# **Network Dynamics in Collective** Motion

http://hal.elte.hu/~vicsek

Collaborators

Zsuzsa Ákos Oxford Máté Nagy Oxford Gábor Vásárhelyi **Enys Mones** 

**Cells: Előd Méhes** Valéria Németh **Dora Biro** 

**Benj Pettit** 







EU FP7

Hung.Acad. Sci. Eötvös Univ.

# First part:

# A brief introduction to the statistical mechanics of collective motion









From BBC (I. Couzin)





http://www.dailymail.co.uk/sciencetech/article-1365538/Japan-earthquake-Swarms-fish-co

Fish

# niversal pattern of motion











#### swirling motion II

video4 - supplement to Fig. 3D

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





#### 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. Middle East Technical University Ankara, Turkey





**Observation:** complex units exhibit simple collective behaviours (collective motion patterns) and simple units produce complex patterns

Our goals are: - classification of patterns

- finding the basic laws <sup>J</sup> (microscopic versus global)

of collective motion

"Universality" (versus specificity)

## **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, lattice of vertices)

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 ripples?) (for elongated particles)

vi) Jamming

#### **Types of transitions**

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

#### **Collective motion**

Tamás Vicsek\*

Department of Biological Physics, Eötvös University - Pázmány Péter stny. 1A, Budapest, Hungary H-1117 Statistical and Biological Physics Research Group of HAS - Pázmány Péter stny. 1A, Budapest, Hungary H-1117

Anna Zafiris<sup>†</sup>

Department of Biological Physics, Eötvös University - Pázmány Péter stny. 1A, Budapest, Hungary H-1117 Department of Mathematics, National University of Athens - Panepistimioupolis 15784 Athens, Greece

We review the observations and the basic laws describing the essential aspects of collective motion - being one of the most common and spectacular manifestation of coordinated behavior. Our aim is to provide a balanced discussion of the various facets of this highly multidisciplinary field, including experiments, mathematical methods and models for simulations, so that readers with a variety of background could get both the basics and a broader, more detailed picture of the field. The observations we report on include systems consisting of units ranging from macromolecules through metallic rods and robots to groups of animals and people. Some emphasis is put on models that are simple and realistic enough to reproduce the numerous related observations and are useful for developing concepts for a better understanding of the complexity of systems consisting of many simultaneously moving entities. As such, these models allow the establishing of a few fundamental principles of flocking. In particular, it is demonstrated, that in spite of considerable differences, a number of deep analogies exist between equilibrium statistical physics systems and those made of self-propelled (in most cases living) units. In both cases only a few well defined macroscopic/collective states occur and the transitions between these states follow a similar scenario, involving discontinuity and algebraic divergences.

#### CONTENTS

Ι

			A. Simplest self-propelled particles (SPP) models
I.	Introduction	2	1. The order of the phase transition
	A. The basic questions we address	2	2. Finite size scaling
	B. Collective behavior	2	B. Variants of the original SPP model
	C. The main difference between equilibrium and		1. Models without alignment rule 2. Models with alignment rule
	self-propelled systems	2	
	D. Goals to be achieved	3	C. Continuous media and mean-field approaches
I.	Observations and experiments A. Physical, chemical and biomolecular systems B. Bacterial colonies	3 4 6	<ul> <li>D. Exact results</li> <li>1. The Cucker-Smale model</li> <li>2. Network and control theoretical aspects</li> <li>E. Relation to collective robotics</li> </ul>
	C. Cells	9	
	D. Insects	11	<ul> <li>V. Modeling actual systems</li> <li>A. Systems involving physical and chemical interactions</li> <li>1. The effects of the medium</li> </ul>
	E. Fish schools and shoals	12	
	F. Bird flocks	13	
	G. Leadership in groups of mammals and crowds	16	

IV. Basic models

#### Phys. Reports 80 pages, 60 Figs.,280 Refs.

22

29 31 32

34 34

34

ALL (ODD)

# **Understanding through modeling**

-Aoki, I.1982. A simulation study on the schooling mechanism in fish. Bull. Jpn. Soc. Sci. Fish. 48:1081 –1088. Realistic details

