source: https://www.youtube.com/watch?v=eakKfY5aHmY

COLLECTIVE MOTION IN LIVING SYSTEMS

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May 3rd 2017

I listened to the messages left behind

By those flocks of birds for mankind

As they flew over unmarked spaces,

And sped from an indistinct past to
an uncertain future.

-Rabindranath Tagore
("A Flight of Geese")

Photo: Bernard Gagnon

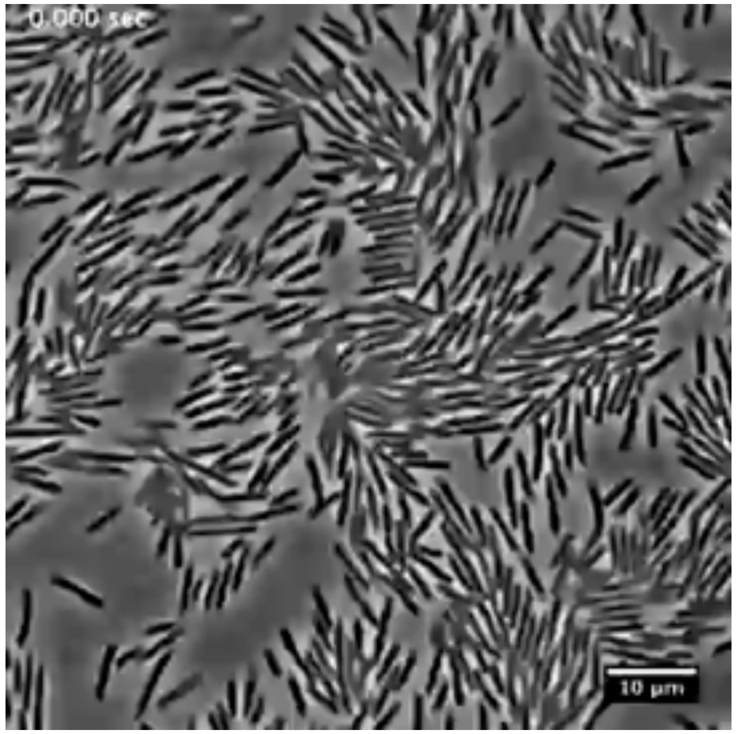
INTRODUCTION

THE UBIQUITY OF COLLECTIVE MOTION

- Collective motion is an emergent phenomenon seen across the living world.
- That is, local interactions determine the emergence of global properties.
- It occurs over a vast range of length scales, and where the constituent entities may be physical, chemical or biological.
- While the reasons for motion may differ, it is intriguing to ask whether there are any *underlying universal principles*.

Photo: Enric Sala, National Geographic

Swarming E coli



source: https://www.youtube.com/watch?v=q27Jn3h4kpE

"Ant Mill"

source: https://www.youtube.com/watch?v=3Rup3EdA0kw

Flock of starlings

source: https://www.youtube.com/watch?v=DmO4Ellgmd0

Crowd at a concert (8x speed)

source: https://www.youtube.com/watch?v=BgpdmAtbhbE

WHY FLOCK?

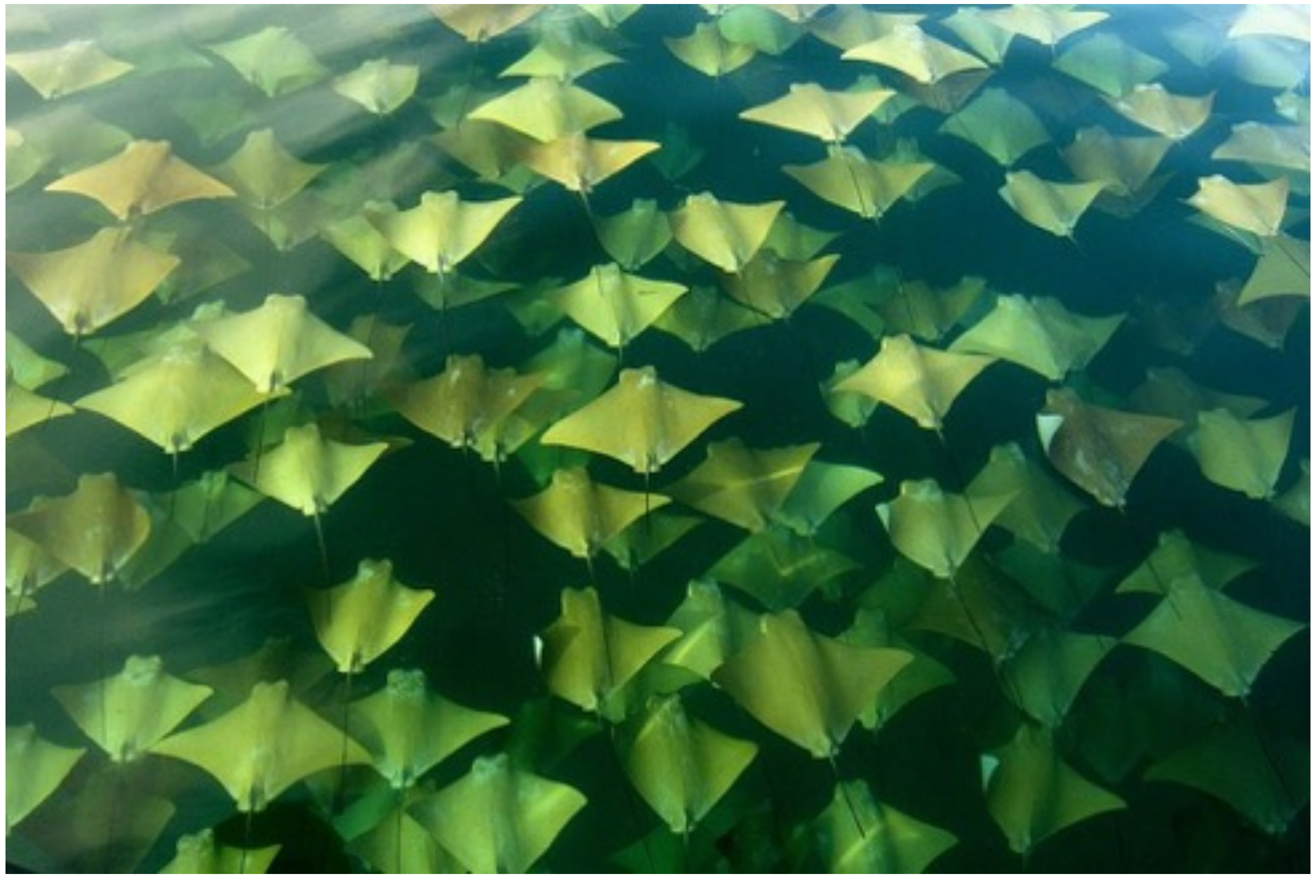


Photo: Sandra Critelli

Photo: Dariusz Paciorek

- Flocking may allow for a more efficient *exploration* for resources or hunting.
- It could provide *defense* against predators.
- *Decision-making* may be improved in a larger group.

Photo: Bilal Tarabey

THE FACETS OF COLLECTIVE MOTION

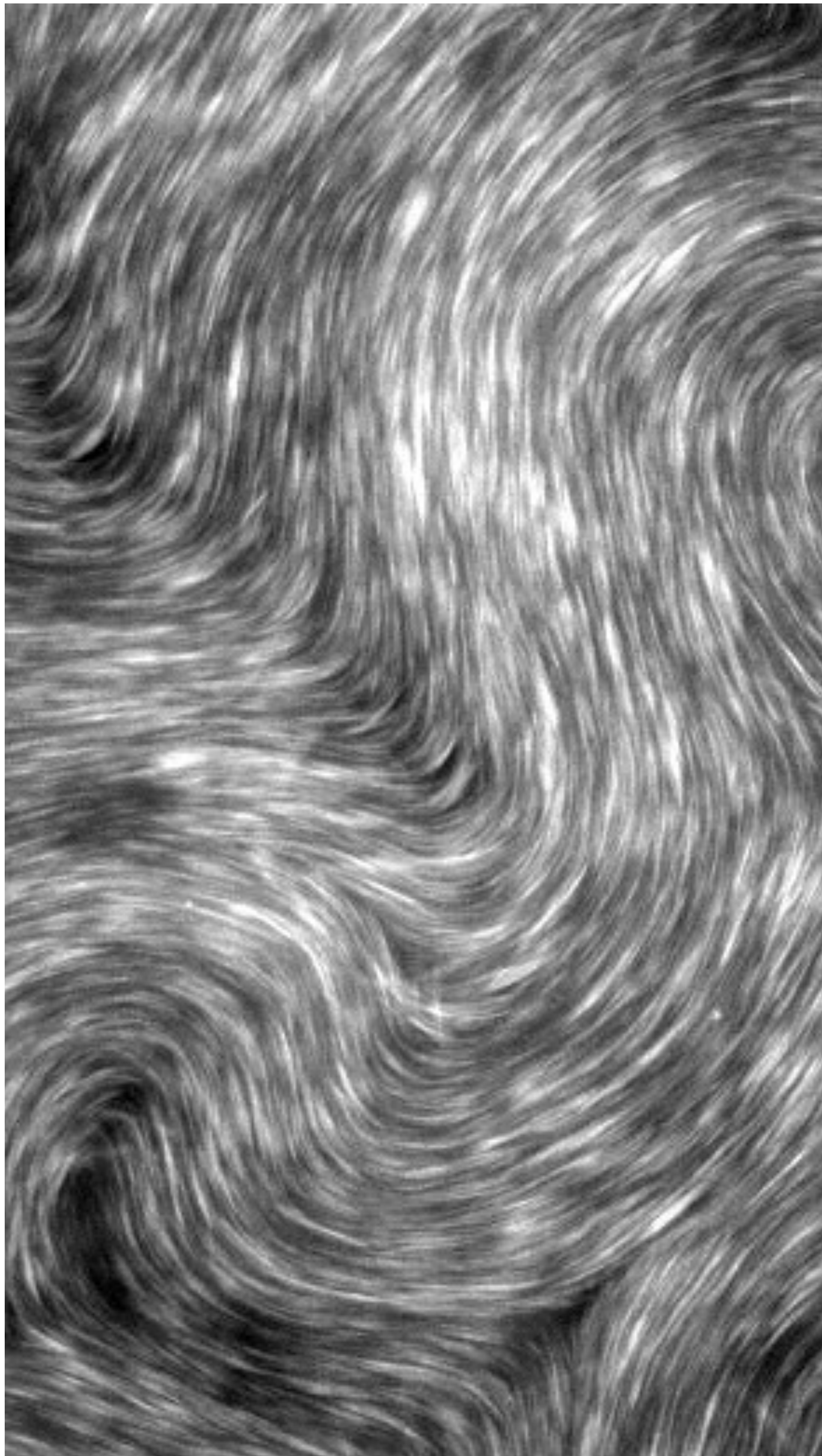
Collective motion / Flocking is typically characterized by the following features:

- The units are virtually indistinguishable and with a constant velocity in the absence of neighbours.
- The nature of interactions between units is either euclidean (within some radius) or topological (nearest neighbours), and involves *alignment*.
- The movement of a unit is dominated by the influence of others.
- May be subject to noise of varying types.

