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Collective dynamics and self organization in biological systems

Lecture 1: Challenges and some examples

Pierre Degond
Imperial College London

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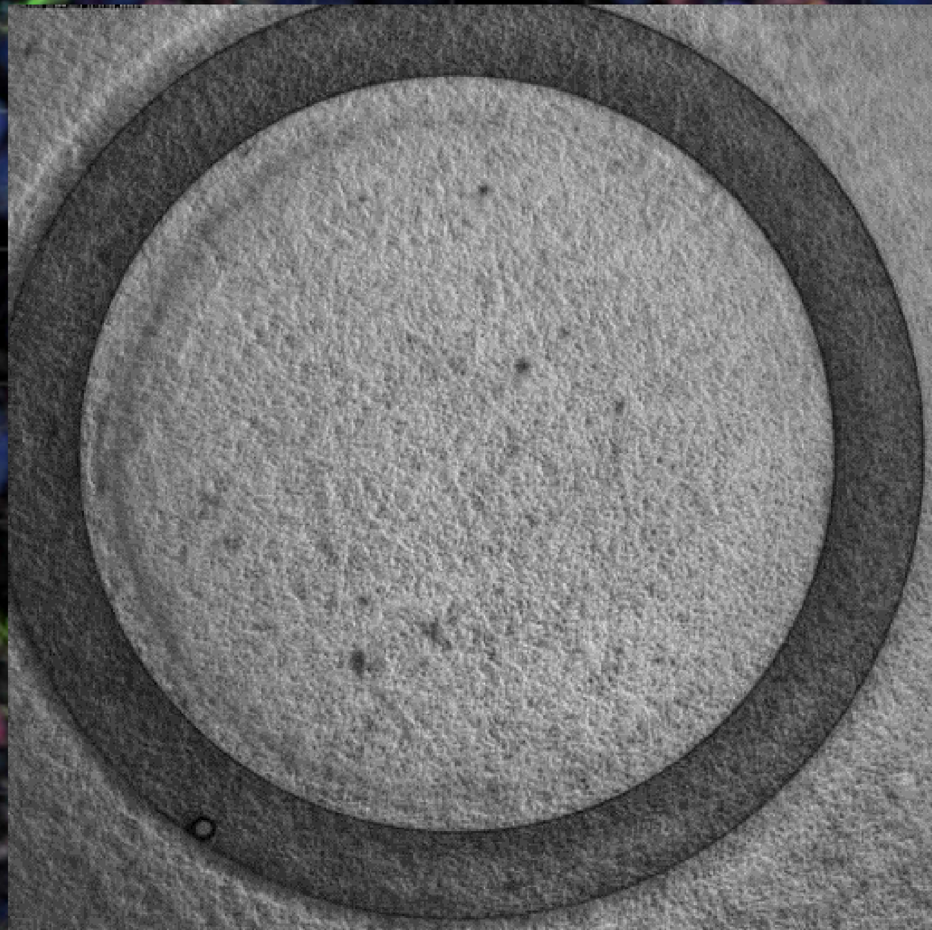
What does "collective dynamics" mean ?

Coordination

Ex. all particles move sponta-neously in the same direction



Sperm confined in an annular chamber.
Creppy, Plouraboué, Praud, Druart, Cazin, Yu, PD, J. Roy Soc. Interface 2016

F. Plouraboué

X. Druart

H. Yu

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What does "collective dynamics" mean ?

Coordination

Self-organization

Ex. spontaneous lane formation


M. Moussaid

J. Pettré

C. Appert-Rolland

G. Theraulaz

Pedestrians walking in an annular corridor.
Moussaïd, Guillot, Moreau, Fehrenbach, Chabiron, Lemercier, Pettré, Appert-Rolland, PD, Theraulaz, PLoS CB, 8 (2012), e1002442

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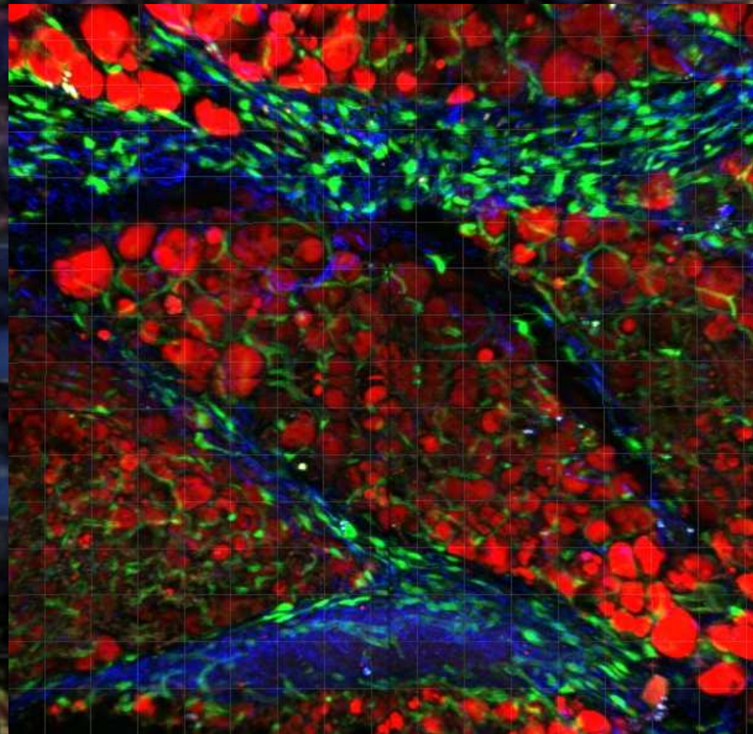
What does "collective dynamics" mean ?

