COLLECTIVE MOTION

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Collective behaviour -> Collective decision-making -> Collective motion

from bacteria to animals, people and drones
PART  I

Introduction to collective motion
Collective motion of

From BBC (I. Couzin)

swirling motion II
video4 - supplement to Fig. 3D

filament density: $\rho = 20 \, \mu m^2$
labeling ratio: $R = 1:320$

Bausch group, Munich
Collective motion of rods (physics) 
shaken from below

Asymmetric units

Just simple rods

Kudrolli et al PRL, 
(2003), (2008)
A universal pattern of motion

Self-Organized Flocking of Kobots in a Closed Arena

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Ants are amazing both individually and when collaborating.
A school of striped eel catfish babies
by Dr. Brigitta Zics, artist, 2018, https://www.ravensbourne.ac.uk/
Observation: complex units exhibit simple collective behaviours (collective motion patterns) and simple units produce complex patterns.

Our goals are: classification of patterns of collective motion, finding the basic laws (microscopic versus global), "Universality" (versus specificity).
Swarms, flocks and herds

- **Model** (SPP): The particles
- maintain a given absolute value of the velocity \( v_0 \)
- follow their neighbours called "ALIGNMENT RULE"
- motion is perturbed by fluctuations \( \eta \)

\[
\bar{e}_i (t + 1) = E\left[E[\left\langle \bar{e}_j (t) \right\rangle_j] + \bar{\eta}(t)\right]
\]

(\( E \) normalizes the magnitude into unity)

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

**Result**: ordering is due to motion
Just trying to keep going with repelling force (*no alignment rule*)

„sudden” ordering
But, e.g., for cells (keratocites, taken from fish scales):

Model with „delicate” turning rule + repulsion

0.5mm
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. **Role of border** is very different

5. Ordering is due to persistent motion! In other words: in SPP systems **momentum is not conserved**!

Simplest alignment model with hard core repulsion
Motion of people in a crowd satisfies Newton’s equations of motion with „desired” velocity + specific interaction rules

\[
m_i \frac{d\vec{v}_i}{dt} = m_i \frac{v_i^0(t)\vec{e}_i^0(t) - \vec{v}_i(t)}{\tau_i} + \sum_{j \neq i} \vec{f}_{ij} + \vec{f}_{iw},
\]

\[
\vec{f}_{ij} = \left[A_i \exp\left[(r_{ij} - d_{ij})/B_i\right] + k\rho (r_{ij} - d_{ij})\right] \vec{n}_{ij} + \rho g (r_{ij} - d_{ij}) \Delta v_{ji}^t \vec{t}_{ij},
\]

494
GUATEMALA: STADIUM
DURATION: 3.12
SHOT: OCTOBER 16-17, 1996
SOUND: NATURAL/SPANISH
SEE SCRIPT FOR RESTRICTIONS

\[
t = 0
\]
\[
N = 200
\]
\[
V0 = 5
\]
Escape: several doors, patient

N = 3000

Colour codes the level of pressure
Escape: several doors, unpatient

Colour codes the level of pressure
Overall escaping time 2 times shorter
On 7th January, 2020, 40 people died and several hundreds were injured before the planned funeral of a supreme Iranian commander (the crowd was huge and the funeral had to be postponed)
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) *Jamming*

*Plus several more exotic phases*
PART II

Selected recent applications

- The physics of group hunting (realistic simulation)
- Hierarchical leadership/dominance in pigeon flocks
- Flocking drones (quadcopters)
Several slower predators chase faster prey(s)
The case of collective hunting

A complex set of equations, taking into account:

- Instantaneous velocities
- Collision avoidance
- Predicted positions
- Delayed reactions
- Perturbations
- Boundary conditions
- Escaping tactics („zig-zag” running)
- Optimizing the parameters
- Etc.
Example: prediction

of chaser

of escaper
We propose a bio-inspired, agent-based approach to describe the natural phenomenon of group chasing in both two and three dimensions with time delay, external noise and limited acceleration. We show that collective chasing strategies can significantly enhance the chasers' success rate.
Hierarchical group dynamics in pigeon flocks

A group of homing pigeons: paradigm of making collective decisions about choosing the right answer
Studies of pigeon flocks have a history
GPS module: Switzerland, U-blox, (17 X 22 mm, 2.1g), 5Hz (2.5 Hz)

antenna, Ireland, Taoglas

accumulator: lipoly 2.9g (100mAh)

Weight: 13g
Hierarchical order

directional correlation delay time network

© M. Nagy, Zs. Ákos, D. Biró & T. Vicsek
2009 Department of Biological Physics, Eötvös University
Technology and life are intimately related...
Robethology

The collective behaviour of **autonomous** quadcopters (NO central computer, communication only between the robots)
Interaction of a dancer with a flock of autonomous drones
(equations in the spirit of the chase and escape project)
Autonomous chasing by drones
(Viceland, Canada, Teaser, Dec, 2016)
Collective target tracking in the dark…
Long exposure fun photos
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+ many more

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Thank you for your attention
Thank you for your attention!
Dynamics of \textit{k}-clique clusters

Two nodes belong to the same cluster if there is connected path of neighbouring \textit{k}-cliques (overlapping cluster analysis of the underlying graph)

Here: \( k = 4 \)


\( \square = 0.4 \)

\( \square = 0.3 \)