Source: http://blogs.brandeis.edu/science/2016/01/06/nature-news-feature-highlights-dogic-lab-active-matter-research/

FLOCKS AS "DRY" ACTIVE MATTER

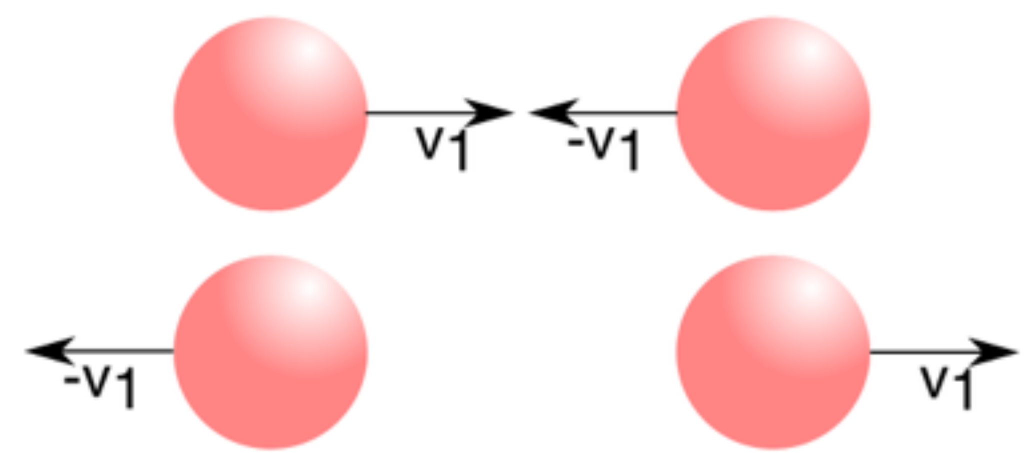
- Flocks are a subset of a class of nonequilibrium condensed systems known as *active matter*.
- Active matter constitutes units/particles that are assumed to be "self-propelled", i.e. they utilise stored or ambient free energy for movement, and is of two broad types:
  - **Wet**: If viscosity damps the relative motion of neighbouring regions (e.g. colloid suspensions).
  - **Dry**: If the particles move in an inert medium that only provides friction (e.g. flocks).



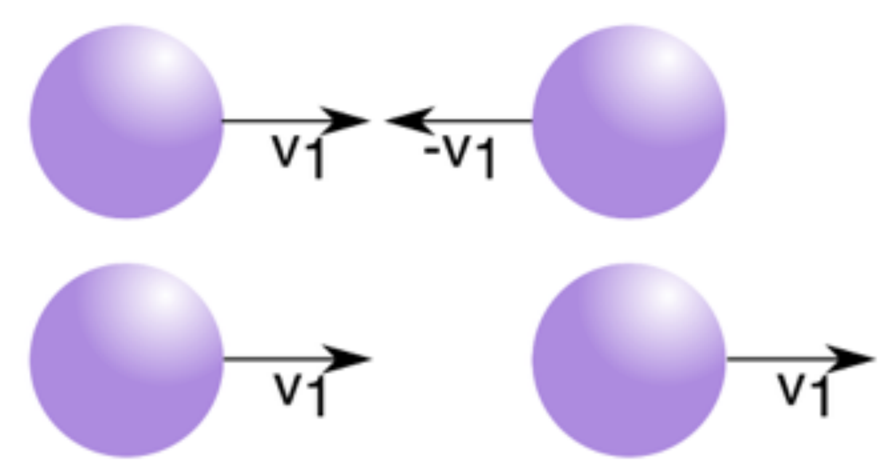
SELF-PROPELLED PARTICLES (SPP) IN A FLOCK

- Unlike in equilibrium systems, momentum is **not conserved** in flocks of self-propelled particles.
- At low noise levels alignment interactions will gradually increase the overall momentum.
- Alignment interactions tend to promote *polar order*, i.e. particles are aligned head to head and tail to tail.
- Such systems exhibit *transitions* between a few well defined collective states.
- Their collective dynamics are often described using agent-based models.

CONSERVATION OF MOMENTUM



SELF-PROPELLED PARTICLES

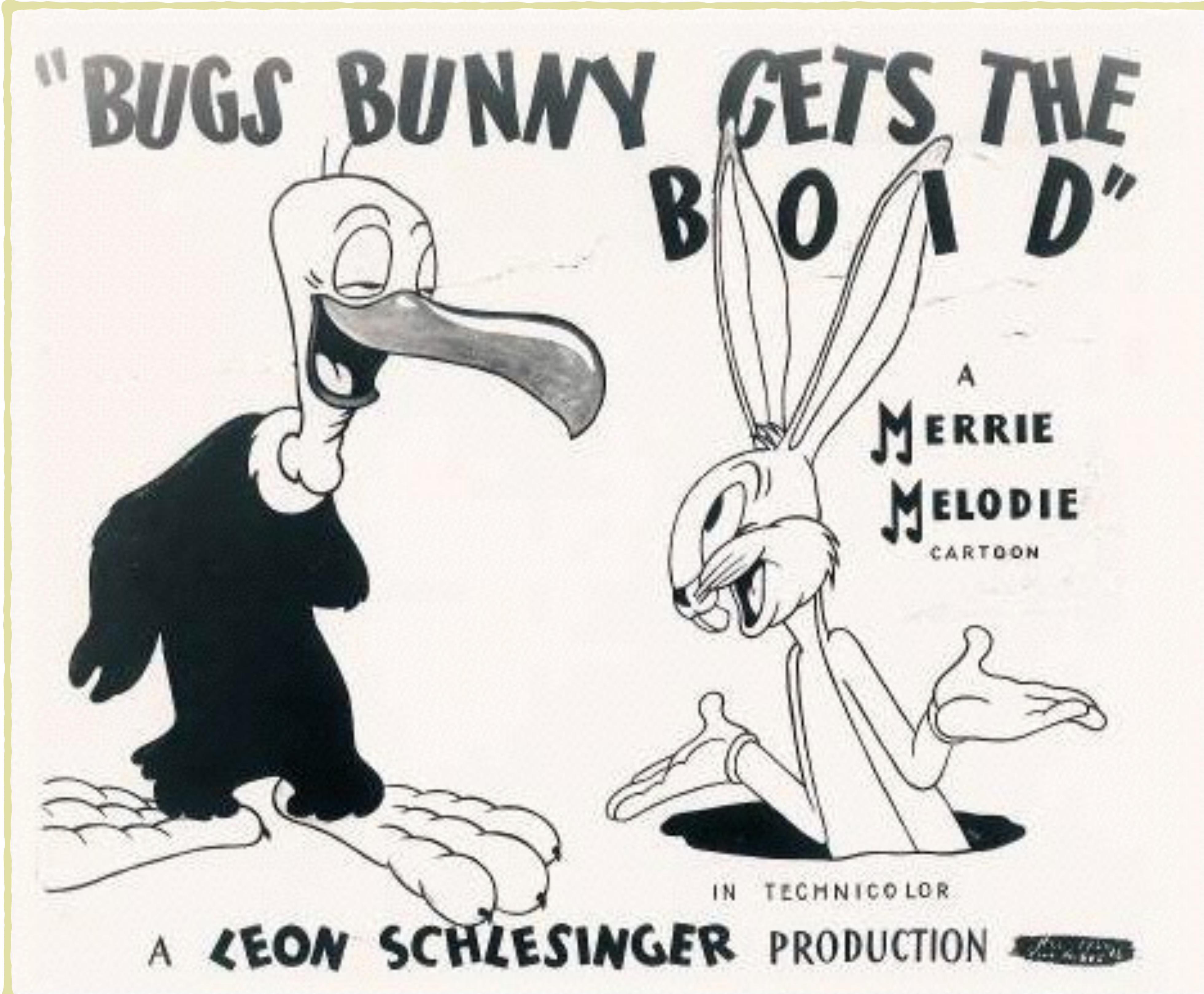


AGENT-BASED MODELS OF SPP

- There have been many attempts to model aspects of the collective dynamics of SPP.
- The models span several scales of complexity but have some similar characteristics.
- Such models often use an **agent-based** approach, wherein the behaviour (viz. motion) of a large number of (typically identical) agents are described through a set of rules.
- The rules often involve information regarding the behaviour of their "neighbours" and sometimes their local environment.
- These models often incorporate noise or uncertainty in either the information received or in the way that agents' actions are updated.

Photo: Will Burrard-Lucas

Merrie Melodies lobby card (1942)



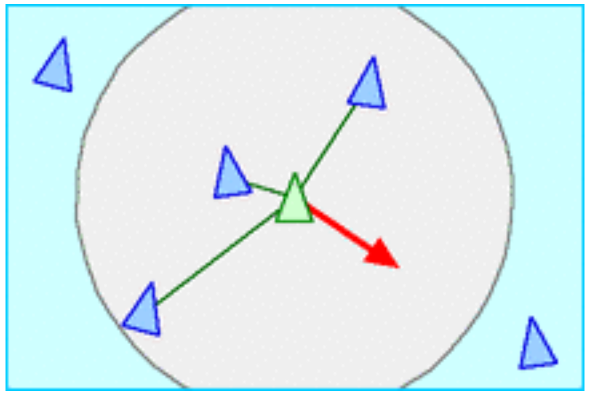
BOIDS

"BOIDS"

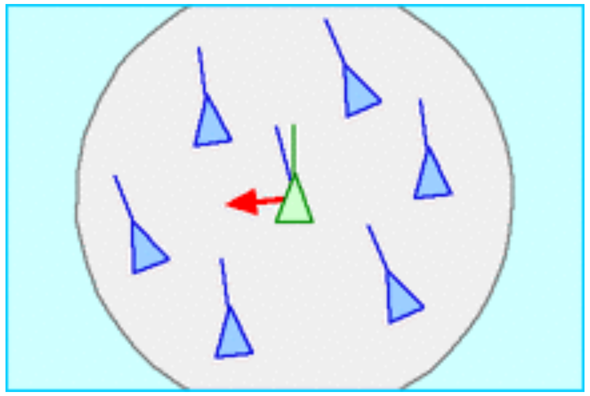
In 1986, Craig Reynolds developed an algorithm for coordinated animal motion for a system of agents (known as "bird-oid objects" or "boids").