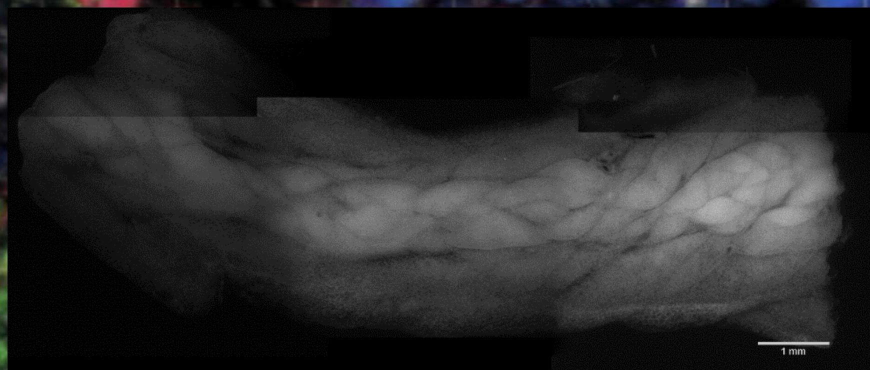
Coordination

Self-organization

Pattern formation

Ex. Network emergence





Network of collagen fibers in adipose tissue. Courtesy of L. Casteilla & A. Lorsignol

L. Casteilla

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What does "collective dynamics" mean ?

Coordination

Self-organization

Pattern formation

Emergent behavior

Not encoded in the individual particle interactions:

"complex systems"

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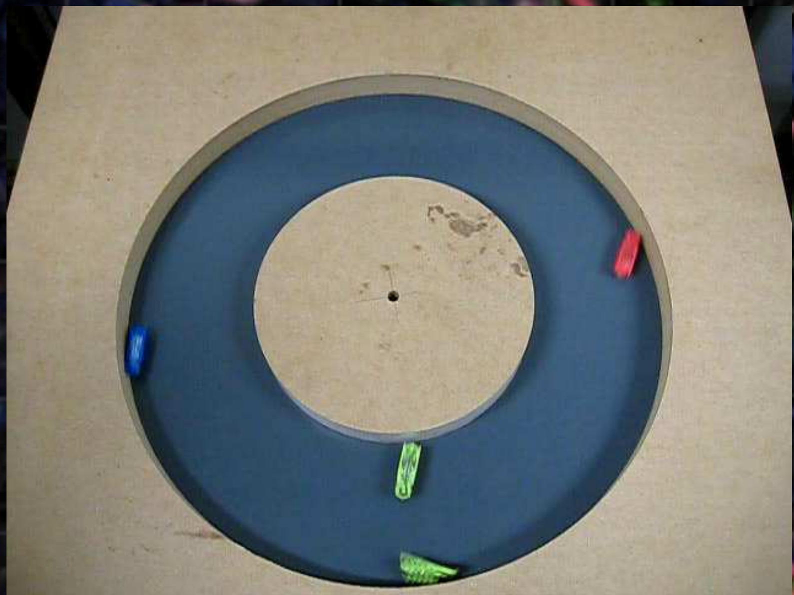
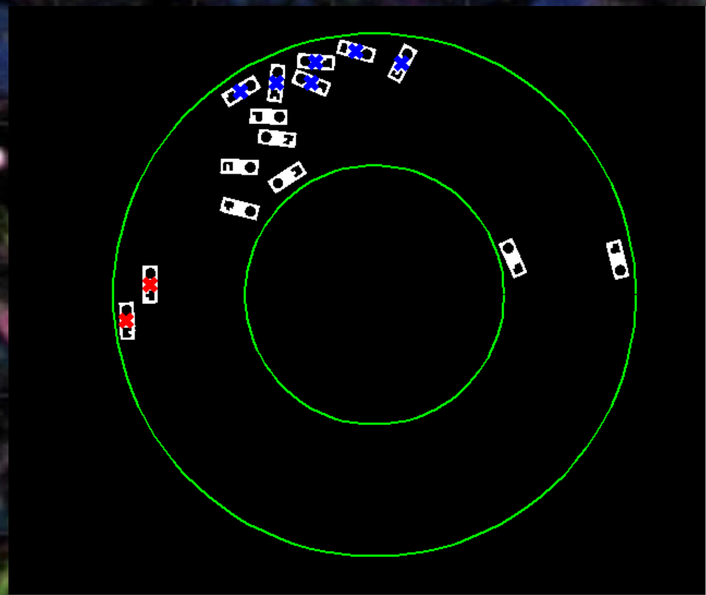
What does "collective dynamics" mean ?

