Universal patterns and network dynamics in collective motion:

Observations, experiments and models of flocking

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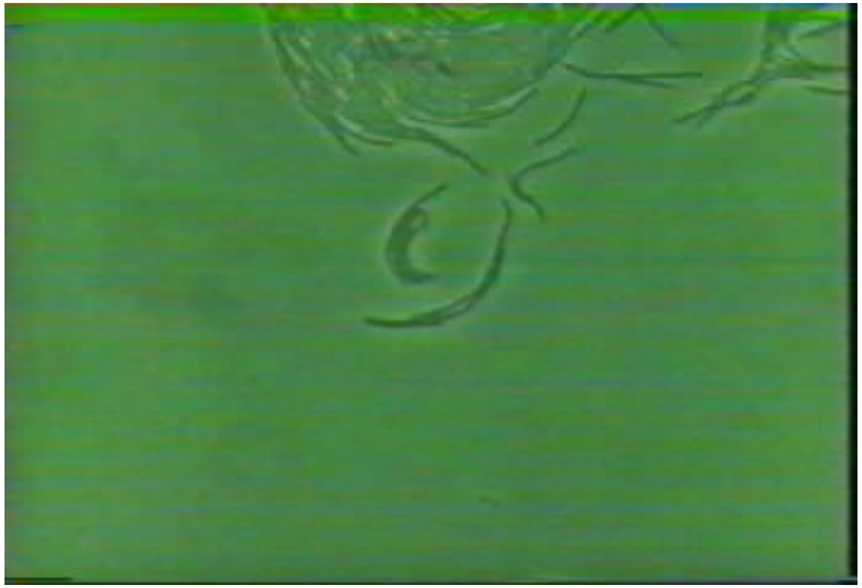
EU FP6 Starflag project
EU ERC COLLMOT project

Collective motion of

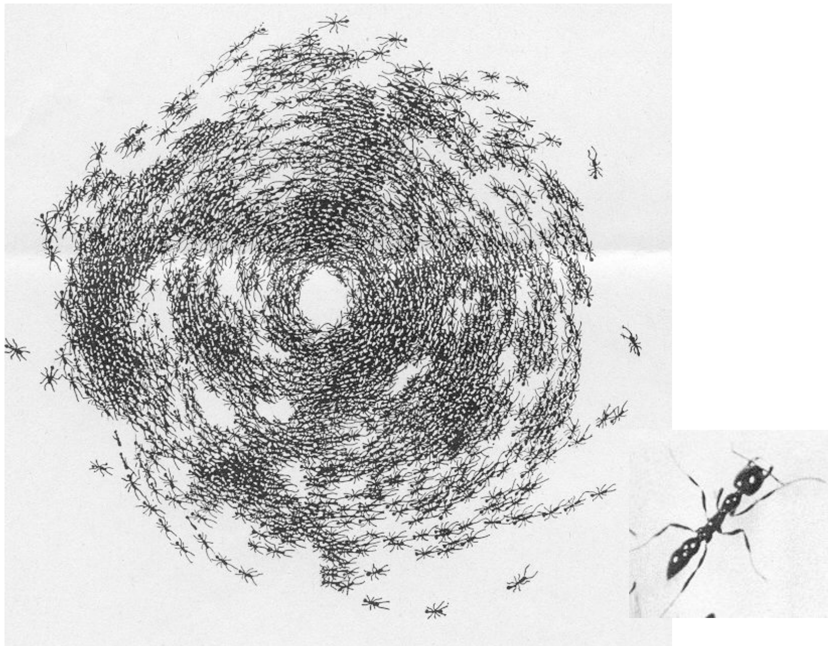


From BBC (I. Couzin)

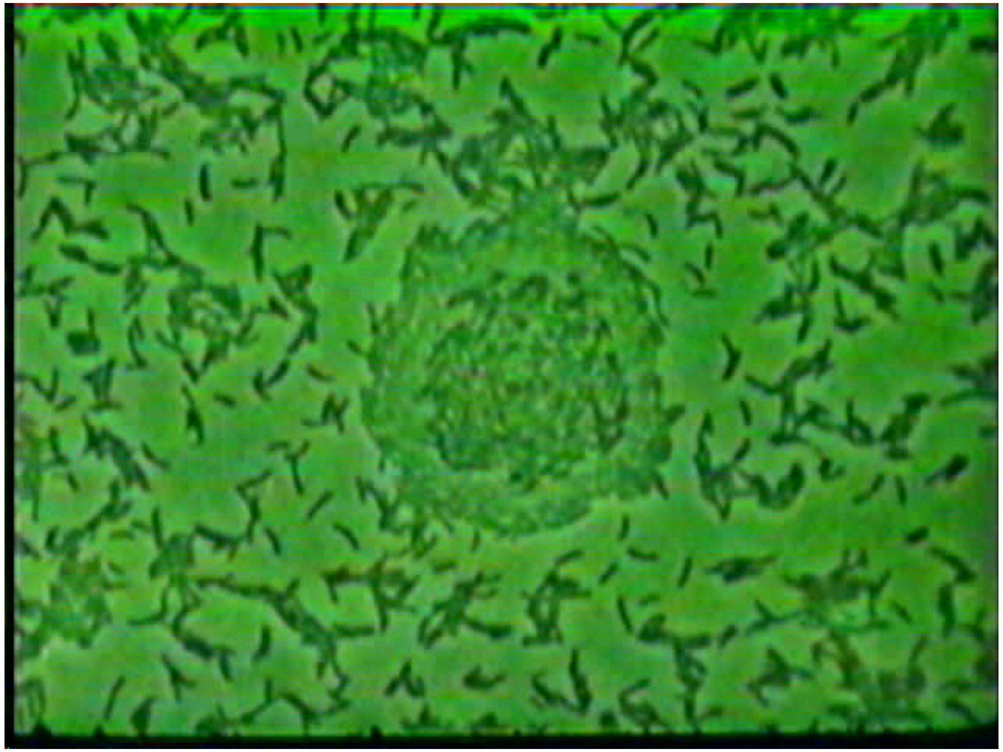
Collective motion of

A universal pattern of motion

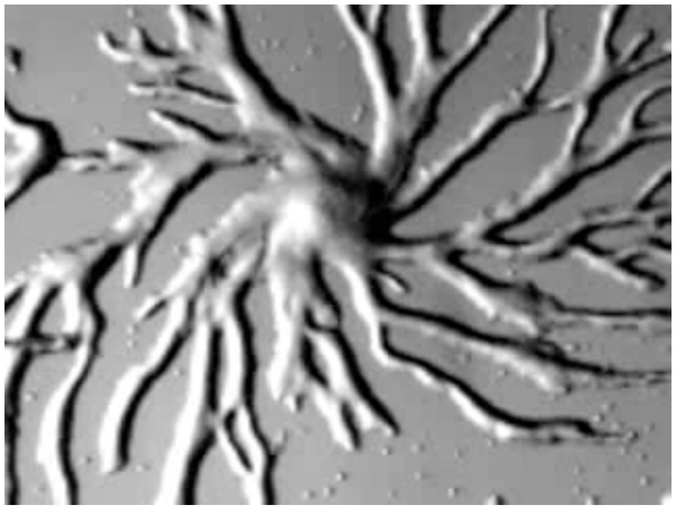
Bacteria (Czirok, Ben-Jacob,…T.V., PRE 1996)