At every point in time, each boid surveys its neighbourhood and notes the positions and directions of all other boids within it.

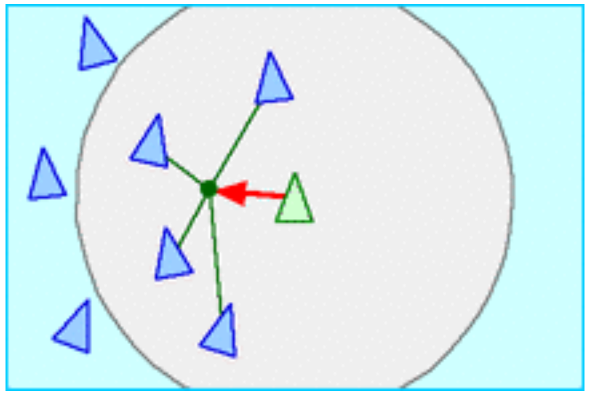
The boid then updates its direction of motion in a way that satisfies three *steering behaviours*, namely separation, alignment and cohesion.



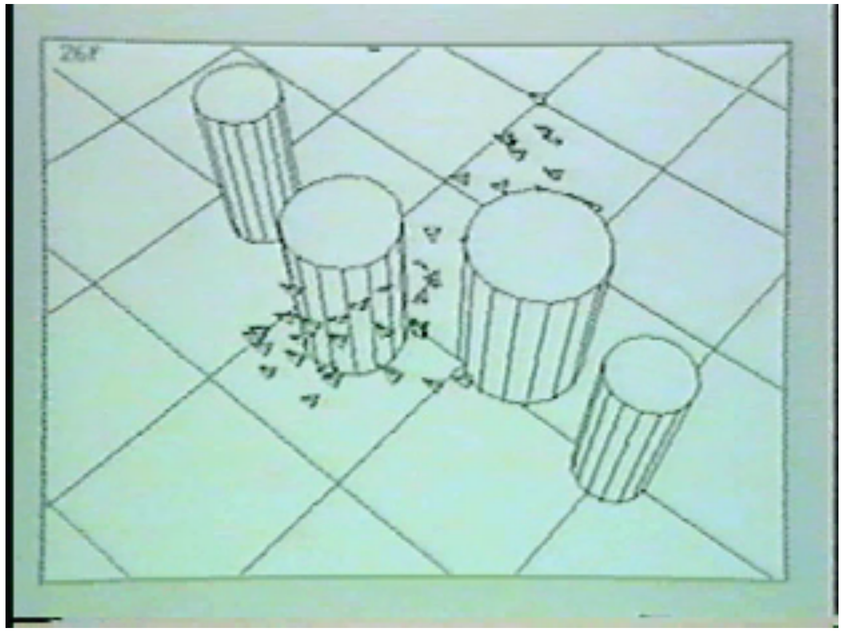
Separation



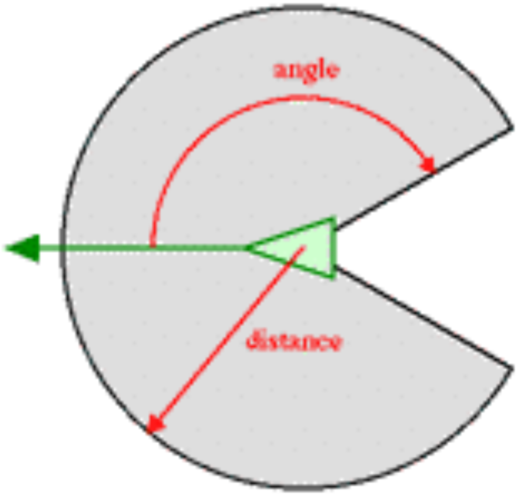
Alignment



Cohesion



Initial simulations



A boid's neighbourhood

source for all media: http://www.red3d.com/cwr/boids/

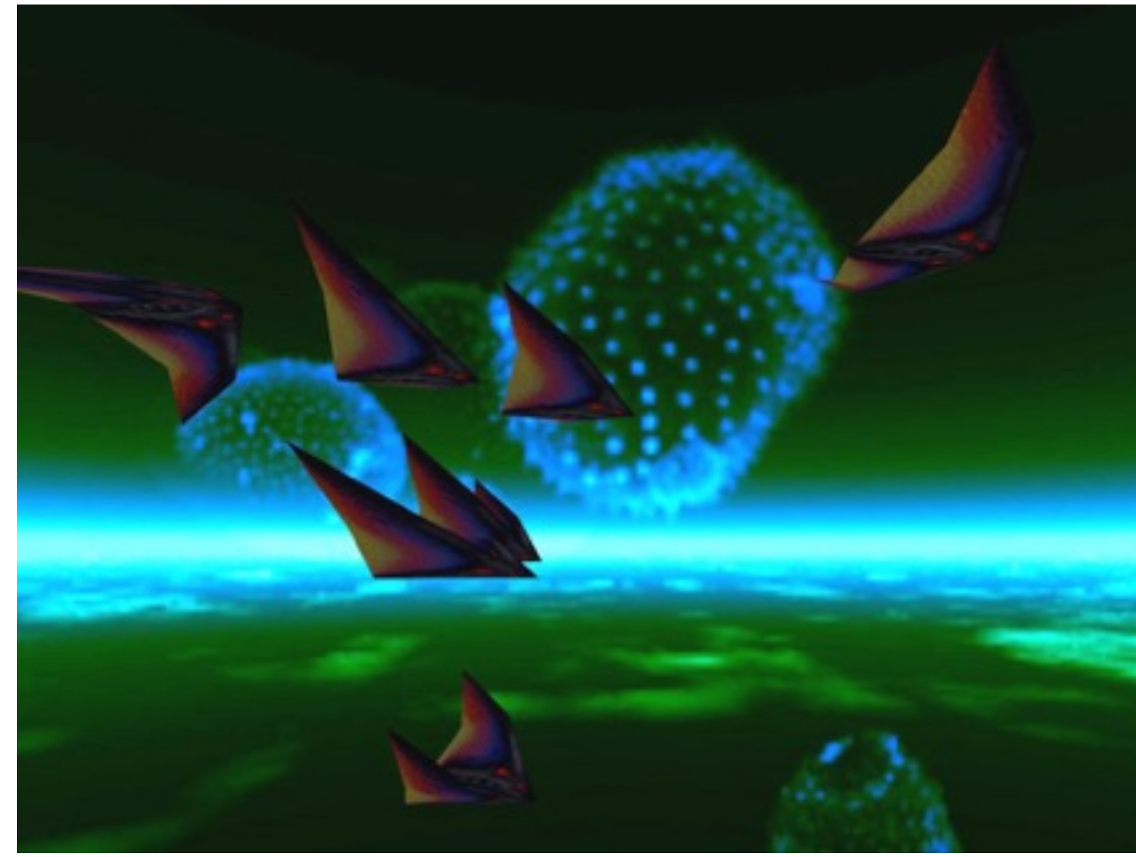
“BOIDS” IN ACTION

Extract from “Stanley and Stella in: Breaking the Ice” (1987), created by: Symbolics Graphics Division

A short film developed by Craig Reynolds and others at Symbolics Graphics Division was premiered at SIGGRAPH ‘87. It showcased the capabilities of the “Boids” algorithm.

“BOIDS” GO MAINSTREAM

Extract from “Batman Returns” (1992), directed by: Tim Burton



From the game “HλLF-LIFE” (1998), developed by: Valve

A few years later, this algorithm was implemented in highly popular movies and video games to display realistic flocking behaviour.

Concurrently, this problem attracted the interest of physicists…

Red-winged Blackbirds over Mattamuskeet Lake *Photo: Guy Livesay*

MODEL #1

THE VICSEK MODEL

Photo: Owen Humphreys

PHASE TRANSITIONS IN SYSTEMS OF SELF-DRIVEN PARTICLES

- In 1995, Vicsek et al investigated the role of *noise* in the collective dynamics of a system of self-propelled particles.
- For simplicity, agents were assumed to be <u>points in 2D space</u> that move with a constant velocity.
- At each time step an agent surveys its neighbourhood and aligns its direction with that of the average direction of motion.
- In addition, in order to account for uncertainty in estimating the average direction, the new direction was subject to a random perturbation.
- It was found that the rotational symmetry is spontaneously broken, giving rise to a kinetic phase transition from no transport (zero average velocity) to finite net transport.

THE MODEL BY VICSEK ET AL (1995)

- The system consists of N agents $\boldsymbol{i}$ that move with a time-invariant absolute velocity v, and in a direction $\theta(t)$ at time t.

