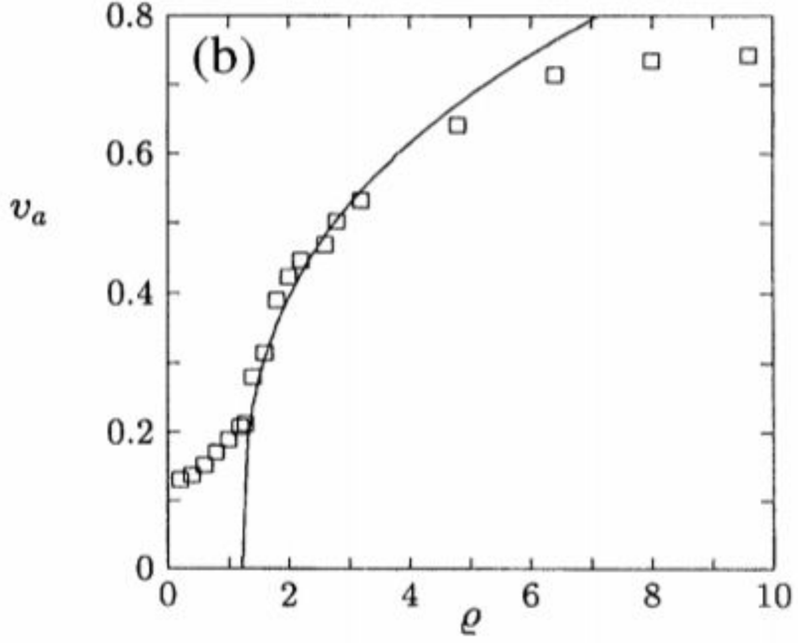
(d) A kinetic phase transition - For low noise levels and/or higher densities :

$$\mathbf{v}_a = \frac{1}{Nv}\left|\sum_{i=1}^{N}\mathbf{v}_i\right| = 1$$



Characterising the transition





Demo

Complexity Explorables - "Flock and Roll"

Comparison to Other Models

- Prior work in other fields:
    - Boid model (simulation focused flocking, 1987)[5]
    - Okubo (kinematic treatment, 1986)[6]
    - Edelstein-Keshet (cells forming parallel arrays, 1990)[7]

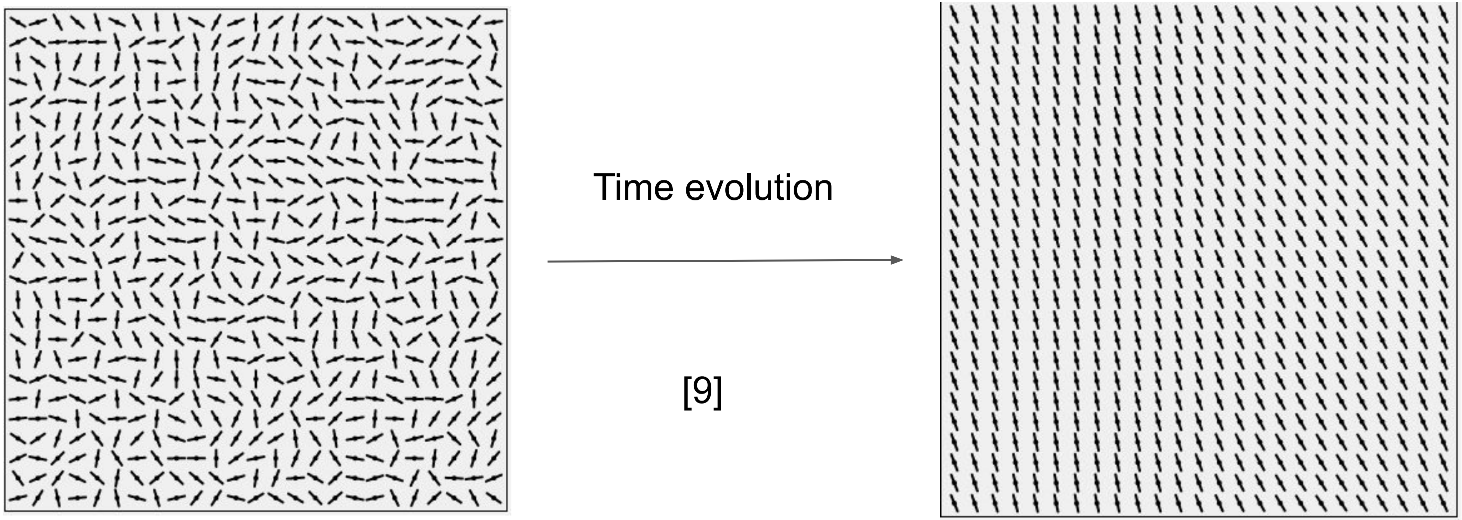
- Recall, there are 3 free parameters to the simulation: η (noise), ϱ (density), v (absolute velocity)