Systems showing emergent behavior do not exclusively come from biology or social sciences





With
E. Climent,
N. Mac,
F. Plouraboué,
O. Praud,

E. Climent

F. Plouraboué

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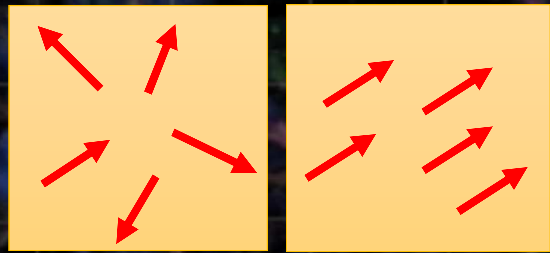
Why is studying emergence difficult ?

Emergence = Transition:
disorder → self-organization

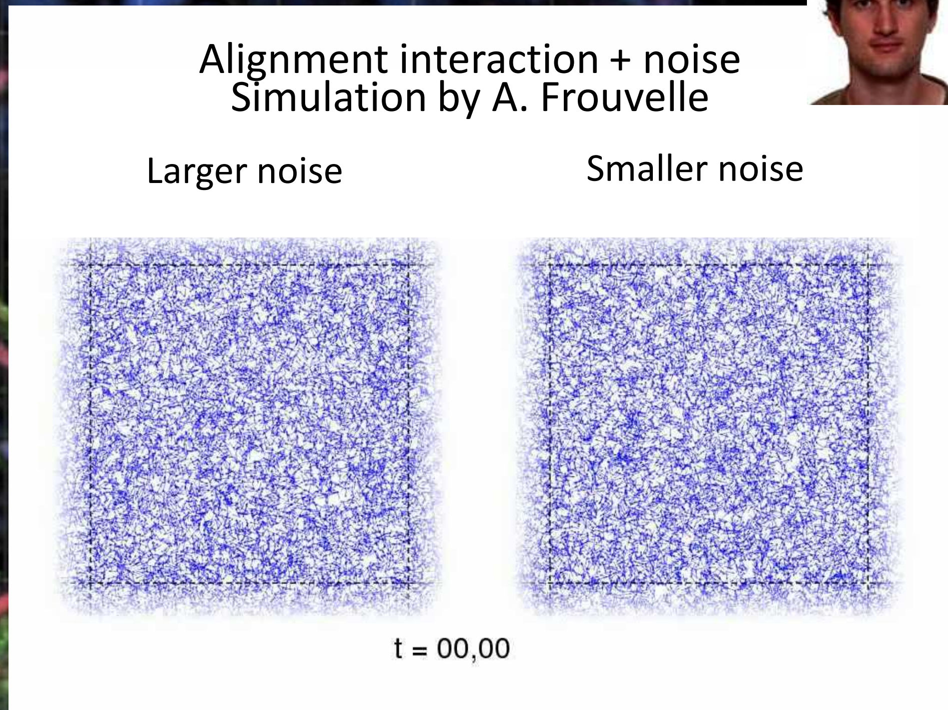
Ex. random state vs aligned state



A. Frouvelle

Depends on noise

i.e. how often particles change orientation randomly



Ex. Vicsek model

self-propulsion + alignment + noise

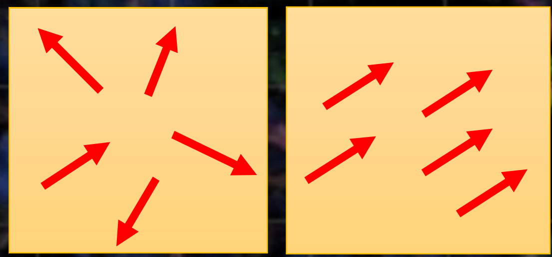
T. Vicsek

Vicsek, Czirók, Ben-Jacob, Cohen, Shochet, PRL 75 (1995) 1226

Why is studying emergence difficult ?

Emergence = Transition:
disorder → self-organization

Ex. random state vs aligned state



Alignment interaction + noise
Simulation by A. Frouvelle

Larger noise

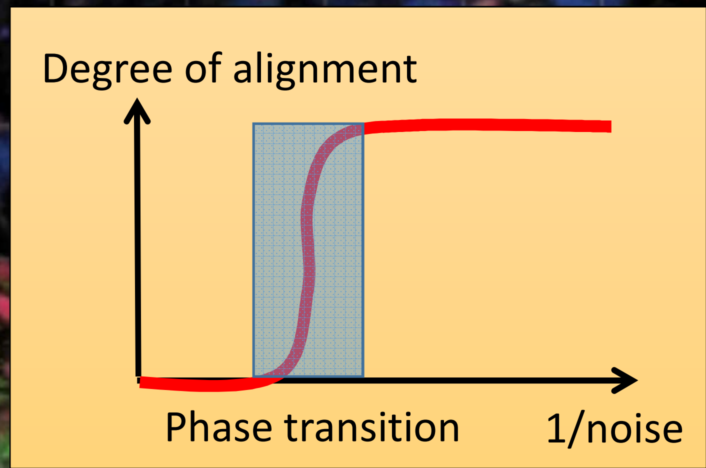
Smaller noise

Depends on noise

In an abrupt way

All variation in narrow parameter range

Phase transition (or bifurcation)



Non-smooth behavior !