- At each time step the position of each agent $\mathbf{x}_i$ is updated:

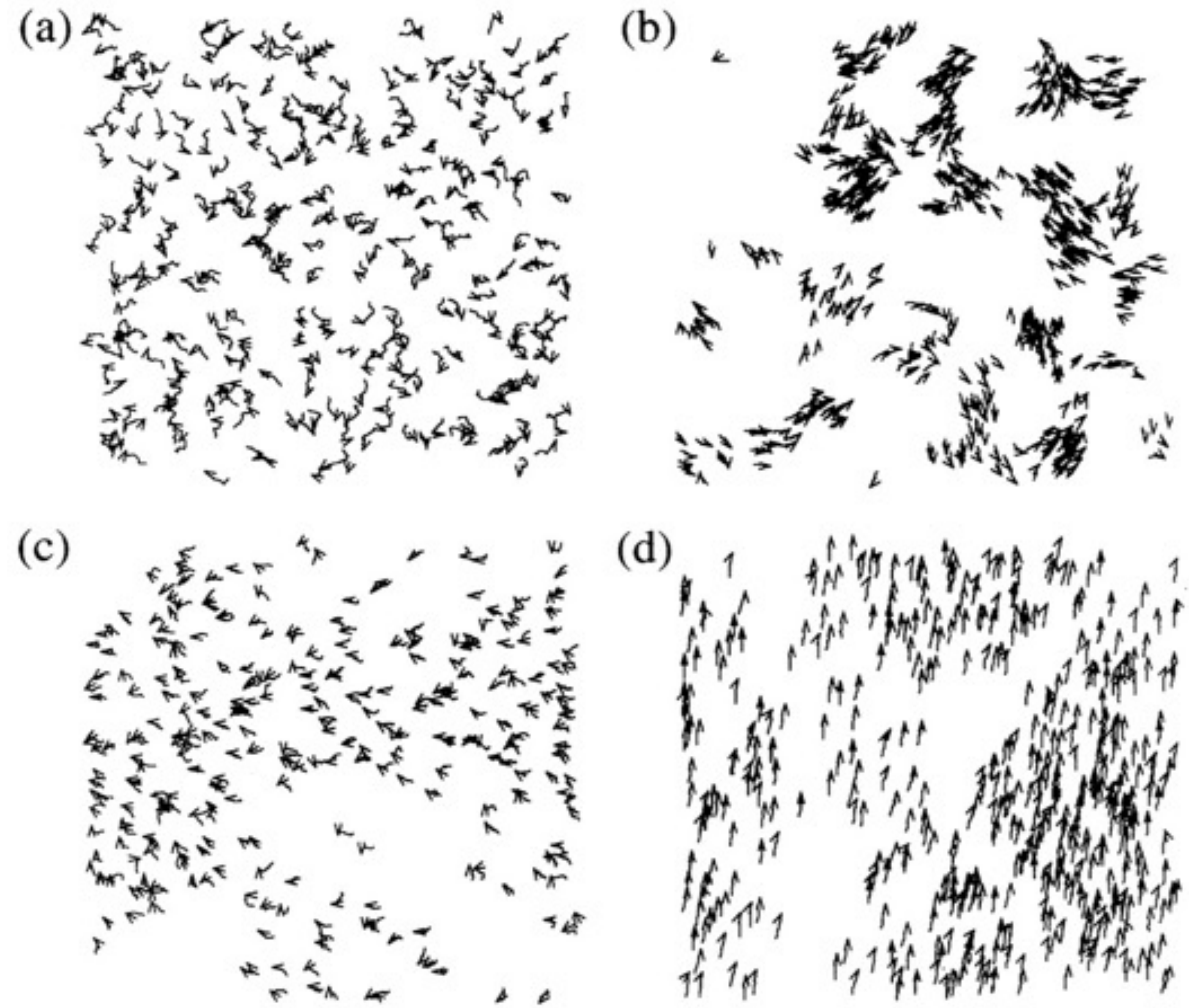
$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{v}_i(t)\Delta t$$

- The direction of each agent is also updated:

$$\theta(t+1) = \arctan\left(\frac{\langle \sin\theta(t)\rangle_r}{\langle \cos\theta(t)\rangle_r}\right) + \Delta\theta$$

where $\Delta\theta \in [-\eta/2, \eta/2]$, r is the radius of the neighbourhood and the noise level is η.

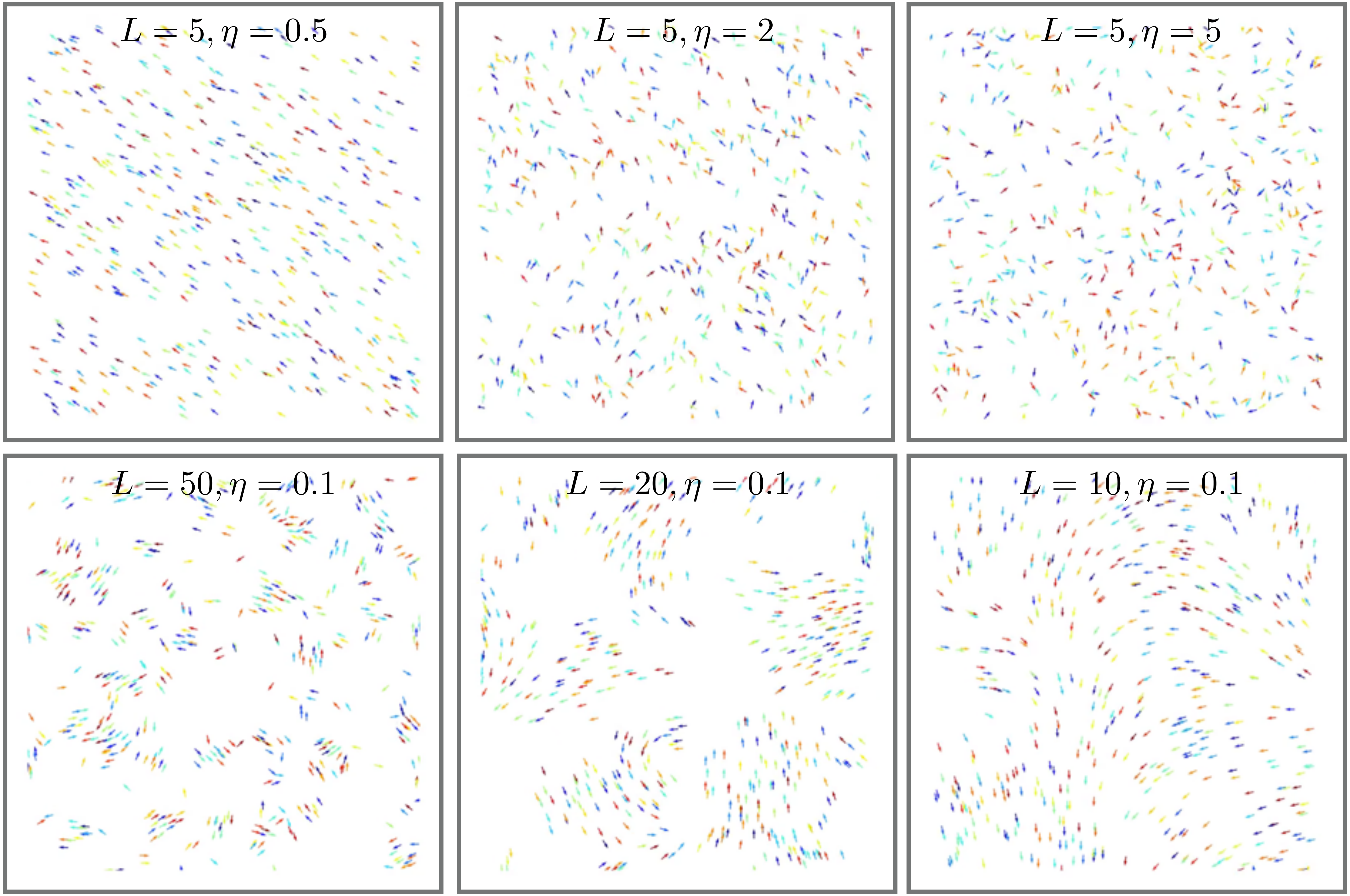
$L = 7, \eta = 2$ $L = 25, \eta = 0.1$



$L = 7, \eta = 2$ (later time) $L = 5, \eta = 0.1$

- Simulations were performed in a box of size L using periodic boundary conditions. On fixing N, the effect of η and L on the collective dynamics was investigated.

SIMULATION RESULTS

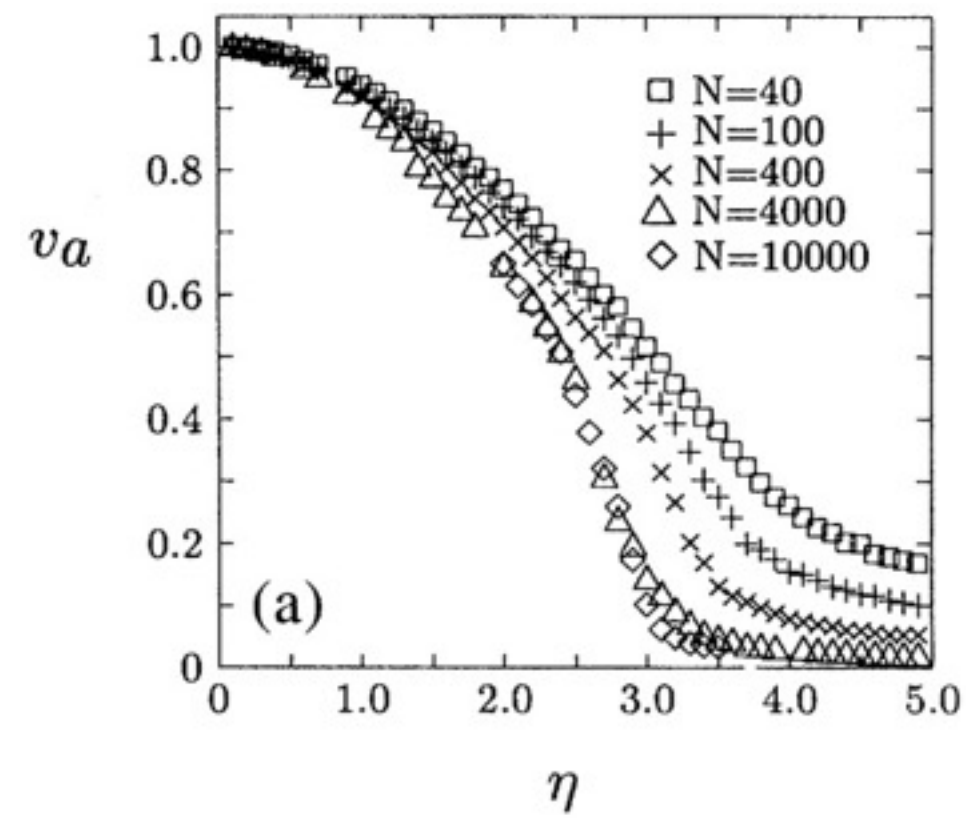


PHASE TRANSITION IN THE VICSEK MODEL

- For large density and small noise, the motion is ordered at the macroscopic scale. That is, the system undergoes a phase transition from an ordered to a disordered state.
- To characterize this, the average normalised velocity is considered:

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

  This is zero in the fully disordered case and one in the fully ordered case.
- Simulations were performed for a range of system sizes. It was found that the average velocity scales as $v_a \sim [\eta_c(\rho) - \eta]^\beta$ where β is around 0.5. From this, the value of $\eta_c(L)$ could be estimated for an infinitely large system.