#### - Graphical 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.):

- vectorial noise, first order phase trans. (2004 Gregoire, Chaté)
- models with "leaders" (Couzin, others, 2005)
- "soft" interaction potential (Cucker and Smale, 2007)
- model with escape and pursuit (Romanczuk, Couzin, & Schimansky-Geier, 2009)
- model with physical collisions only (Grossman et al 2008)
- self-propelled rods (Chaté and co-workers, 2010)

# Swarms, flocks and herds

- Model\* (SPP) : The particles
- maintain a given absolute value of the velocity  $v_o$
- follow their neighbours
- motion is perturbed by fluctuations  $\eta$

$$e_i(t+1) = E\left[E\left[\left\langle e_j(t)\right\rangle_j\right] + \eta(t)\right]$$

- (*E* normalizes the magnitude into unity)
- Follow the neighbours rule is an abstract way to take into account interactions of very different possible origins
- <u>Result:</u> ordering is due to <u>motion</u>





### A few nice recent *theoretical* results related to SPP models

 Network models related to SPP models show both first and second order phase transitions depending on the nature of noise (Aldana et al 2007)

 Equilibrium stat. mech. type finite-size scaling is valid for the original ('95) SPP model, with a hyperscaling relationship (Baglietto, Albano, 2008)

$$\varphi(\eta, L) = L^{-\beta/\nu} \widetilde{\varphi}((\eta - \eta_c) L^{1/\nu}) \qquad d\nu - 2\beta = \gamma \qquad \chi = \operatorname{Var}(\varphi) L^2$$
$$\chi(\eta, L) = L^{\gamma/\nu} \widetilde{\chi}((\eta - \eta_c) L^{1/\nu})$$

- Deriving continuum (hydrodynamic equations for self-propelled particles and rods. (Bertin et al 2006-2010, Mishra, Baskaran, Marchetti, 2009, 201
- Cucker and Smale model (2007) exact results for flocking



#### Model!

$$\partial_t \vec{v} + \lambda_1 (\vec{v} \nabla) \vec{v} + \lambda_2 (\nabla \vec{v}) \vec{v} + \lambda_3 \nabla (|\vec{v}|^2) = \\ \alpha \vec{v} - \beta |\vec{v}|^2 \vec{v} - \nabla P + D_L \nabla (\nabla \vec{v}) + D_1 \nabla^2 \vec{v} + D_2 (\vec{v} \nabla)^2 \vec{v} + \vec{\xi}$$

$$\partial_t \rho + \nabla(\rho \vec{v}) = 0.$$
  $P = P(\rho) = \sum_{n=1}^{\infty} \sigma_n (\rho - \rho_0)^n$ 





#### 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!





# **Collective motion beyond similar units**

Segregation of two types of collectively moving cells

Hierarchical organization of pigeons within a flock

Dominance hierarchy in a loft

# Collective motion-mediated cell segregation in vitro

Motivation: patterning mechanism based on collective cell motility, e.g., during *embryonic development* 

#### Inpired by

Slow (logarithmic) segregation with random motion vs. fast (power law) segregation with collective (self-propelled) motion

Belmonte JM, Thomas GL, Brunnet LG, de Almeida RM, Chaté H. 2008 Phys Rev Lett.

# Can collective cell migration enhance cell segregation?

In vitro system:

- Mixed co-culture
- No prepattern
  - Differential adhesion





#### **Comparing the motility of different cell types**



#### **Clustering increases directional persistence**



 $d^{2}(t) = 4D\left[t - T_{p}\left(1 - e^{-t/T_{p}}\right)\right],$ 



Persistence length







High directional persistence facilitates cell segregation



# **Hierarchical dynamics in pigeon flocks**







GPS : Switzerland, U-blox, (17 X 22 mm, 2,1g), 5Hz (2,5 Hz)

Total weight : 16g











Velocity autocorrelation function

$$C_{ij}(\tau) = \left\langle \overrightarrow{v_i}(t) \cdot \overrightarrow{v_j}(t+\tau) \right\rangle$$





#### Newcomers hardly perturb the original hierarchy





#### Pigeons at home:

#### Dominance hierarchy from digital video analysis



#### Digital video analysis of the moving pigeons around the feeding cup

Pairwise dominance graph as determined from "who is closer to the feeding cup"





### PECKING order





## A few questions arising

Does collective cell migration play an important role during embryonic development?

Do pigeons make use of a sophisticated hierarchical negotiation procedure to make collective decisions?

Are the knowledge based and the "physical" dominance roles related?

### Thank you for your attention!