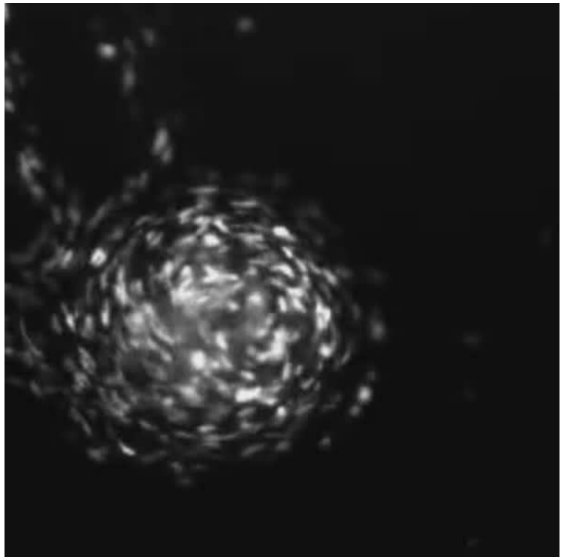


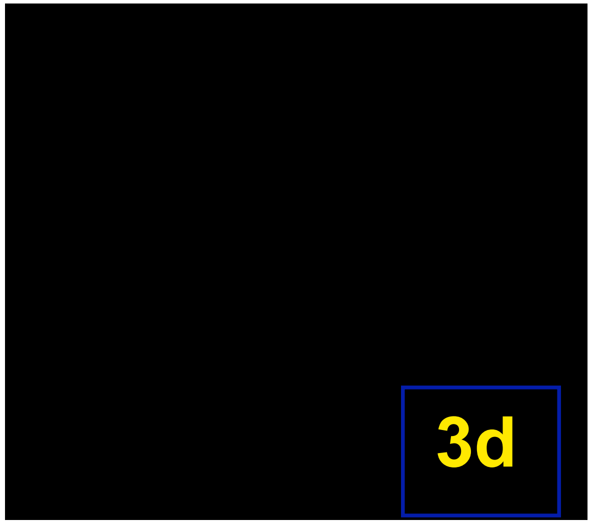
Locusts (Buhl, Sumpter, Couzin et al, *Science*, 2006)



bacteria







Amobae (dyctyostelium discodeum)


Self-Organized Flocking
of Kobots in a Closed Arena
Ali E. Turgut, Hande Çelikkanat,
Fatih Gökçe and Erol Şahin
KOVAN Research Lab.
Dept. of Computer Eng.
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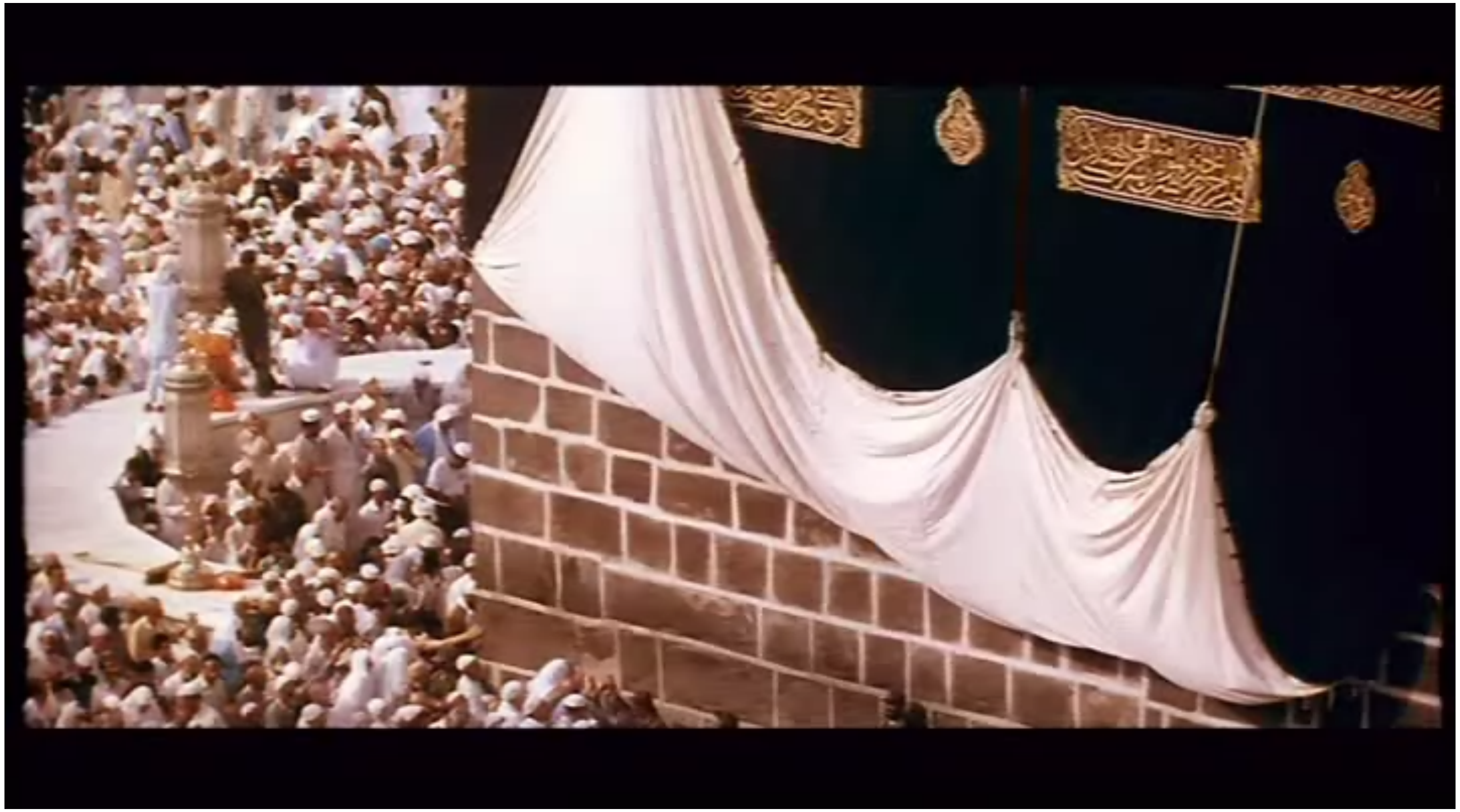
Ankara, Turkey



Observation: complex units exhibit simple collective behaviours.

Different types of collective motion patterns in a sense correspond to various kinds of „consensus”.