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Different types of phase transitions

Symmetry breaking

Ex. isotropic to polarized

Groups of Khulia mugil in tank. Courtesy of G. Theraulaz et al


G. Theraulaz

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Different types of phase transitions

Symmetry breaking

Packing

- Compressible to incompressible
- Volume exclusion constraint

Courtesy of R. Bon, G. Theraulaz et al.

Sheep herds in the Mecantour range, south-east of France.

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Different types of phase transitions

Symmetry breaking

Packing

Continuum to networks

S. Garnier

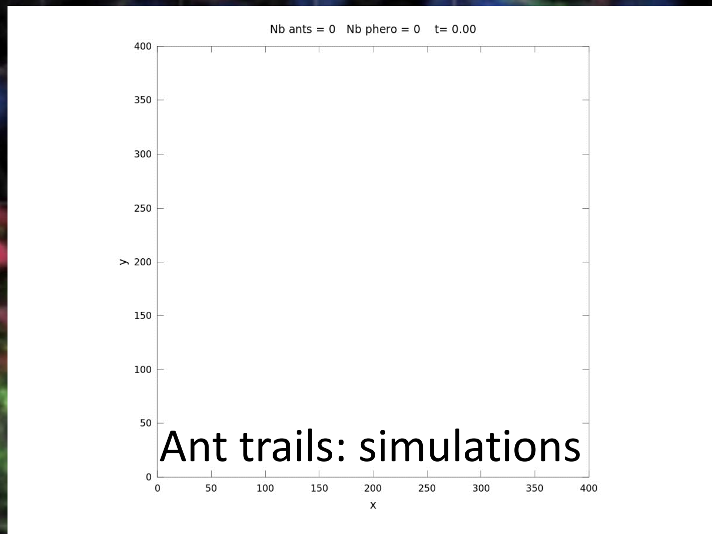
Emergent networks

Expe: Perna, Granovskiy, Garnier, Nicolis, Labédan, Theraulaz, Fourcassié, Sumpter, PLoS CB 8 (2012), e1002592.

Simulations: Boissard, PD, Motsch, JTB 66 (2013) 1267

S. Motsch

Ant trails: ants enter arena from center and reach to the circular boundary



Ant trails: simulations

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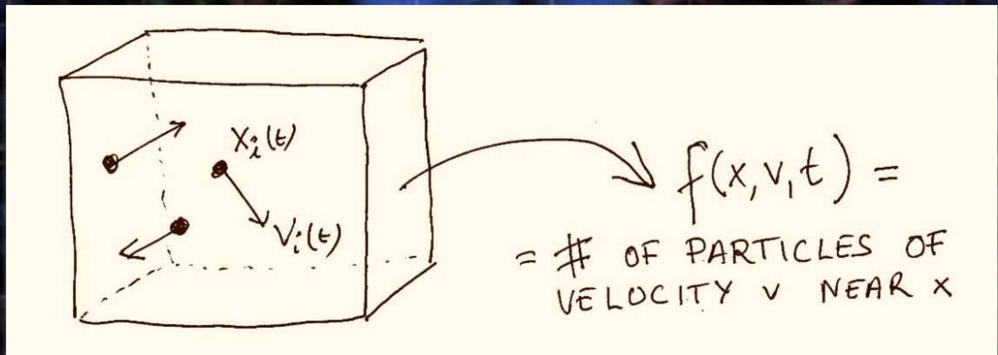
1st step: kinetic equation

Start with individual particles

Construct Probability f=f(x,v,t)



Equation for f requires influence of any given particle on the system be very small

Propagation of chaos

Propagation of chaos may be untrue for systems exhibiting emergence

Carlen, Chatelin, PD, Wennberg, Physica D 260 (2013) 90 & M3AS 23 (2013) 1339.

E. Carlen

B. Wennberg

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2nd step: complexity reduction

Remove velocity variable by integration

$$\rho(x,t) = \int f(x,v,t)\,dv \qquad \text{PARTICLE DENSITY AT } x$$

$$\langle v\rangle(x,t) = \frac{1}{\rho(x,t)} \int f(x,v,t)\, v\, dv \qquad \text{MEAN VELOCITY AT } x.$$

Macroscopic equations (for ρ and $\langle v \rangle$) derived from conservations

In classical cases (gases):

CONSERVATION OF MOMENTUM $\quad V_1' + V_2' = V_1 + V_2$

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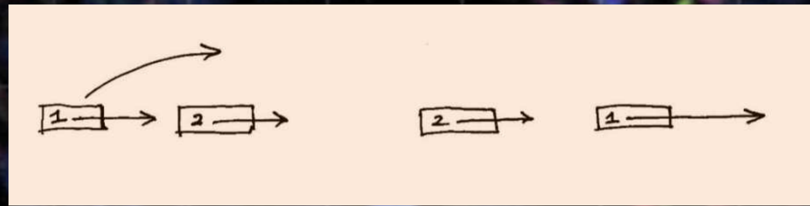
No conservations for ''exotic'' particles

Ex. vehicles:
no momentum conservation



How to obtain macroscopic equations ?