- Altering these parameters, changes the dynamics of the system, which can be compared to other statistical models in limiting cases

Limiting Case: Reducing Absolute Velocity

- Setting v = 0, the particles are unable to move, but still attempt to align themselves with its neighbors.

- Behavior is similar to the typical XY model in statistical physics; akin to dipole alignment in lattices.



Limiting Case: Increasing Absolute Velocity

- Setting the velocity to infinity, the total configuration of the system changes with each timestep. Any alignment formed in a timestep gets destroyed.

- Setting the alignment radius to the domain size also prevents any order, as the particle averages direction from every other particle.

- These effects are similar to a random walk distribution with no interactions.

These limiting cases, while showing interesting properties, cannot help us infer the Vicsek model behaviors.

Critical Analysis

- Only two parameters, the noise and the density investigated.
- Phase diagram?
- The order-disorder transition, though stated to be continuous in the paper, was later found to be discontinuous
- Mistake was an artifact of finite-size effects

Critical Analysis (cont’d)

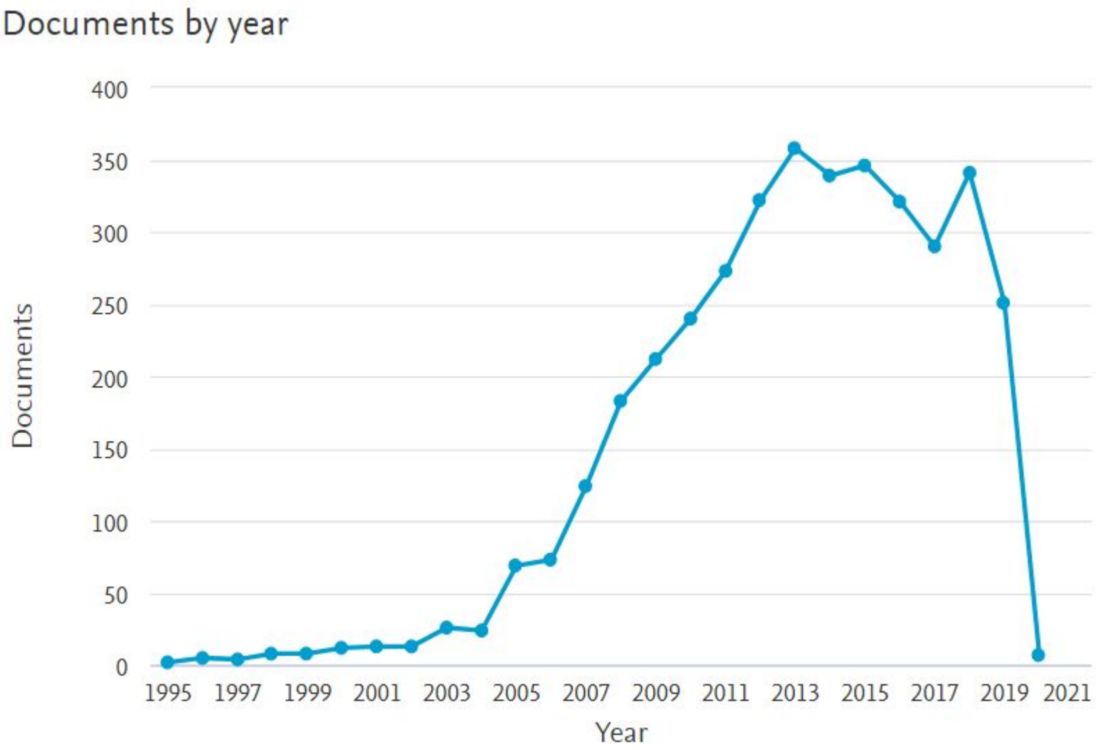
- Too minimalistic to adequately explain complex living or ecological systems
- To what extent does the model describe real active matter and self-driven particles?
- “Only” a phenomenological model
- Claims to universality unclear - discovered later