Our goals are:

- classification of patterns of collective motion
- finding the basic laws of collective motion (microscopic versus global)

Understanding through modeling and simulation

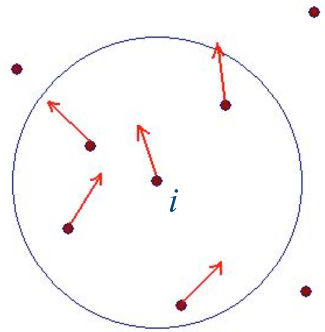
- **First flocking model by C. Reynolds, 1987,**
    - few dozen "boids", computer graphics appl.
    - attraction, repulsion, common direction (continuous, deterministic)

- **Statistical physics model for flocking**, T.V. et al, 1995
    - many thousands of particles (SPP)
    - average direction + noise (discrete in time) phase transition (continuous)

Recent models (stat. phys.):
- average direction, cohesion + noise (Gregoire et al, 2003)
- vectorial noise, first order phase trans. (2004 Gregoire, Chaté)
- interacting active Brownian particles (Ebeling, Schweitzer, others)
- models with "leaders" (Couzin, others, 2005)
- „soft" interaction potential (Cucker and Smale, 2005)
- model with escape and pursuit (Romanczuk, Couzin, & Schimansky-Geier, 2009)
- model with physical collisions only (Grossman et al 2008)
- cell-sorting enhanced by swarming (Chaté and co-workers, 2008)

Swarms, flocks and herds

- <u>Model*:</u> The particles



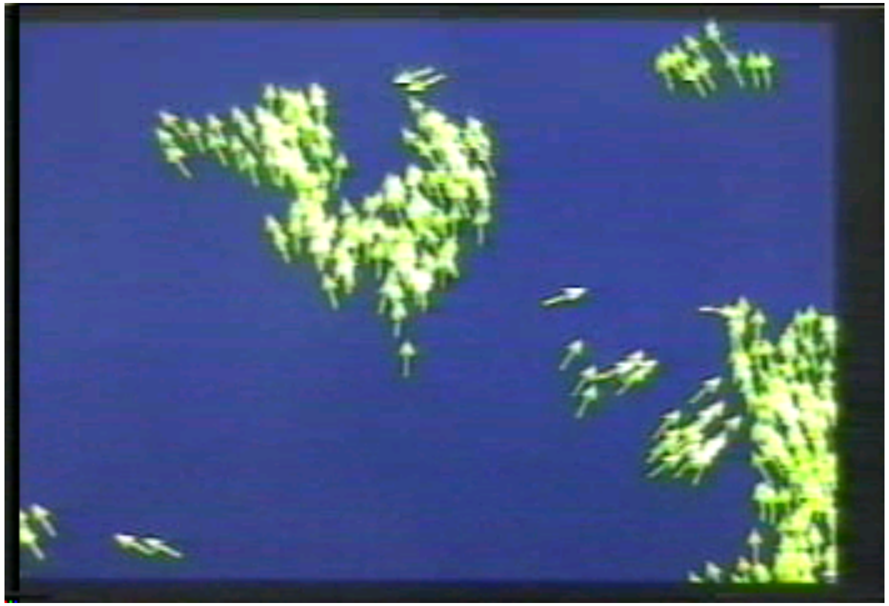
- maintain a given absolute value of the velocity v_0
- follow their neighbours
- motion is perturbed by fluctuations η

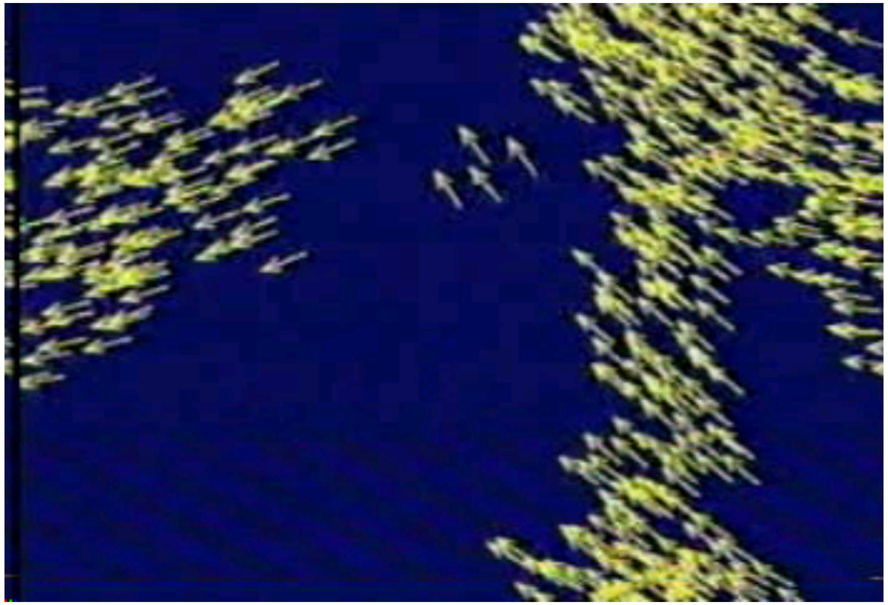
$$\vec{e}_i\,(t+1) = E\Big[E[\langle \vec{e}_j\,(t)\rangle_j\,] + \vec{\eta}(t)\Big]$$

(E normalizes the magnitude into unity)

- Follow the neighbours rule is an abstract way to take into account interactions of very different possible origins

- <u>Result:</u> *ordering is due to <u>motion</u>*





* T.V, A. Czirok, E. Ben-Jacob and I. Cohen, PRL, 1995

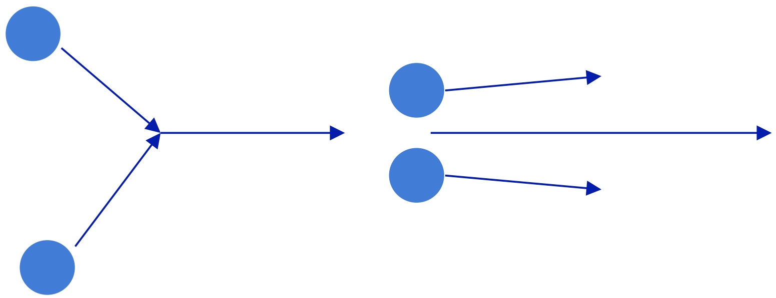
Lessons:

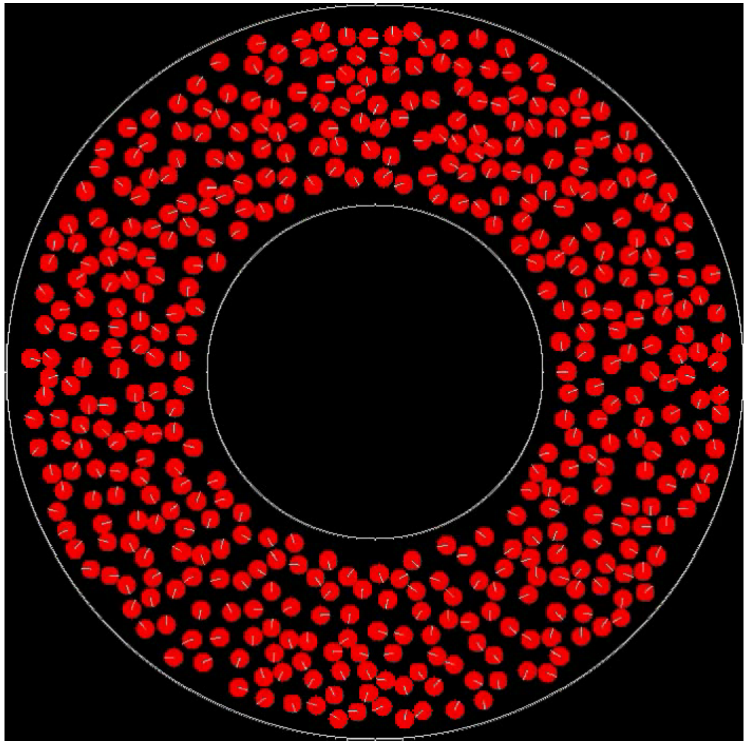
1. Most patterns of collective motion are *universal*

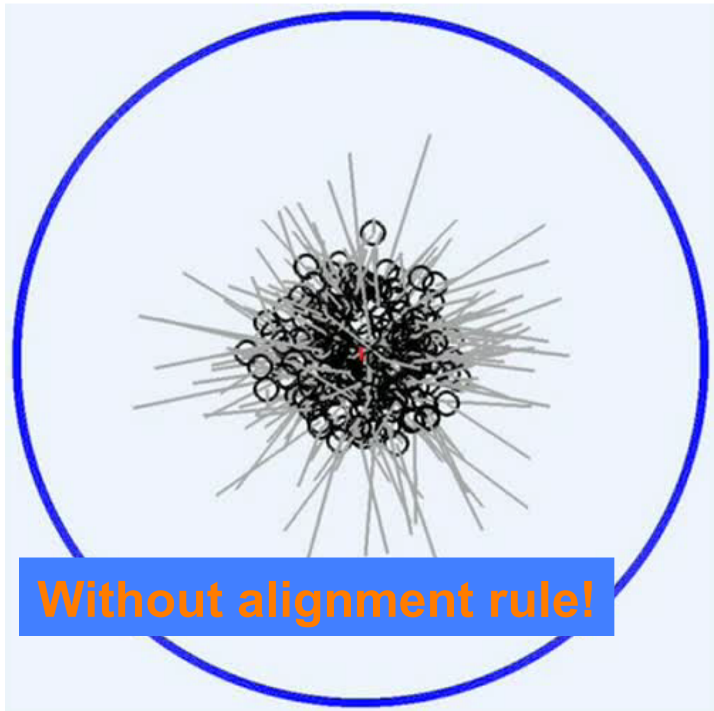
2. Simple models can reproduce this behavior

3. A simple noise term can account for numerous complex deterministic factors

4. In many cases ordering is due to motion! In other words: in SPP systems momentum is not conserved!







Visualizations of various 3d versions

Scalar noise
(1995 PRL Vicsek et al model)
Low velocity (v=0.1)

More “realistic” model
(***with repulsion + attraction***
Reynolds, Couzin and others)
Periodic boundary conditions

More “realistic” model

In a cylinder

More “realistic” model

Birds’ view

A further lesson:

The „critical" state (between ordered and disordered, with large fluctuations) seems to be optimal for the propagation of information (due to higher level of mixing) which is useful from the points of

- exploration
- collective decision making

Universal classes of flocking patterns ("phases")

i) *disordered* (particles moving in random directions)

ii) *fully ordered* (particles moving in the same direction)

iii) *rotational* (within a rectangular or circular area)

vi) *critical* (flocks of all sizes moving coherently in different directions. The whole system is very sensitive to perturbations)

v) *quasi-long range* velocity correlations (ripple?) (for elongated particles)

vi) *Jamming*

Types of transitions

- Continuous (second order)
- Discontinuous (first order)
- No singularity in the level of directedness
- Jamming

Second part:

Recent, ongoing investigations in our lab

a) Dynamically changing clusters in the simplest SPP model

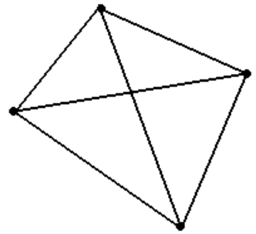
b) Tracking the trajectory of

- toy boats and
- homing pigeons

Network dynamics in flocking models

Network: nodes (particles) and edges (connections, representing interaction)

Network of *k*-cliques (*k (e.g., k*=4*)* fully connected particles), representing a stronger, more relevant tie within a cluster of particles



Comoving boundary condition!

$\vec{F}_i^{wall}(t)$ is interaction with the "wall" of a given slope, co-moving with the centre of mass

"side view" of the associated potential

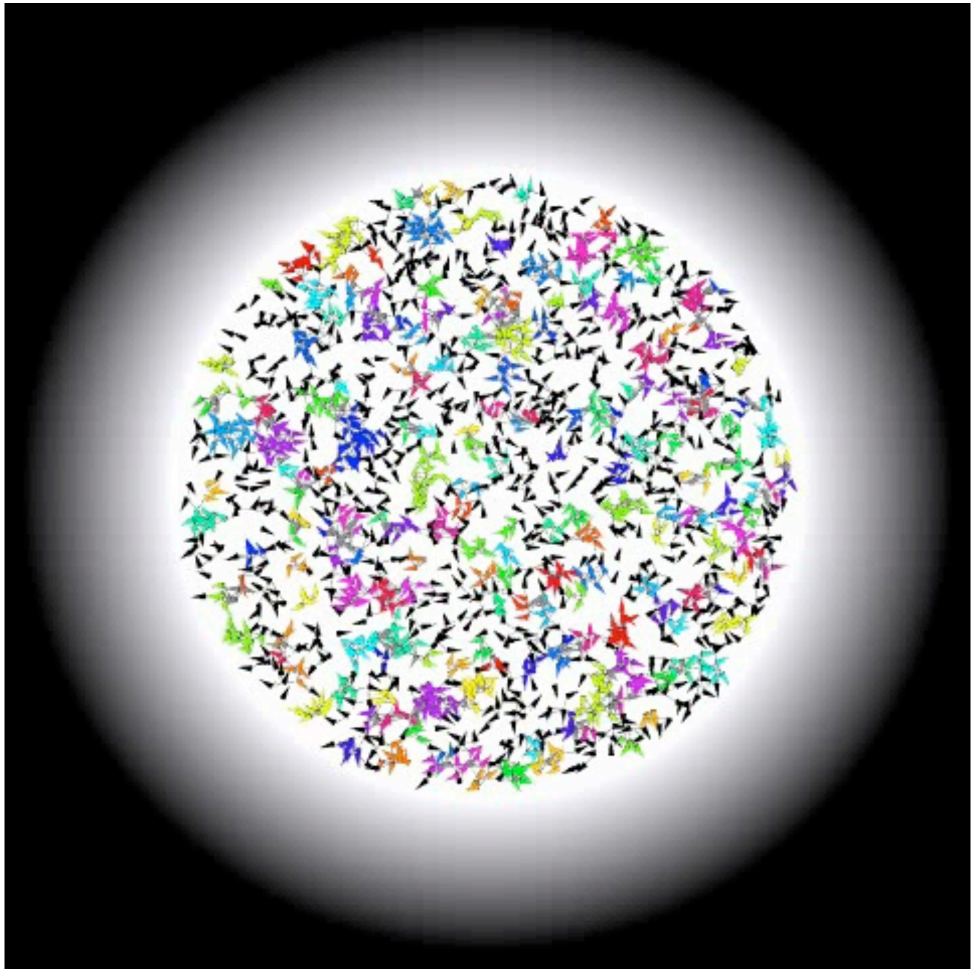
Questions:

What is p the probability that a "large" cluster exists?
What is the rate of change of clusters?