''weaker'' conservation:
''generalized collision invariant''

Application: Vicsek
Self propulsion + alignment + noise

Macroscopic model is

$$\partial_t \rho + c_1 \nabla_x (\rho u) = 0$$
$$\rho \left(\partial_t u + c_2 (u \cdot \nabla_x) u \right) + P_{u^\perp} \nabla_x \rho = 0$$
$$|u| = 1$$

S. Motsch

PD, Motsch, M3AS 18 Suppl (2008) 1193

Self-Organized Hydrodynamics (SOH)

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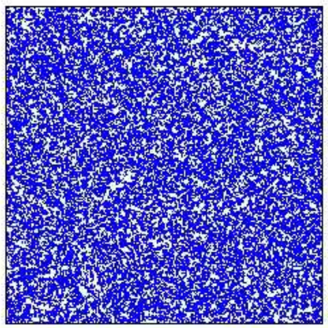
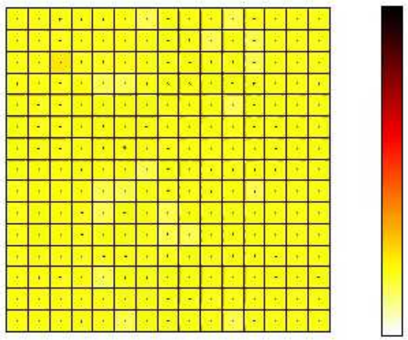
Vicsek (micro) vs SOH (macro)

Micro model (Vicsek)

Self propulsion + alignment + noise

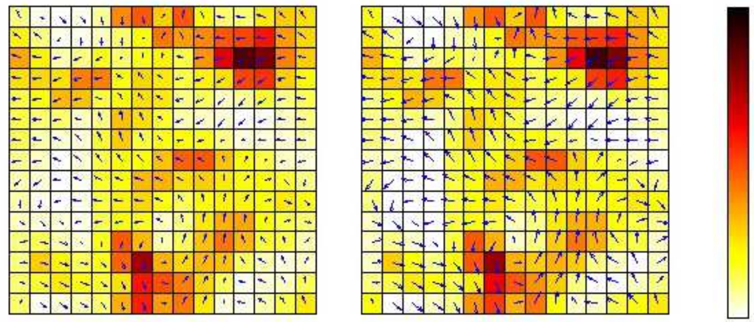




Particles

Density (color)
Velocity (arrows)

Micro (Vicsek) Macro (SOH)



Density (color)
Velocity (arrows)

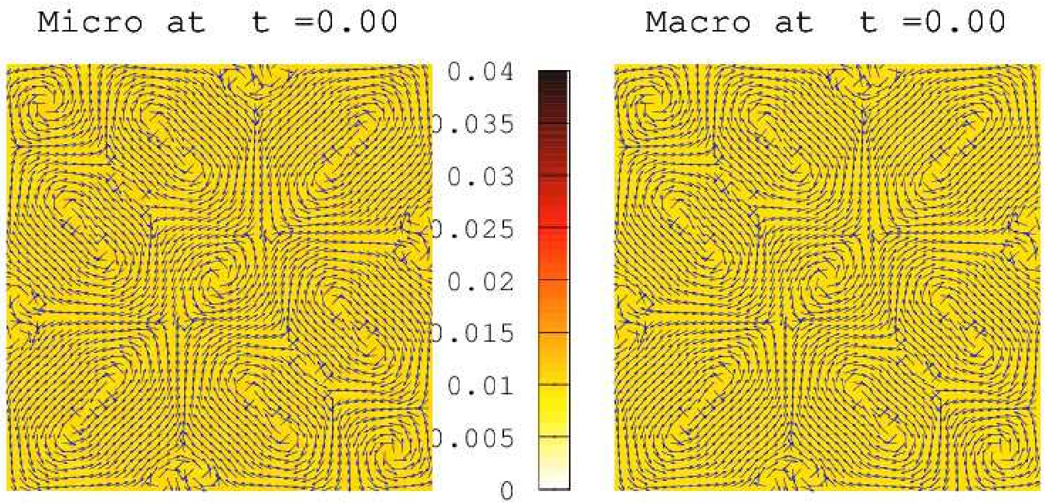
Simulations by S. Motsch

Vicsek (micro) vs SOH (macro)

Micro (Vicsek)

Self propulsion + alignment + noise + repulsion

Macro (SOH)



Density (color)
Velocity (arrows)

Simulations by G. Dimarco and N. Mac

G. Dimarco

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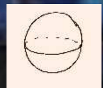
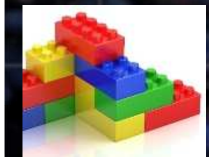
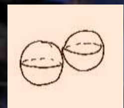
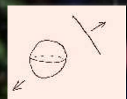
Tissue self-organization

