Collective dynamics and self organization in biological systems

Lecture 1: Challenges and some examples

Pierre Degond
Imperial College London

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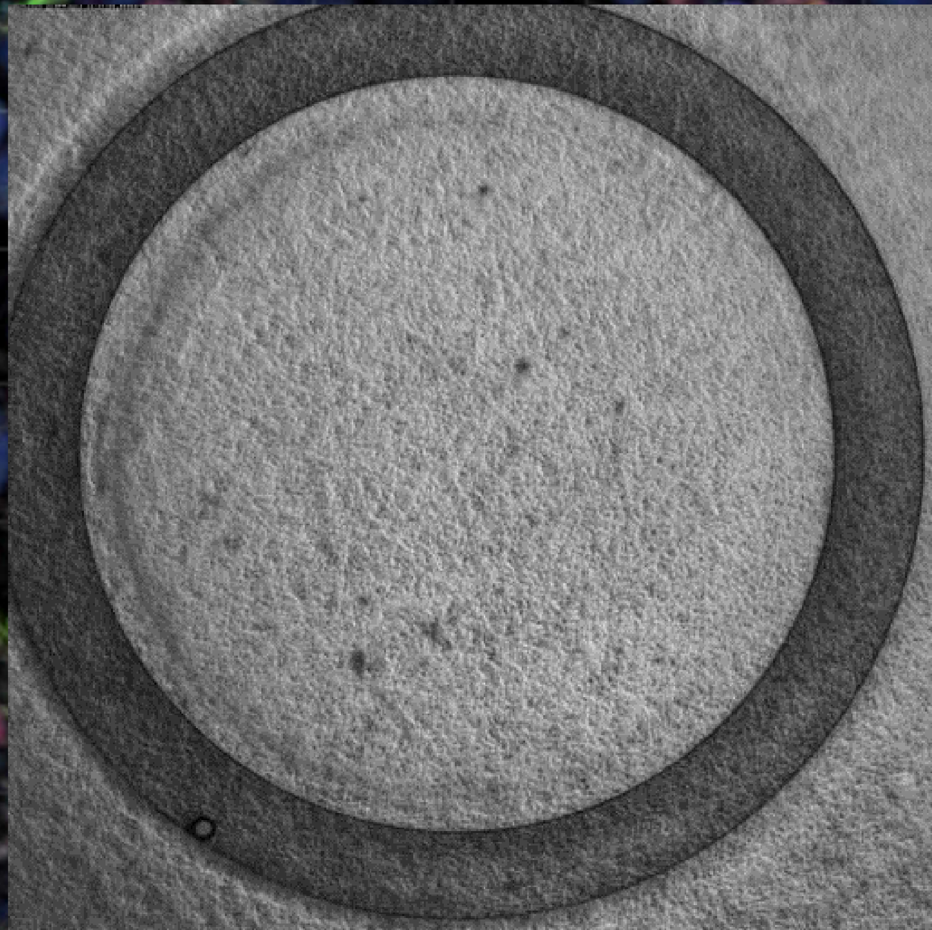
What does "collective dynamics" mean ?