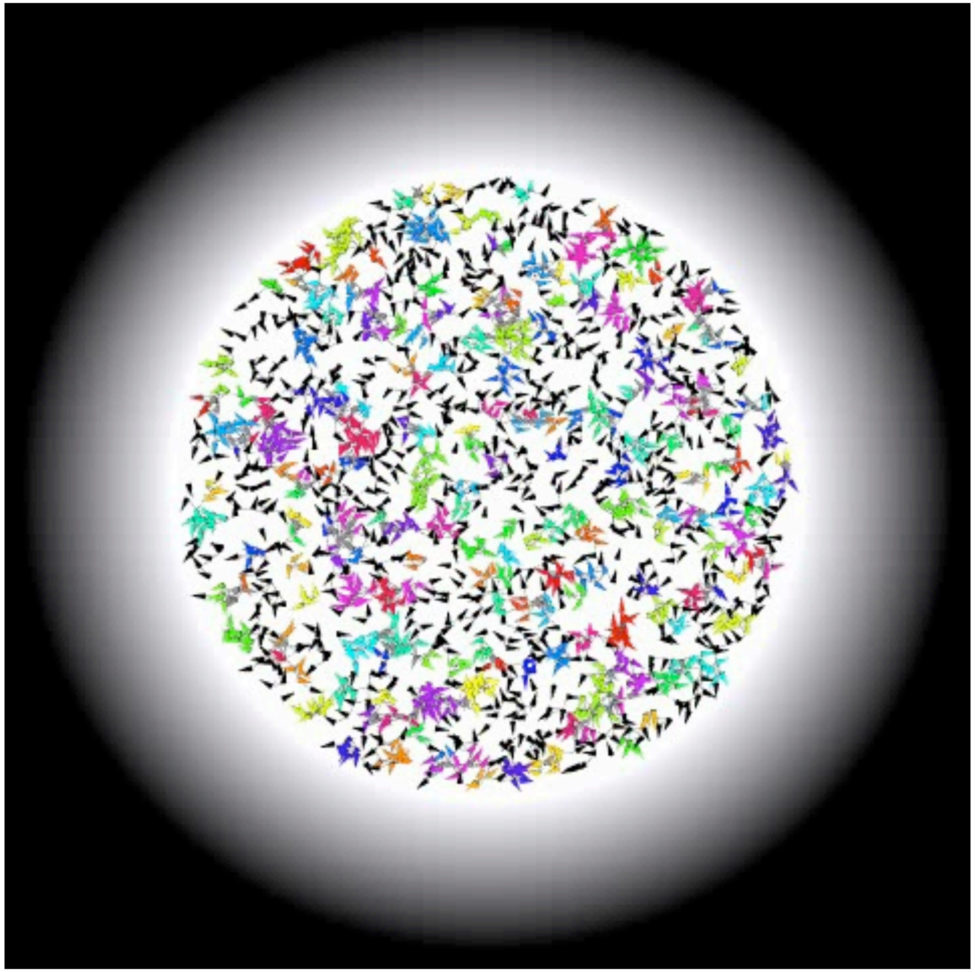
Dynamics of *k*-clique clusters

Two nodes belong to the same cluster if there is connected path of neighbouring *k*-cliques (overlapping cluster analysis of the underlying graph)
Here: $k = 4$
Method after Palla, Barabasi and T.V, *Nature*, 2007