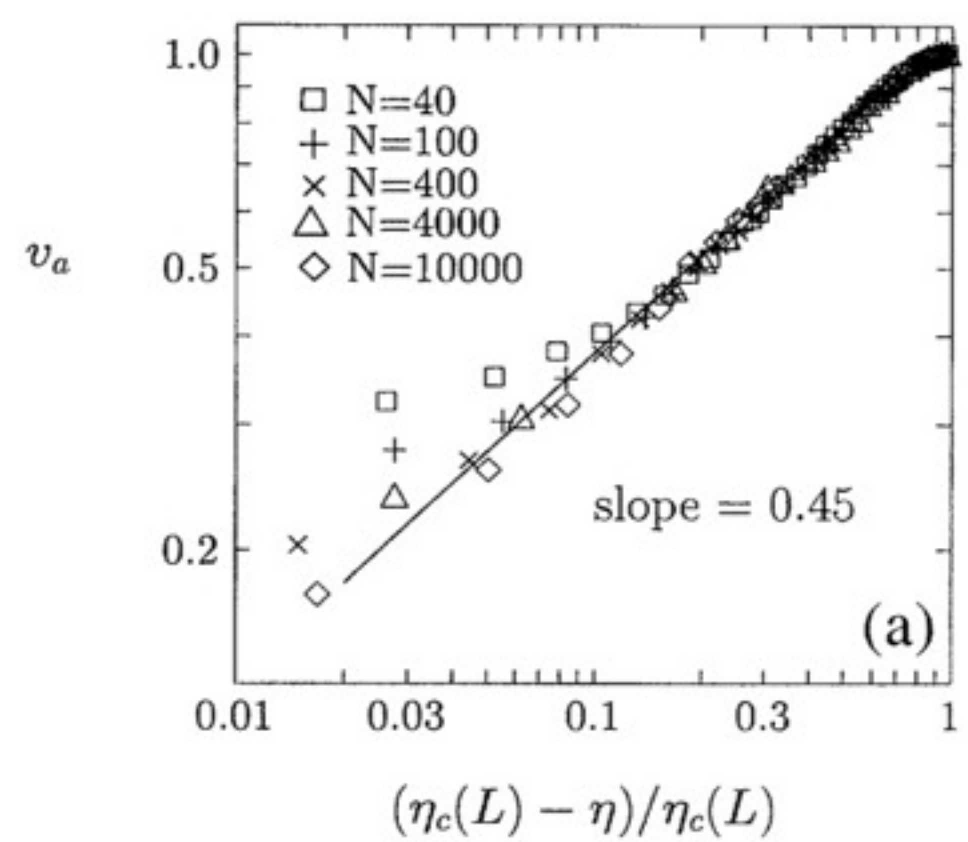


Photo:Laura Frazier

SIGNIFICANCE OF THE MODEL

- This model is a non-equilibrium dynamical analogue of the *ferromagnetic* type of models. Here, in place of spin alignment, there is direction alignment, and perturbations play the role of temperature.
- The system develops long-range order, even with only short-range interaction. This allows it to spontaneously break a continuous symmetry and hence exhibit a phase transition. Such behaviour cannot arise in equilibrium systems.
- As self-propelled particles are ubiquitous in biological contexts, and since biological subjects tend to imitate the actions of neighbours, this model is well-suited to describe collective motion in biological systems.

Colony of the vortex morphotype of Bacillus subtilis

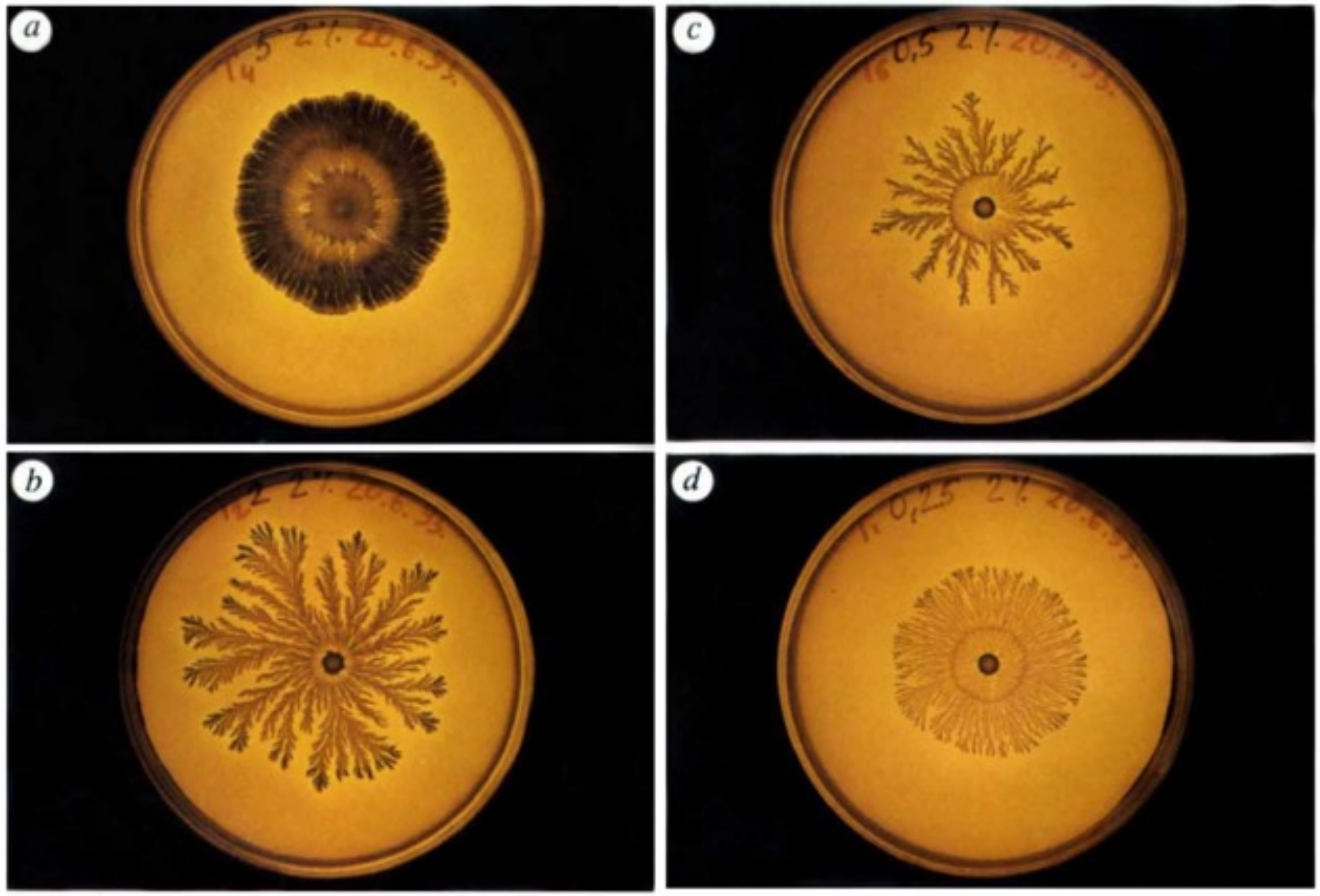
Photo: Eshel Ben-Jacob

MODEL #2

PATTERNS IN BACTERIAL COLONIES

COOPERATIVE GROWTH PATTERNS IN BACTERIAL COLONIES

Patterns in Bacillus subtilis at different levels of peptones.



- To cope with poor nutrient conditions bacterial colonies can exhibit complex growth patterns that arise from cooperative behaviour.
- Here, bacteria communicate indirectly by means of chemotactic feedback. That is, cells secrete a signalling chemical that other cells respond to.

THE MODEL BY BEN-JACOB ET AL (1994)

- The model consists of N walkers i that move via an off-lattice random walk of step size d, and whose location is $\mathbf{r}_i$.
- These walkers are self-propelled particles with a finite energy store W_i. As walkers move, they lose energy at a fixed rate e. They replenish W_i by consuming the underlying nutrient (peptone) at a rate c_r (or, if in a low nutrient environment, the full amount that lies below it).
- If W_i drops to zero, the walker becomes stationary, while if it crosses a threshold t_r the walker reproduces, i.e. divides into two walkers.
- In addition to being consumed by walkers, the nutrient $c(\mathbf{r}, t)$ diffuses at a rate D_c.
- The movement of walkers occurs within an envelope defined on a triangular lattice. Each segment of the envelope moves after being hit by the walkers N_c times. This represents the “pushing” of the agar.

THE MODEL (CONTD.)