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

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


M. Moussaid


J. Pettré


C. Appert-Rolland


G. Theraulaz

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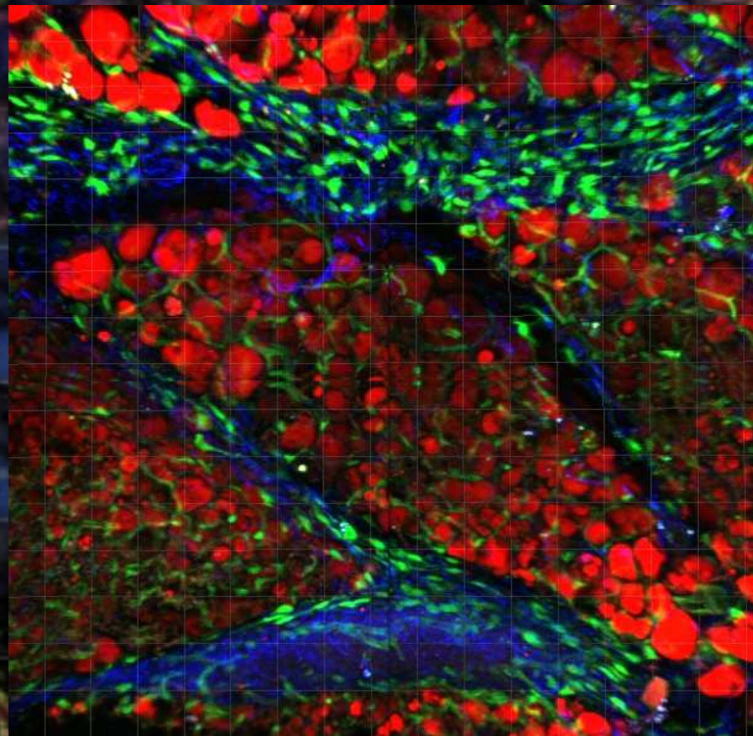
What does "collective dynamics" mean ?

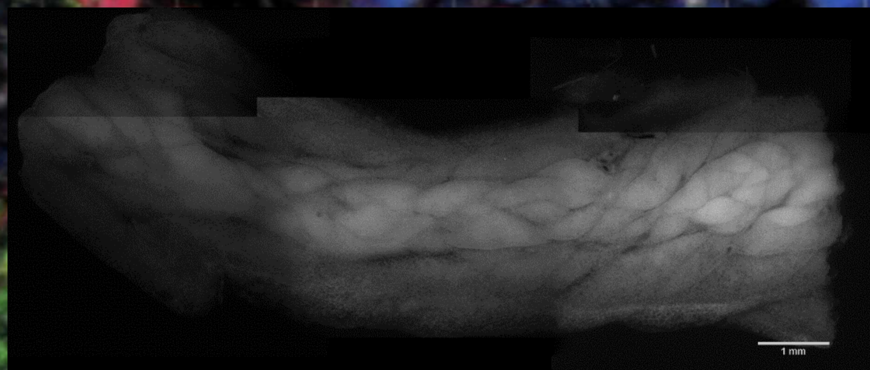


Coordination

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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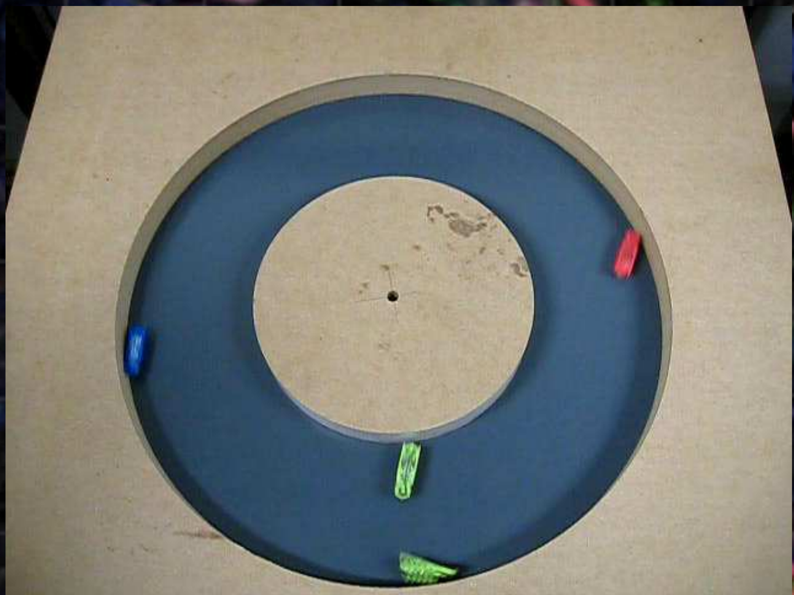
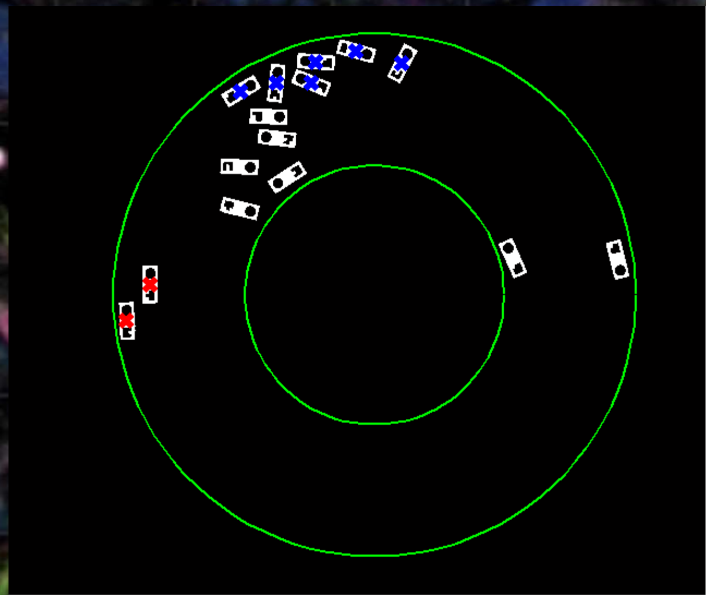
What does "collective dynamics" mean ?