Cells: 2D spheres 

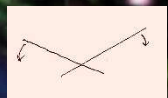
Fibers: line segments 

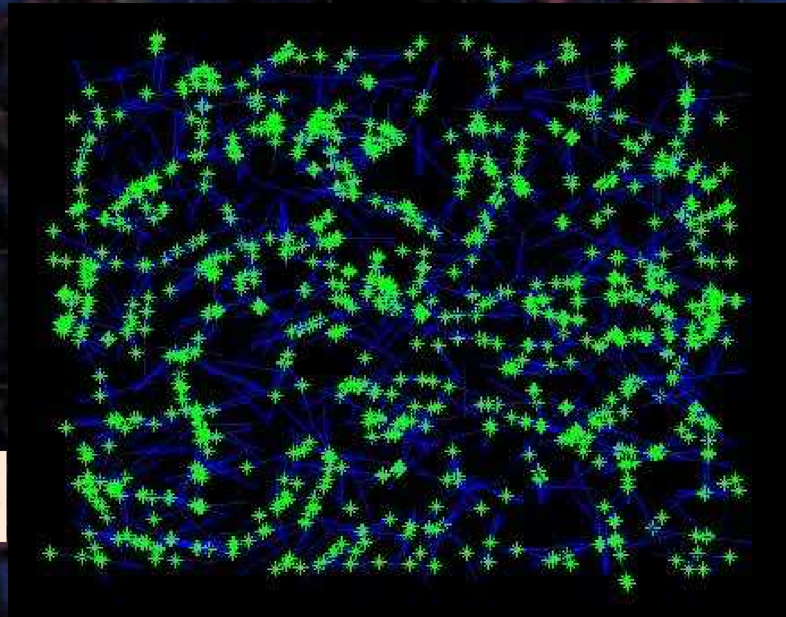


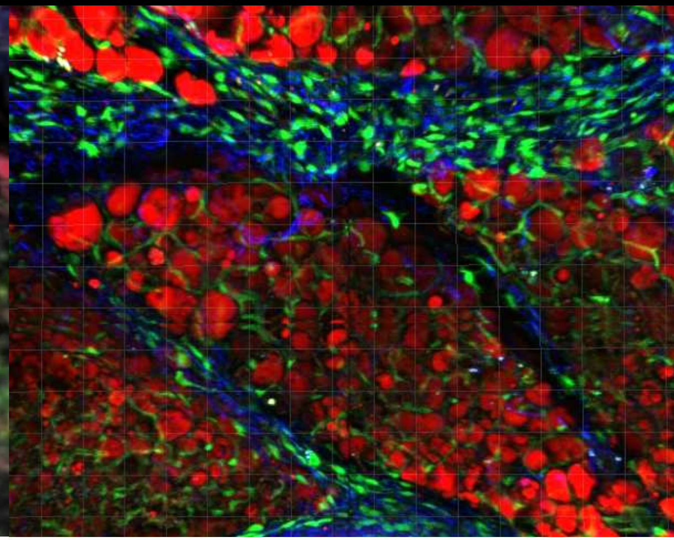
Cell-cell volume exclusion 

Cell-fiber repulsion 

Fiber-fiber cross-linking 

Fiber-fiber alignment 





D. Peurichard, F. Delebecque, A. Lorsignol, C. Barreau, J. Rouquette, X. Descombes, L. Casteilla, PD, sub.

L. Casteilla

D. Peurichard

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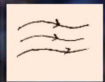
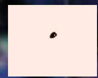
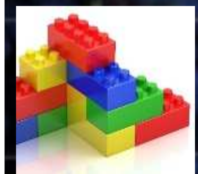
Blood capillary formation

Blood: fluid 

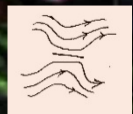
Oxygen (O2): point particles 

Capillaries: line segments 



Oxygen transport by blood 

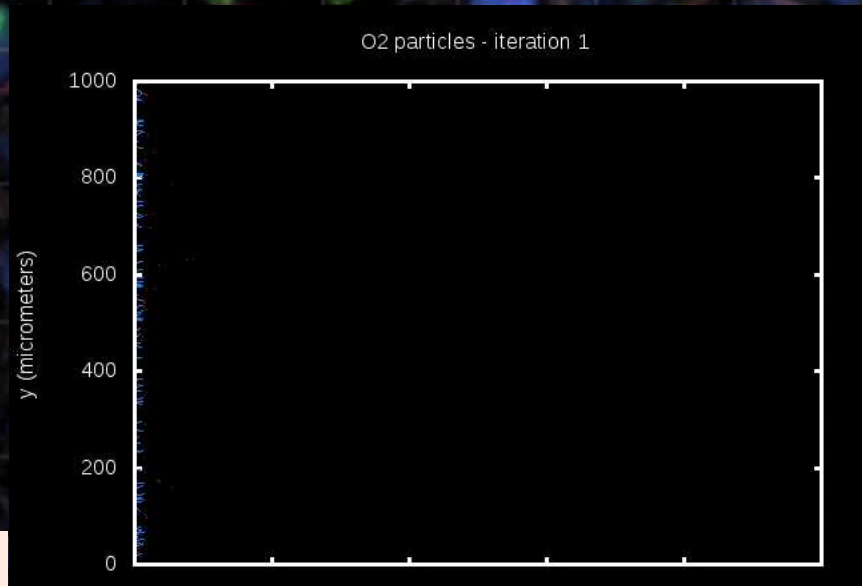
Capillary creation/deletion
In response to blood/O2 