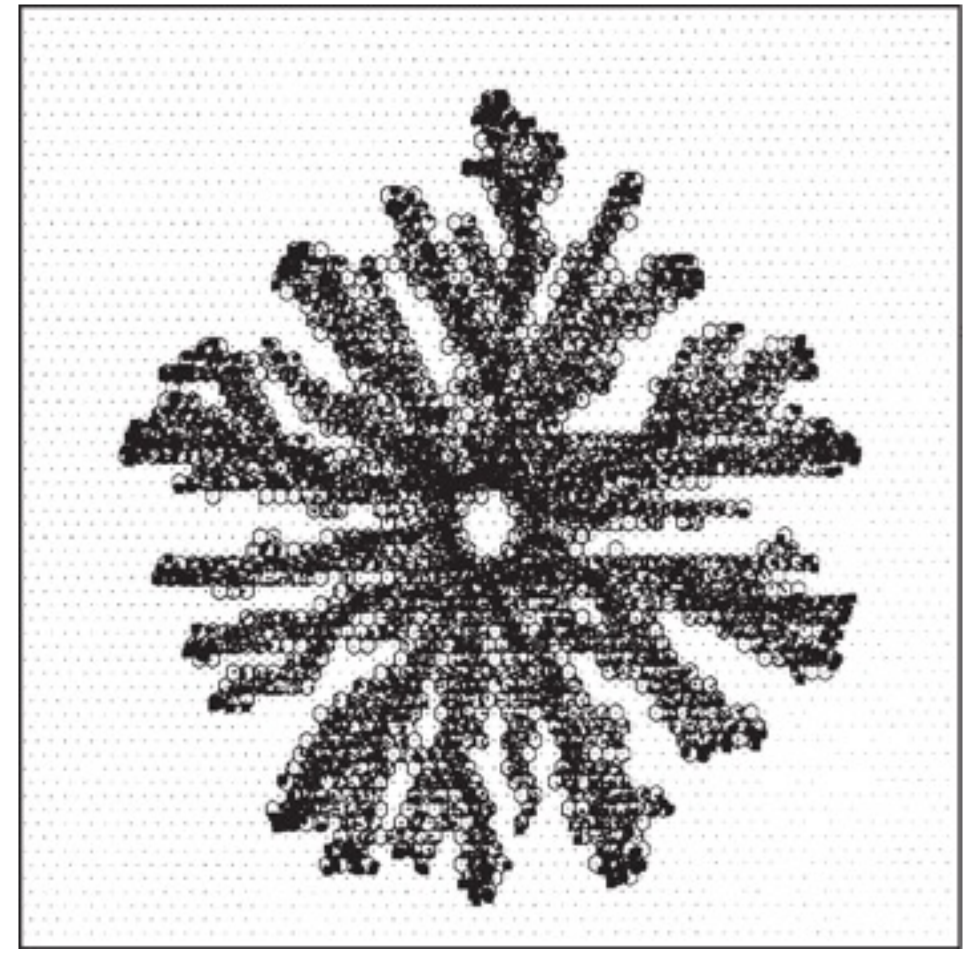
- Thus, the walkers update their positions through the expression

$$\mathbf{r}_i^{'} = \mathbf{r}_i + d(\cos\Theta, \sin\Theta), \quad \Theta \in [0, 2\pi]$$

- The internal energy store evolves as:

$$\frac{dW_i}{dt} = \min(c_r, c(\mathbf{r}, t)) - e$$

- The nutrient concentration is described by



$$\frac{\partial c(\mathbf{r}, t)}{\partial t} = D_c \nabla^2 c(\mathbf{r}, t) - \sum_{\substack{active \\ walkers}} \delta(\mathbf{r} - \mathbf{r}_i) \min(c_r, c(\mathbf{r}, t))$$

- Simulations were performed for different initial values of $c(\mathbf{r}, t)$, i.e. the peptone level P and agar concentration N_c. The system size is 600×600 with $\sim 10^4$ walkers (each walker represents 10^5 bacteria).

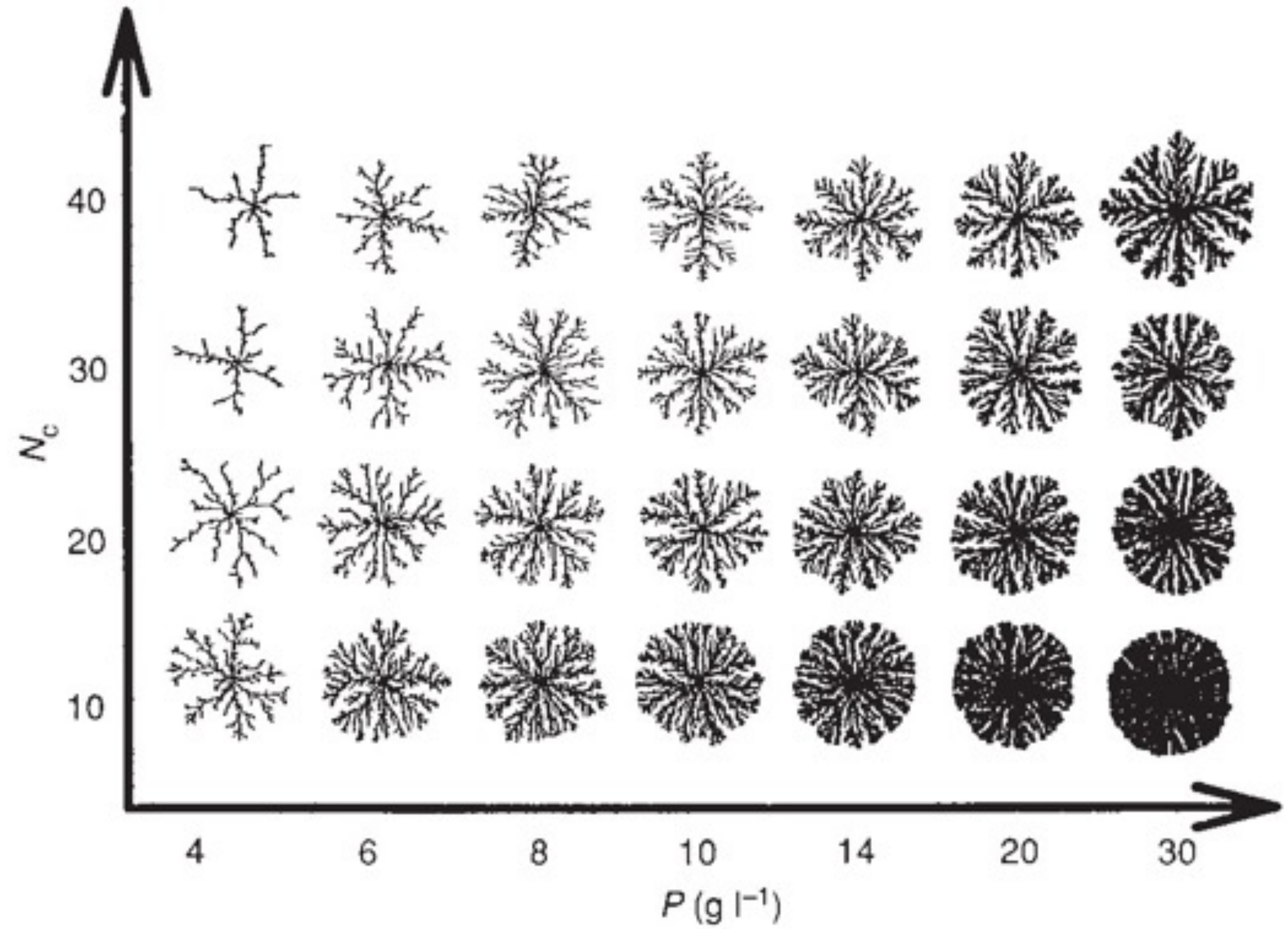
RESULTS

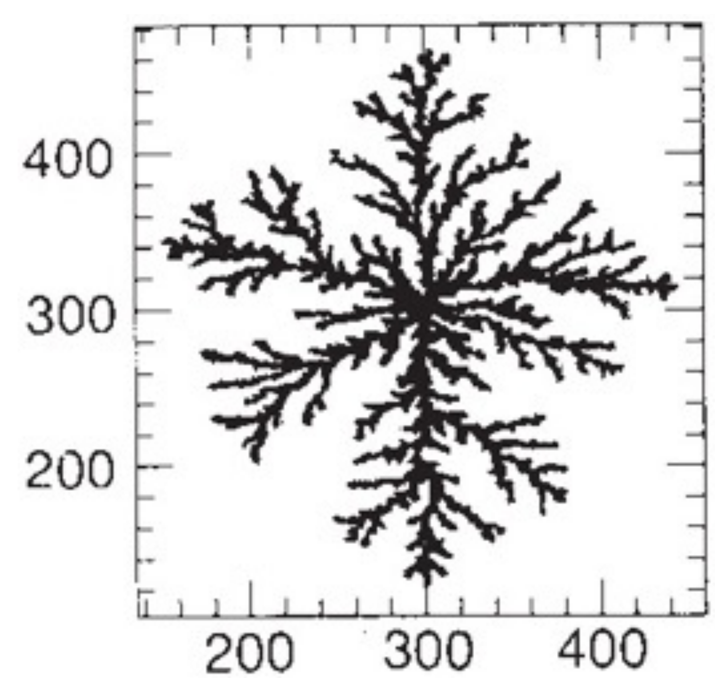
- The patterns are compact/fractal at high/low peptone levels. The patterns are more ramified at higher agar concentrations.

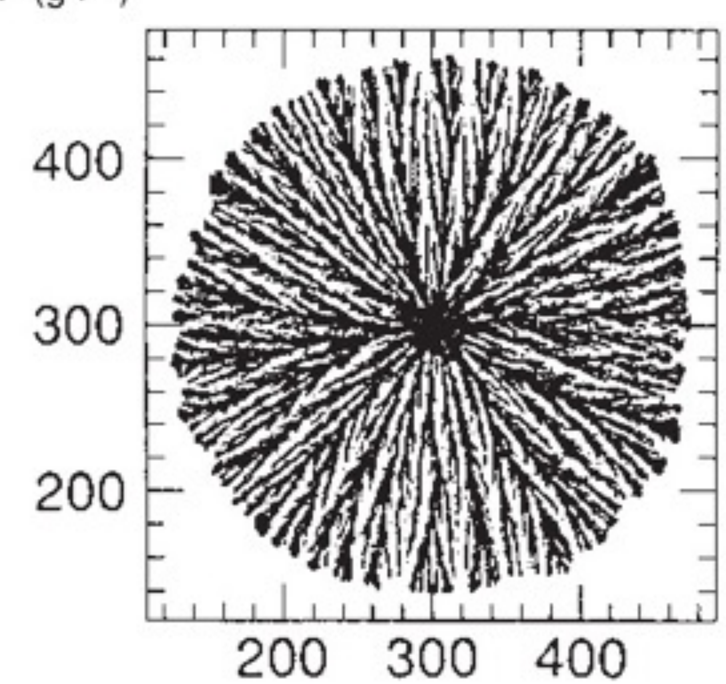
- Chemotactic communication is added to the model by allowing stationary walkers to produce a chemical at rate s_r with the intent of driving away other walkers. In addition, active walkers consume this chemical at rate c_c. Thus,

$$\frac{\partial s(\mathbf{r},t)}{\partial t} = D_s \nabla^2 s(\mathbf{r},t) + \sum_{\substack{stationary\\walkers}} \delta(\mathbf{r}-\mathbf{r}_i)s_r - \sum_{\substack{active\\walkers}} \delta(\mathbf{r}-\mathbf{r}_i)\min(c_c, s(\mathbf{r},t))$$

- If one now introduces a bias for moving towards higher chemical density, aggregation is enhanced.