$\eta = 0.4$

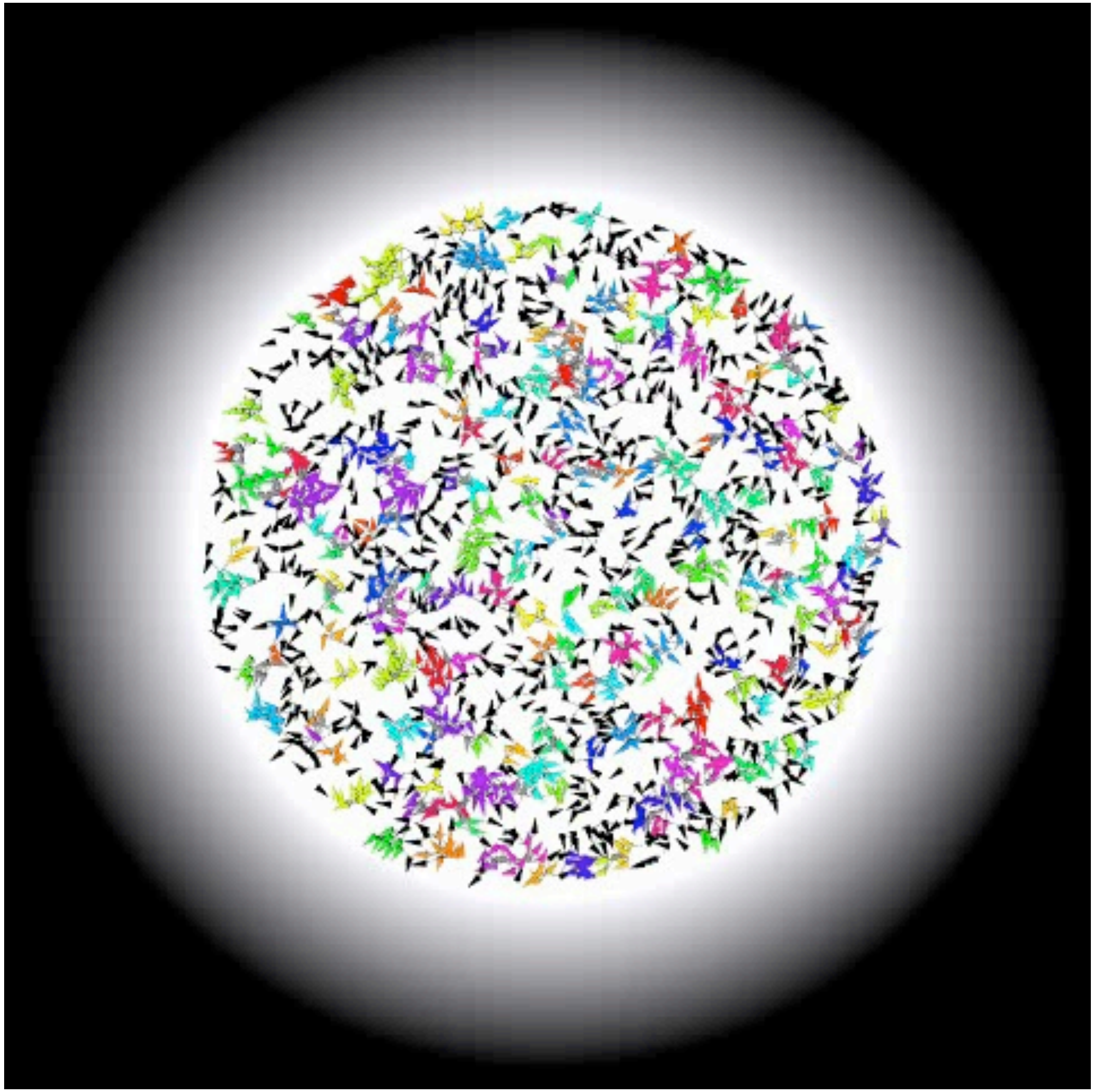


$\eta = 0.3$



Dynamics of *k*-clique clusters

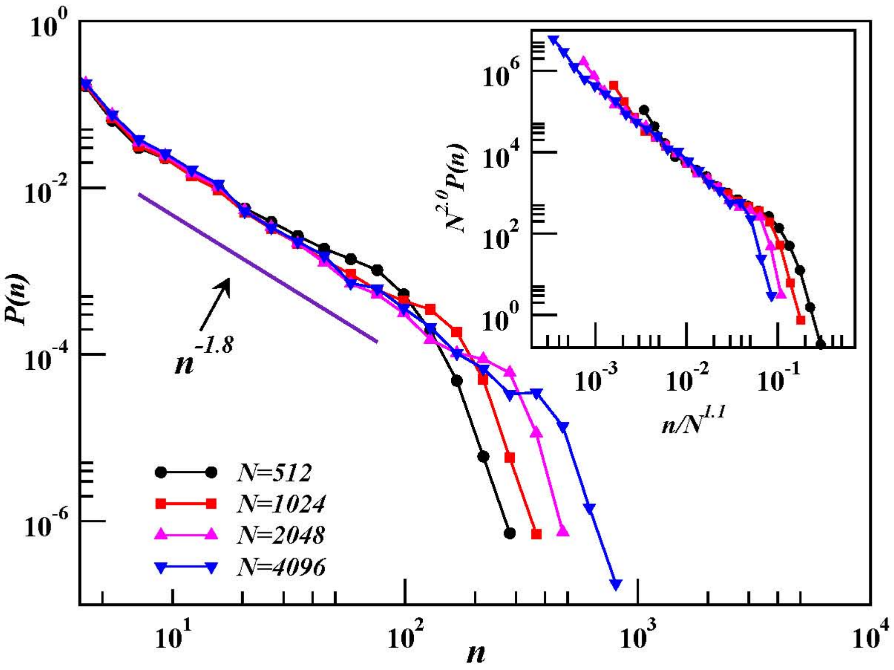
Emergence of a large single k-clique component (a percolating cluster)



η = 0.10

Cluster size distribution

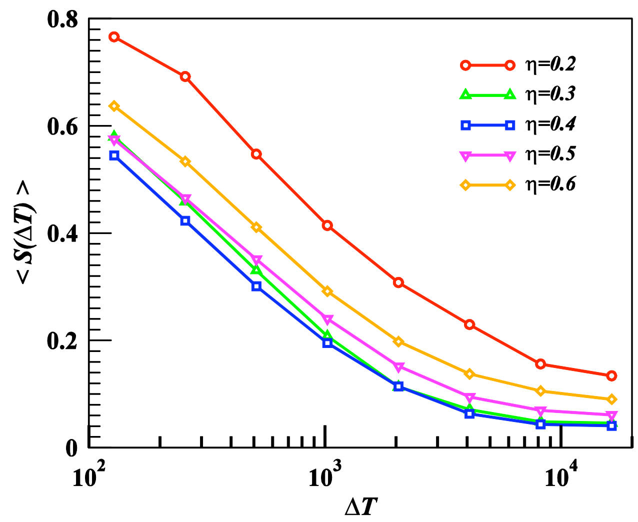
$\eta = 0.4$



Power law, all sizes

1 - Rate of change

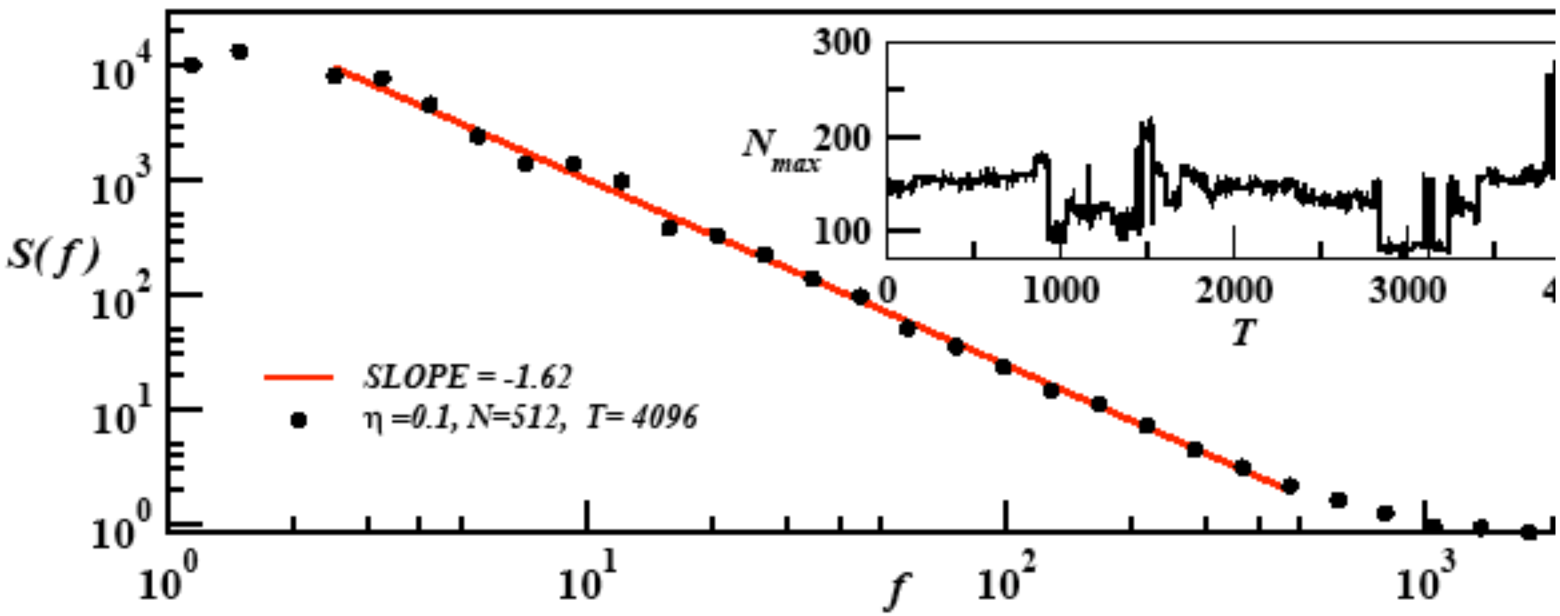
probability of belonging to the same cluster after time ΔT