Impact on the Field

- Pioneered field of collective motion & active matter
- Introduced a simple method that became “the model”
  - Self-driven movement systems
- Huge push over past 25 years
  - Universally accepted and used.
- Macroscopic Level: Colonies of bacteria, micro/nano-particles
- Everyday: Flocks of birds, schools of fish, herds, crowds, traffic
- Won 2020 Lars Onsager Prize

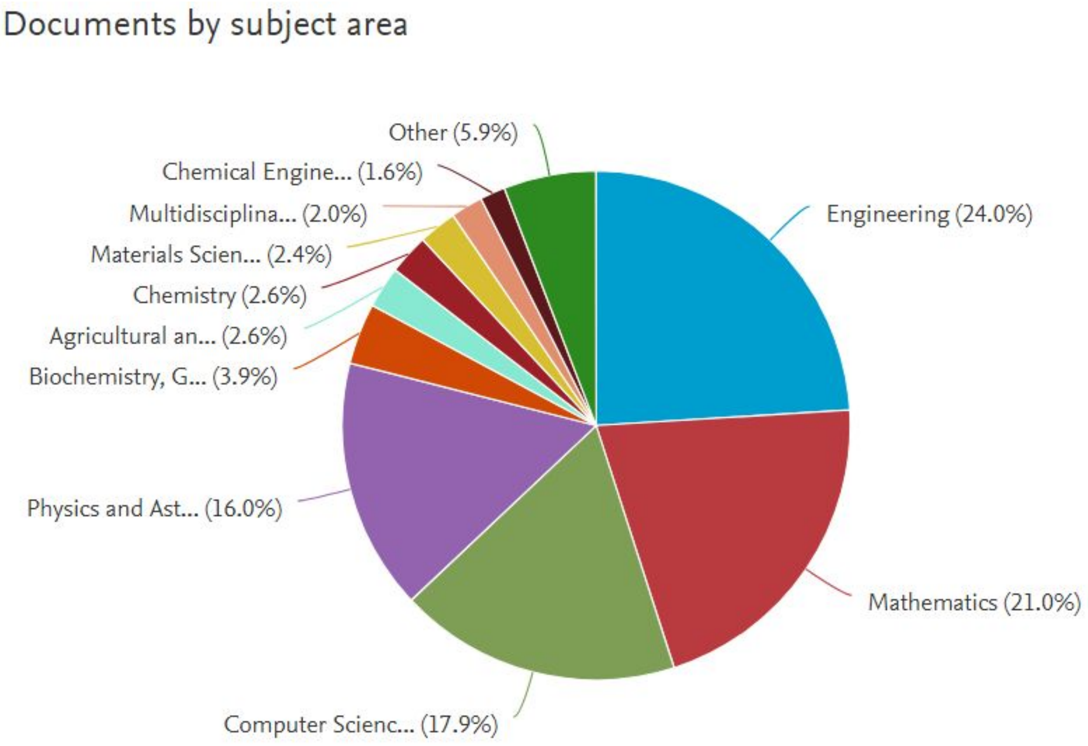
Citation Analysis

- Article cited by 3864 documents
    - (SCOPUS)
- 200-350 citations/year for the last 10 years.
- Vicsek cited 27,959 times by 21,645 documents
    - (co)authored 241 articles
- Field has grown with increased citations trend



Citation Analysis

Cited in nearly *every* field of science



- Engineering(1,719)
- Mathematics(1,503)
- Computer Science(1,283)
- Physics and Astronomy(1,143)
- Biochemistry, Genetics and Molecular Biology(277)
- Agricultural and Biological Sciences(189)
- Chemistry(184)
- Materials Science(174)
- Multidisciplinary(145)
- Chemical Engineering(115)
- Neuroscience(75)
- Environmental Science(73)
- Decision Sciences(71)
- Immunology and Microbiology(45)
- Social Sciences(41)
- And many more!

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