Love Parade disaster (Duisberg, Germany, 2010) *Photo: Eric Wiffers*

MODEL #3

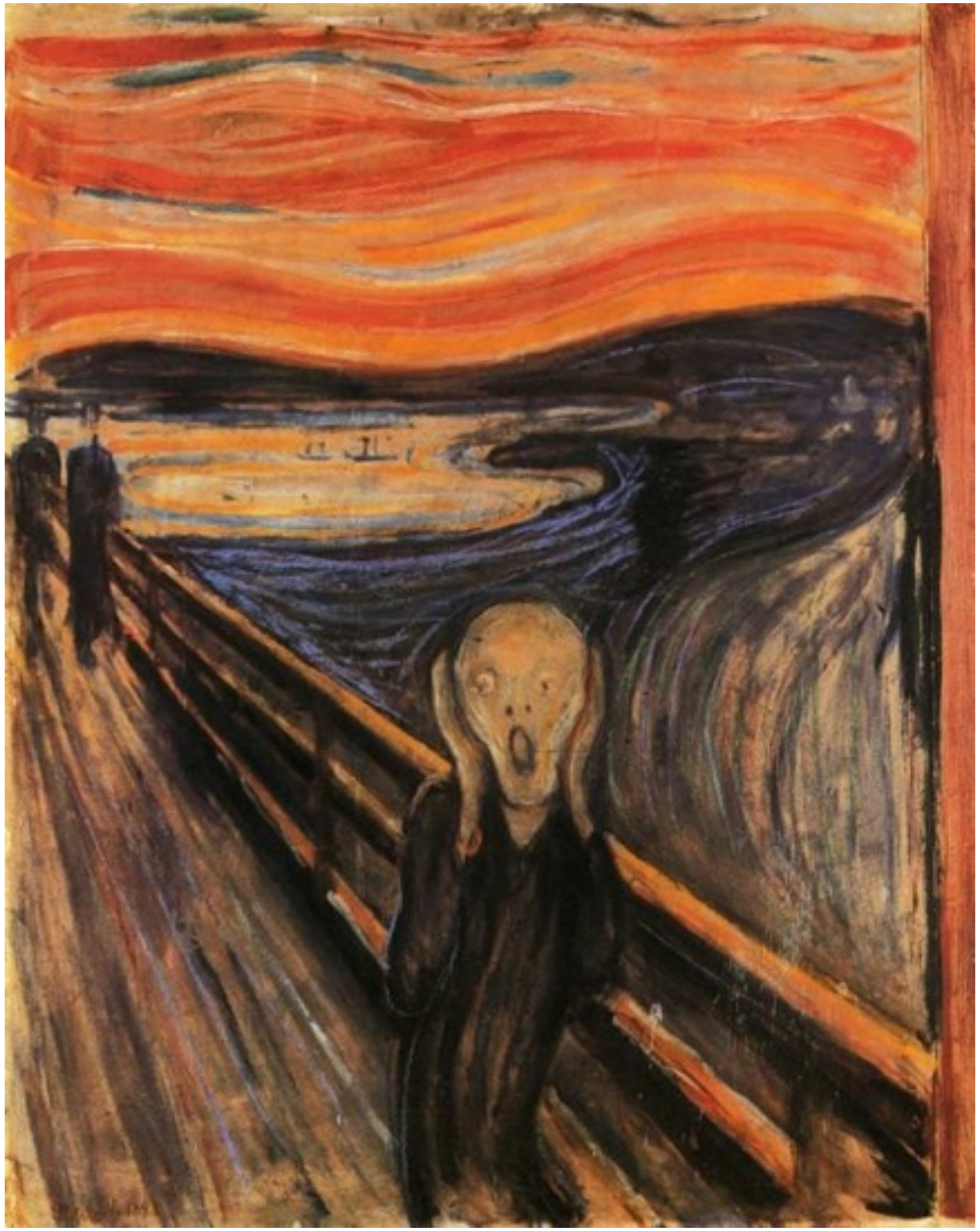
CROWD PANIC

Photo: Ulrike Biets

CROWD STAMPEDES

- Can arise as a result of an emergency, or in a collective state of excitement.
- Its prevention is often an engineering/design issue, but has a component of individual/collective strategy.
- Panic has mostly been examined through the lens of social psychology, and very few theories of crowd dynamics have been developed to date.
- This issue remains urgent due to the continuing occurrences of stampedes at mass events.

PANIC



“The Scream”, Edvard Munch, 1893

- Panic is known to cause mass behaviour such as jamming/ overcrowding.
- This behaviour has been previously studied through conceptual frameworks such as social contagion* theory.
- Jamming results from uncoordinated motion, and depends on the expected “reward”.

* The spread of ideas, attitudes, or behaviour patterns in a group through imitation and conformity. (http://www.oxfordreference.com)

CHARACTERISTICS OF CROWD PANIC

1. Individuals move faster than normal.
2. Physical interactions (pushing) ensue.
3. Bottleneck passing becomes uncoordinated.
4. Arching and clogging is observed at exits.
5. Jams build up.
6. Dangerous pressures build up in the jammed crowd, which can bend/break barriers and walls.
7. Fallen/injured people are now “obstacles” that slow down escape further.
8. Mass behaviour (imitation) occurs.
9. Alternative exits are overlooked or not used efficiently.

Hillsborough disaster (1989)

A MODEL FOR CROWD PANIC BY HELBING ET AL (2000)

- N agents i of mass m_i intend to move with speed v_i^0 in a direction $\mathbf{e}_i^0$.
- Each agent modifies their velocity $\mathbf{v}_i$ with a characteristic time τ_i based on interactions, leading to a change in position $\mathbf{v}_i(t) = \mathrm{d}\mathbf{r}_i / \mathrm{d}t$.
- Each force expression consists of
  - A repulsive interaction term $A_i \exp[(r_{ij} - d_{ij})/B_i]\mathbf{n}_{ij}$, where $r_{ij} = r_i + r_j$ $d_{ij} = \left\|\mathbf{r}_i - \mathbf{r}_j\right\|$ and $\mathbf{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\mathbf{r}_i - \mathbf{r}_j)/d_{ij}$ is the normalised vector pointing from j to i (note that i is trying to move away from j).
  - A body force that counteracts body compression $k(r_{ij} - d_{ij})\mathbf{n}_{ij}$
  - A sliding friction force that impedes relative tangential motion, $\kappa(r_{ij} - d_{ij})\Delta v_{ji}^t \mathbf{t}_{ij}$, where $\mathbf{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$ and $\Delta v_{ji}^t = (\mathbf{v}_j - \mathbf{v}_i) \cdot \mathbf{t}_{ij}$.

THE MODEL (CONTD.)

- The change in velocity is specified through the equations:

$$m_i \frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_W \mathbf{f}_{iW}$$

$$\mathbf{f}_{ij} = \left\{ A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij}) \right\} \mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij}) \Delta v_{ji}^t \mathbf{t}_{ij}$$

$$\mathbf{f}_{iW} = \left\{ A_i \exp[(r_i - d_{iW})/B_i] + kg(r_i - d_{iW}) \right\} \mathbf{n}_{iW} - \kappa g(r_i - d_{iW})(\mathbf{v}_i \cdot \mathbf{t}_{iw})\mathbf{t}_{iW}$$

where j are the neighbours and W are the walls, and where $g(x)$ is zero if there is no contact, i.e. $d_{ij} > r_{ij}$. The following parameters are used:

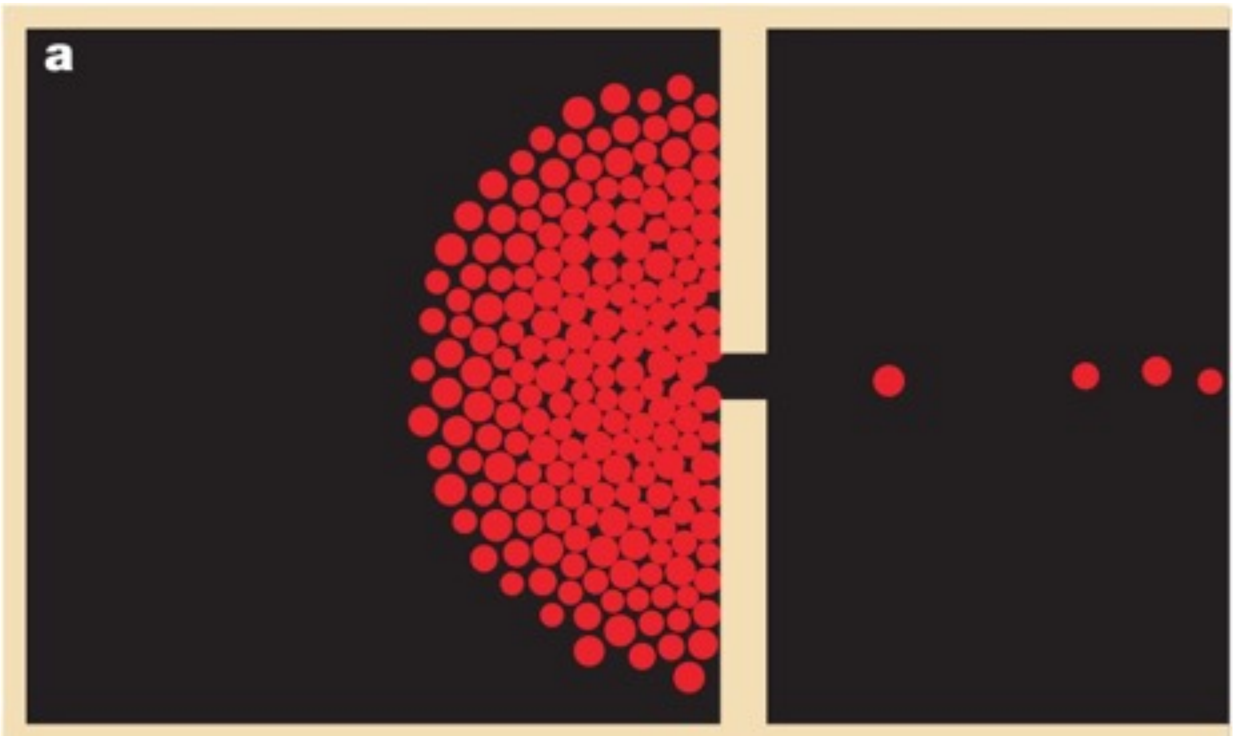
$$m_i = 80\mathrm{kg},\ \mathrm{v}_i^0 \approx 0.8\mathrm{m\ s}^{-1},\ \tau_i = 0.5\mathrm{s},$$