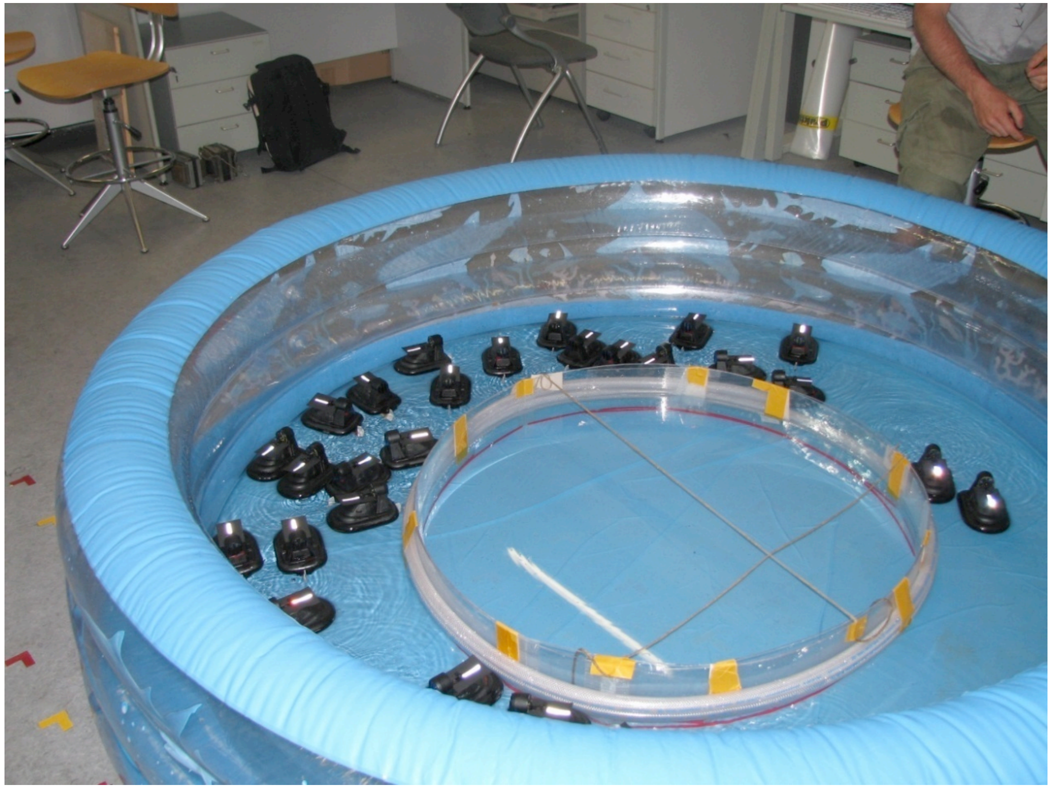
Smallest close to criticality

Dynamics of *the largest* cluster

Power spectrum of the time dependence of the number of particles in the largest cluster



Toy boats in a circular pool



Radio control
forward
stop
Noise: backward (with some random turning, like bacteria)

We control: duration of propelling/not propelling the boats

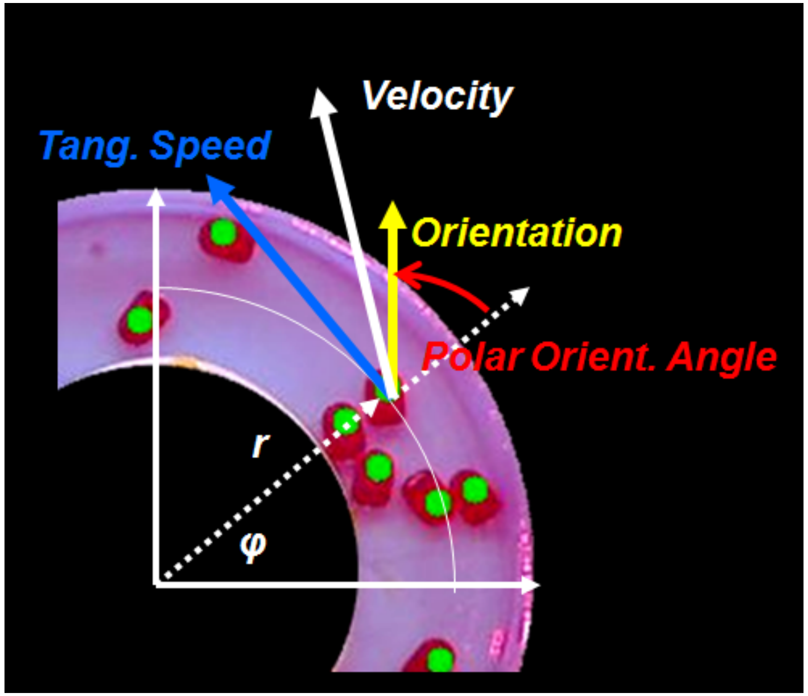
sequence
-> forward -> no propelling ->
-> backward -> no propelling ->

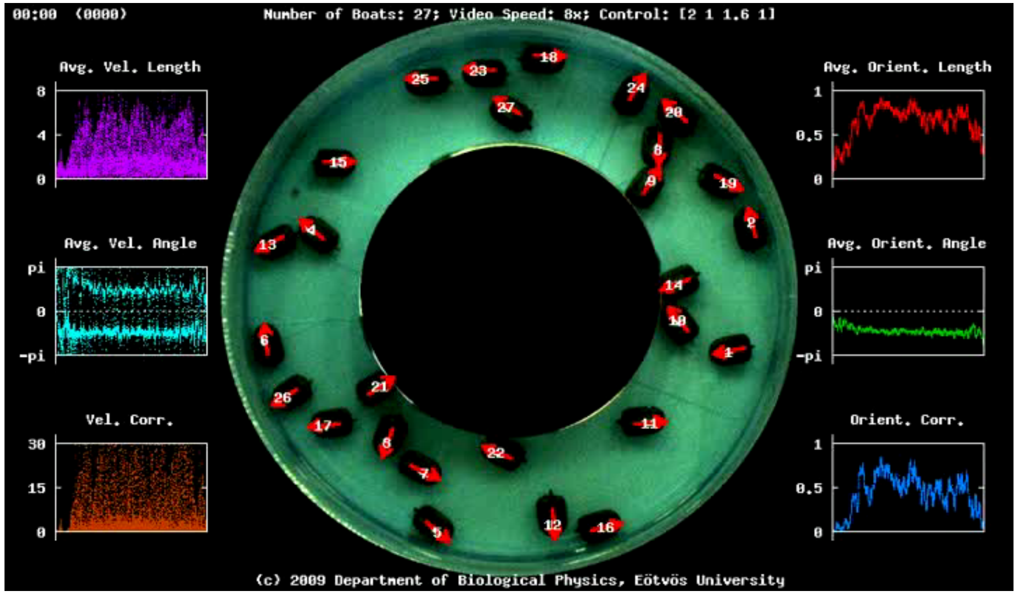
Video from above, digital video analysis

Note: there is no alignment force !
Do physical constraints alone lead to ordered motion?