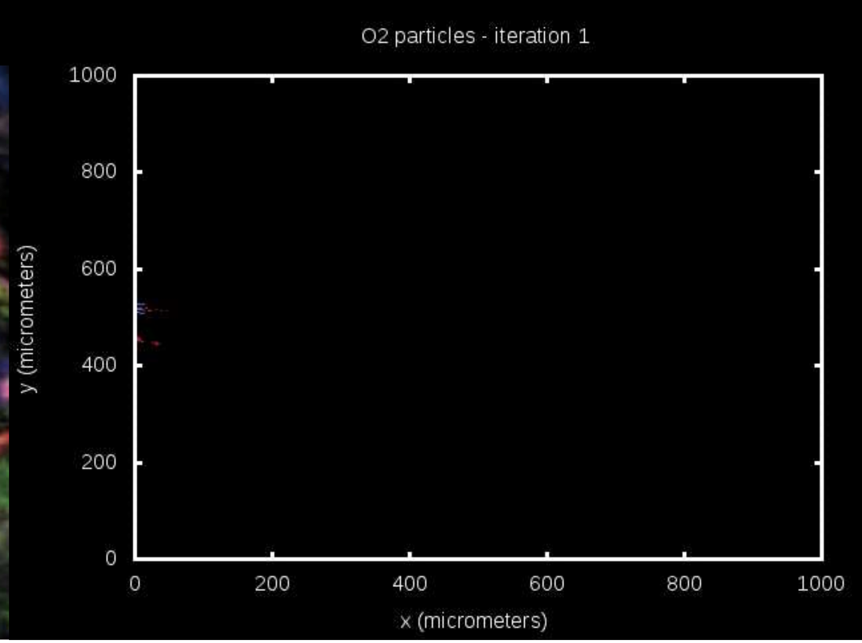
Blood/O2 transport
enhanced by capillaries 

B. Aymard

F. Plouraboué

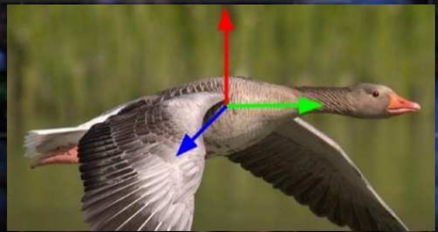
B. Aymard, A. Lorsignol, L. Casteilla, P. Kennel, F. Plouraboué, PD, in preparation