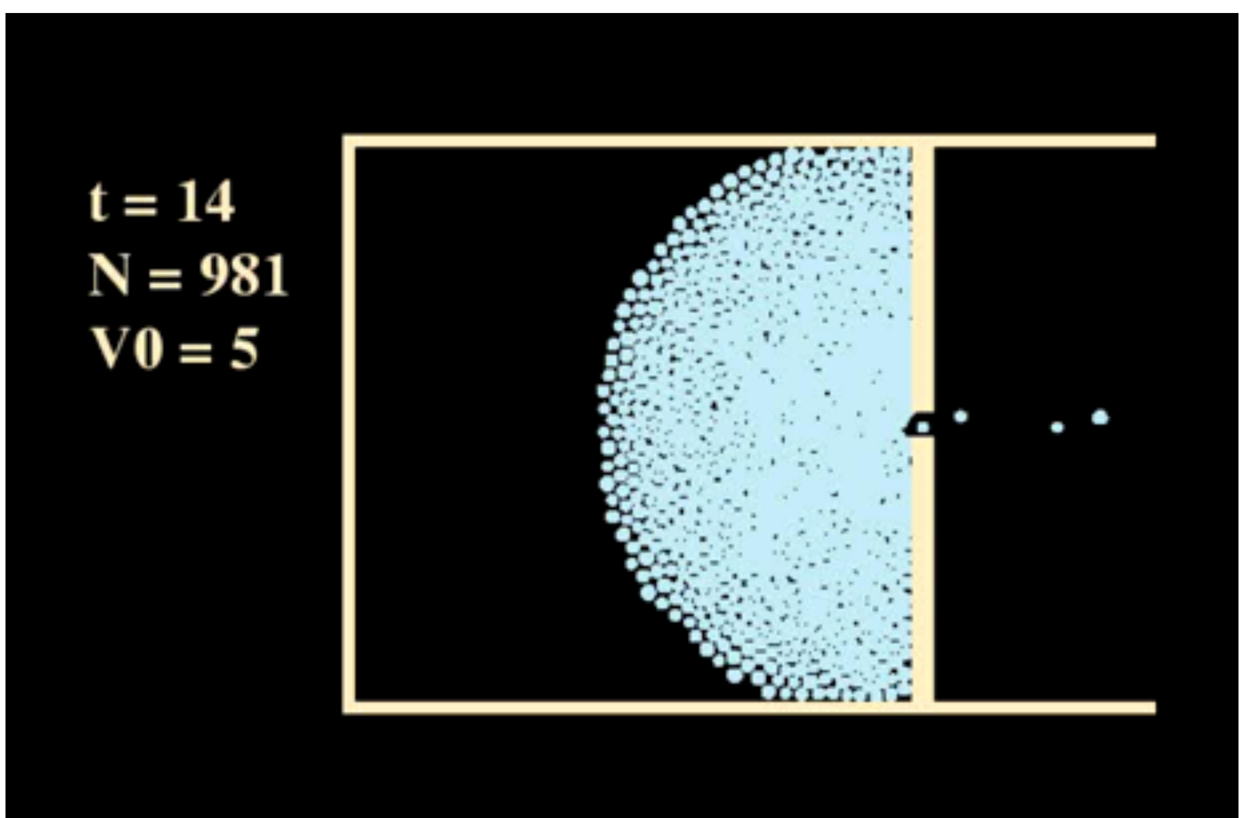
$$A_{\mathrm{i}} = 2 \times 10^3 \mathrm{N},\ B_{\mathrm{i}} = 0.08\mathrm{m},$$

$$k = 1.2 \times 10^5 \mathrm{kg\ s}^{-2},\ \kappa = 2.4 \times 10^5 \mathrm{kg\ m}^{-1}\mathrm{s}^{-1}$$

and the agent's diameters are randomly chosen from the range [0.5m, 0.7m].

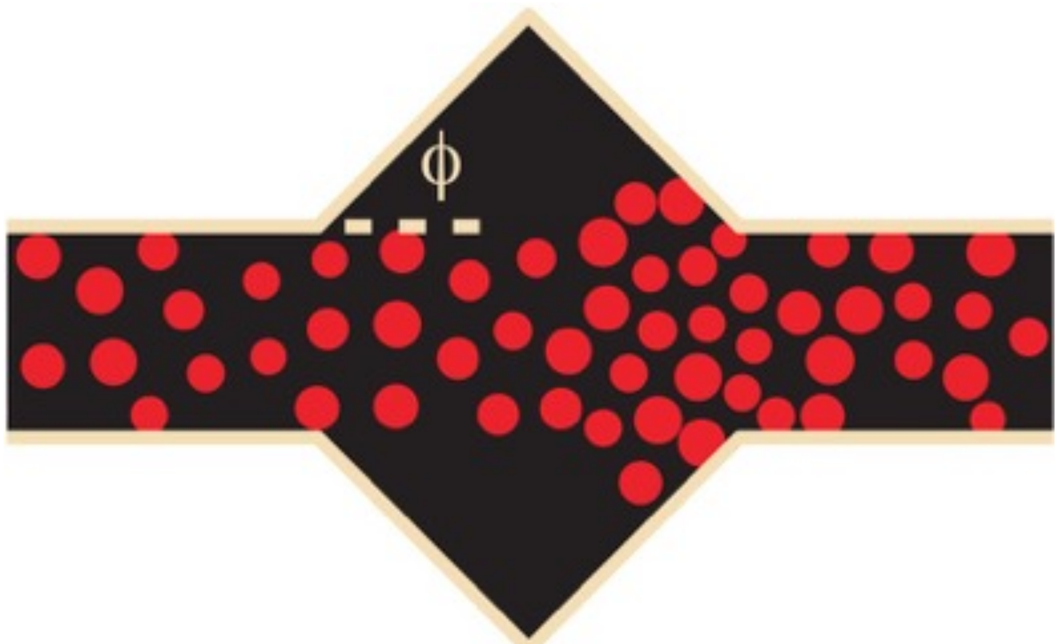
CASE #1: CLOGGING

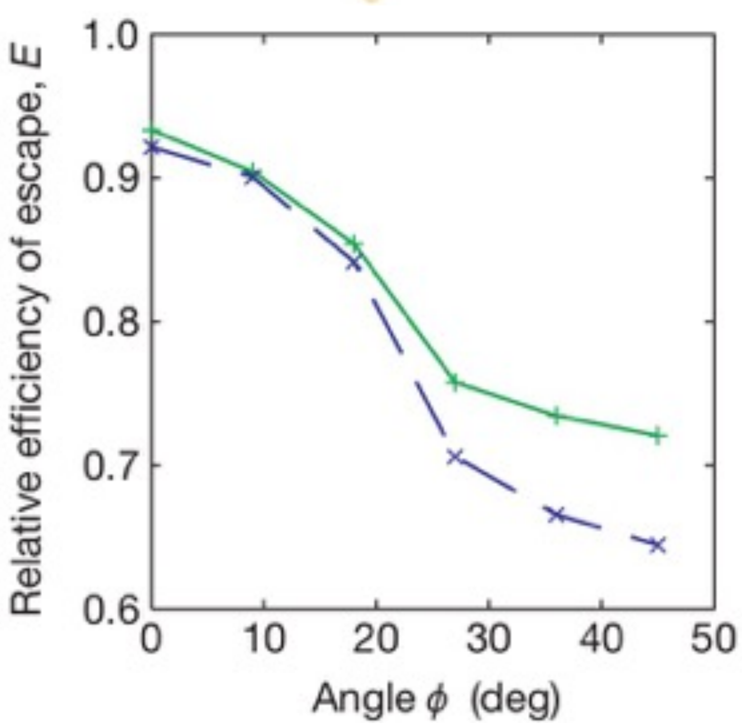




- An orderly evacuation is observed for low desired velocities.
- For large desired velocities, arch-like blocking is observed at the exit.
- Avalanche like bunches of pedestrians leave when the arches break.
- This is comparable to intermittent clogging in granular flows through funnels or hoppers.

CASE #2: WIDER ESCAPE ROUTE





- Clogging can be prevented by avoiding bottlenecks when constructing stadia and public buildings.
- However, jamming can still occur in some cases.
- In the example shown to the left, the relative escape efficiency $E = \left\langle \mathbf{v}_i \cdot \mathbf{e}_i^0 \right\rangle / v_0$ decreases as the angle of the widening increases.
- This is due to overtaking, and repulsion-initiated arching.

OUTLOOK

Source: http://theconversation.com/standing-room-only-32737

Source: http://crowdmanagementacademy.com/usacrowdmanagement.htm

- The model is based on plausible crowd interactions, drawing from socio-psychological literature, media reports, empirical investigations and engineering handbooks.
- The dynamics can be altered from normal to panic situations through a single parameter.
- The results are robust with respect to changes in parameter values.
- The model could be used to test building designs, i.e. predict outcomes of emergency situations in crowded rooms.

Penguin March

Photo: Jerome Maison

CONCLUSIONS

FEATURES OF COLLECTIVE MOTION

- Such systems have common features:
  - Qualitative aspects can be described with simple models.
  - Stochasticity can be implemented in a very straightforward way.
  - Global order arises as momentum is <u>not conserved</u>.
  - There exist "universal" patterns (disordered, fully ordered, jammed, etc).

- Such systems exhibit transitions between collective states upon changing the density or magnitude of noise.

source: https://beptonranger.com

WHY STUDY COLLECTIVE MOTION?

- Understanding this may help in
  - Predicting global displacement of fish schools.
  - Preserving biodiversity of migrating birds or mammals.
  - Minimizing fatalities during crowd panic.
- There remain several challenges:
  - How does one acquire more accurate empirical data?
  - What is the role of leadership/heirarchy?
  - Are there any underlying laws that hold across scales?

source: https://ronmitchelladventure.com

Photo: Arni Einarsson

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Photo: Frans Lanting

FURTHER READING

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source: https://www.youtube.com/watch?v=tDQw21ntR64

Thank you!