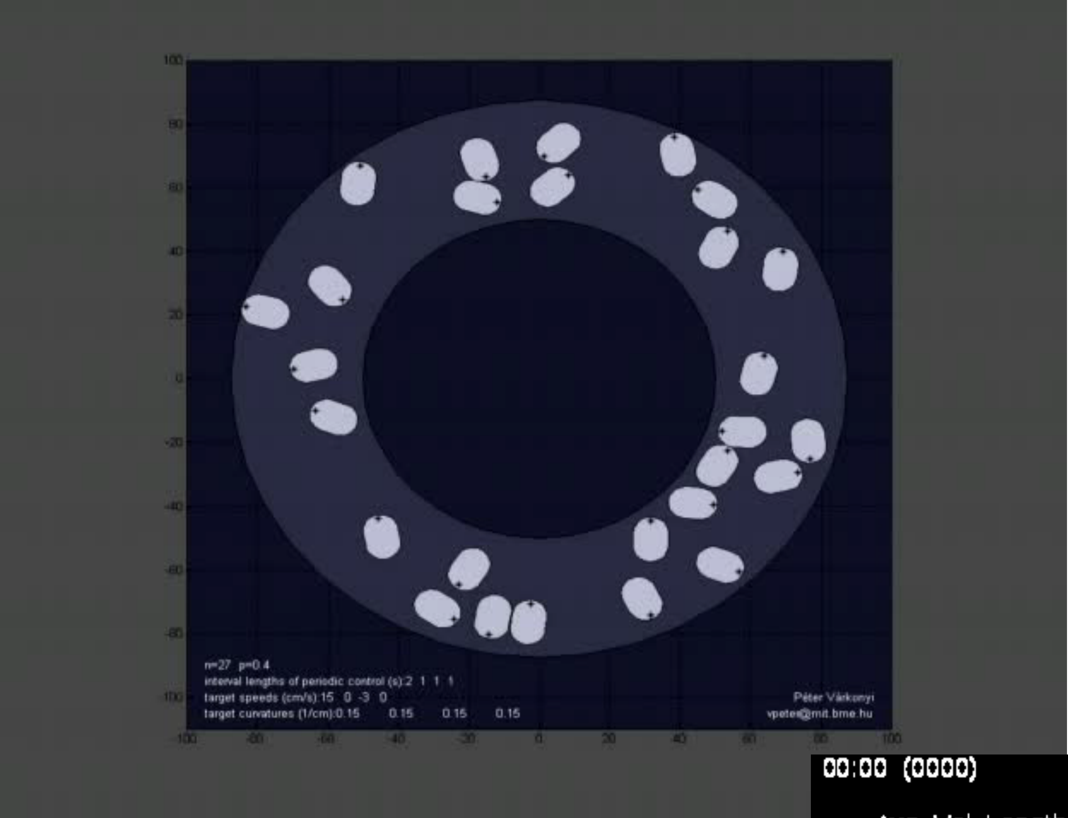
Next stage: we shall introduce computer controlled „leaders”

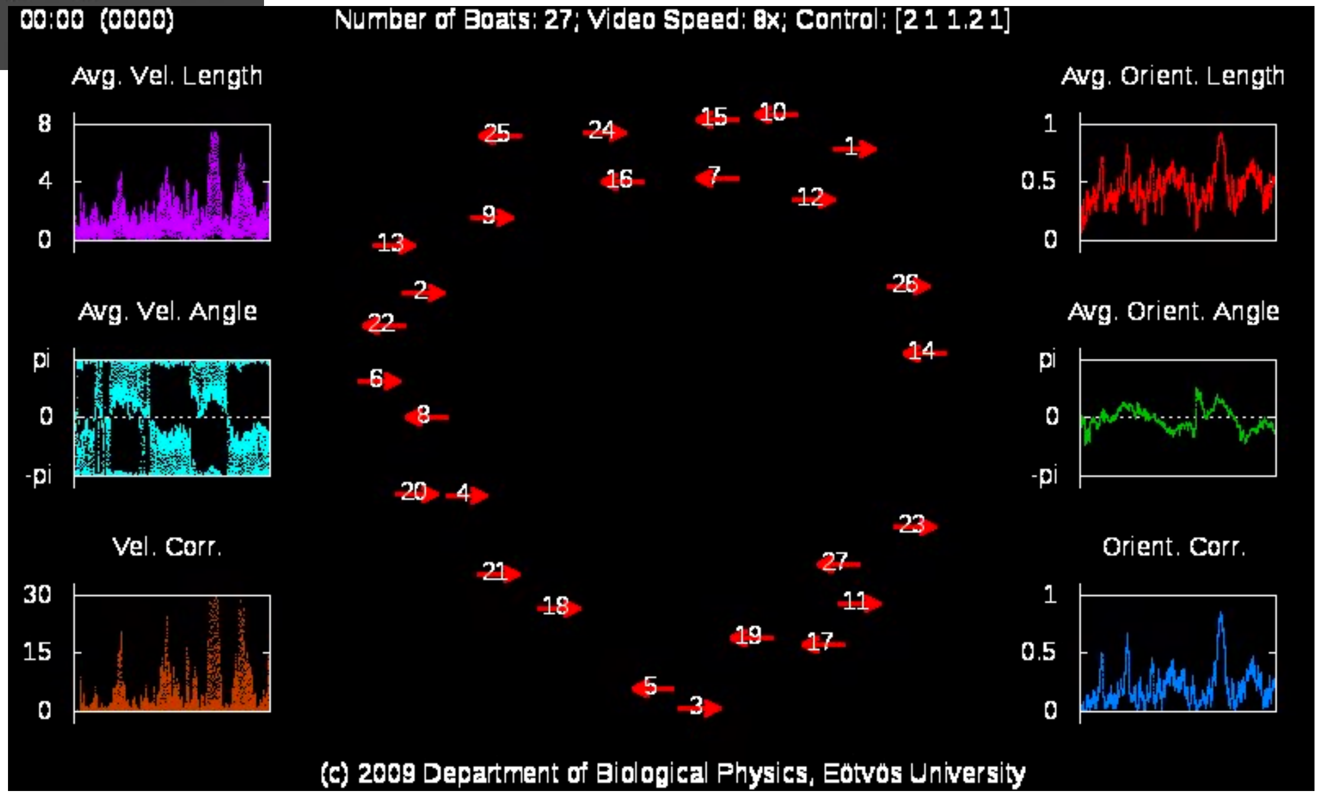
Results from digital image analysis





Simulations by P. Várkonyi





Hierarchical group dynamics in pigeon flocks

M. Nagy, Zs. Akos, D. Biro and TV, this part cannot be made public yet