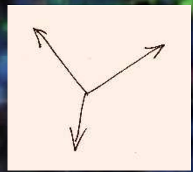




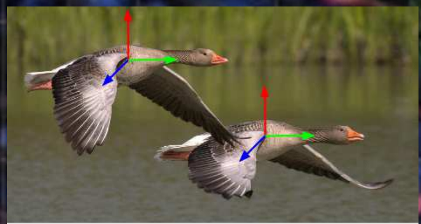
Body attitude coordination

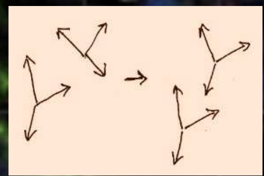
Birds, fish: frames





Frame alignment





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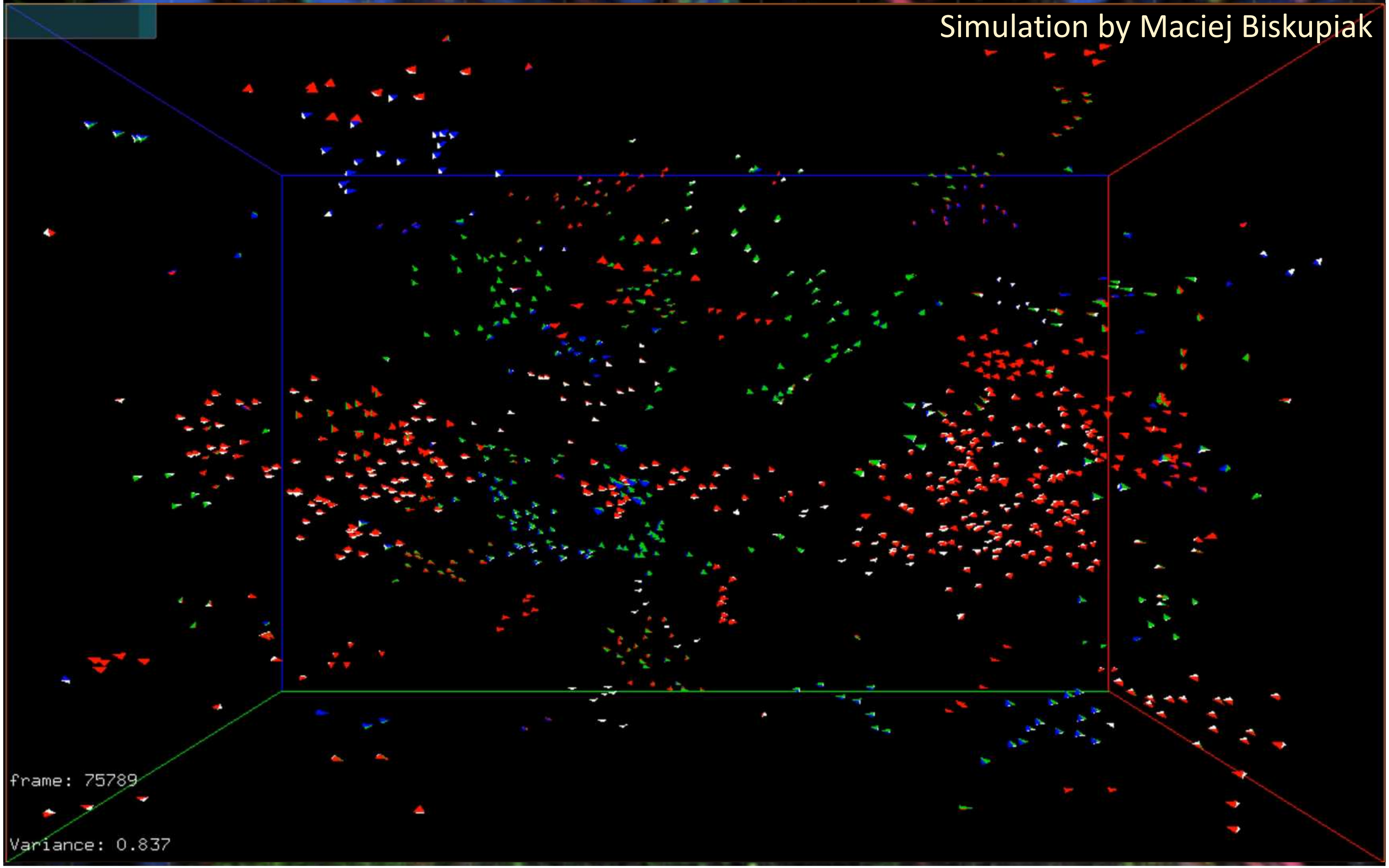
Body attitude coordination



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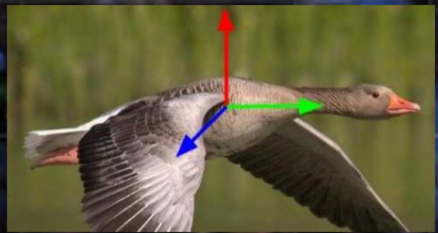
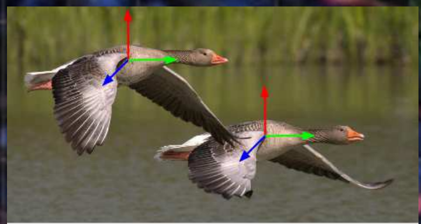
Body attitude coordination

Birds, fish: frames



Frame alignment



Macroscopic model:

$$
\begin{aligned}
&\partial_t \rho + c_1 \nabla_x \cdot (\rho\, \Lambda \mathbf{e_1}) = 0, \\
&\rho\Big(\partial_t \Lambda + c_2\big((\Lambda \mathbf{e_1}) \cdot \nabla_x\big)\Lambda\Big) \\
&\qquad + \Big[(\Lambda \mathbf{e_1}) \times \big(c_3 \nabla_x \rho + c_4 \rho\, \mathbf{r}_x(\Lambda)\big) \\
&\qquad\qquad + c_4 \rho\, \delta_x(\Lambda) \Lambda \mathbf{e_1}\Big]_\times \Lambda = 0.
\end{aligned}
$$

A. Frouvelle

S. Merino-Aceituno

PD, A. Frouvelle, S. Merino-Aceituno, arXiv:1605.03509 to appear in M3AS

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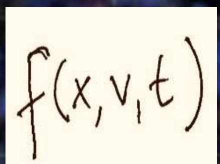
Conclusion

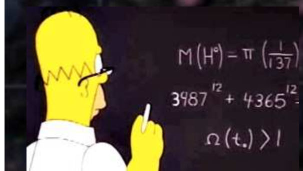
Emergence: Property of systems that develop patterns on scales larger than those of their individual components

Emergent systems are important in science and engineering

Emergence is a phase transition: a brutal change of the system's properties in response to small parameter changes



Kinetic theory is a method of choice to derive models of emergent systems in line of Hilbert's 6th problem



But emergence requires developing concepts beyond the state of the art

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Special thanks to all my collaborators and students

and to the many missing here !!

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Special thanks to my sponsors

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