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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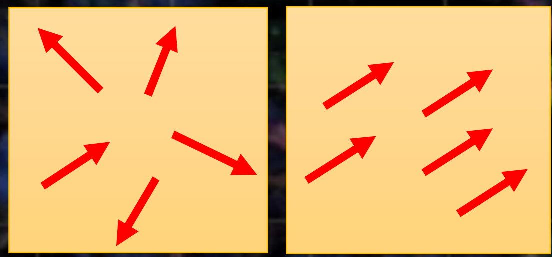
Why is studying emergence difficult ?

Emergence = Transition:
disorder → self-organization

Ex. random state vs aligned state



A. Frouvelle

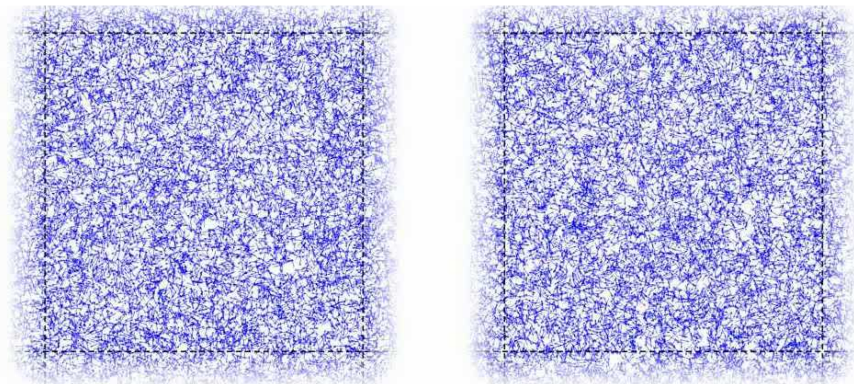
Depends on noise

i.e. how often particles change orientation randomly

Alignment interaction + noise
Simulation by A. Frouvelle

Larger noise

Smaller noise



t = 00,00

Ex. Vicsek model

self-propulsion + alignment + noise

T. Vicsek

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

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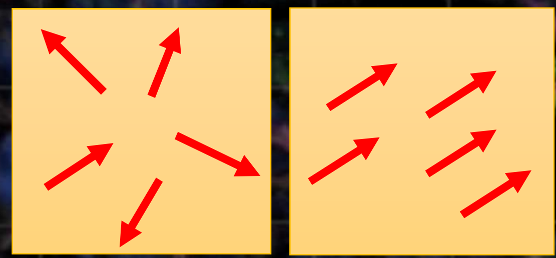
Why is studying emergence difficult ?

Emergence = Transition:
disorder → self-organization

Ex. random state vs aligned state

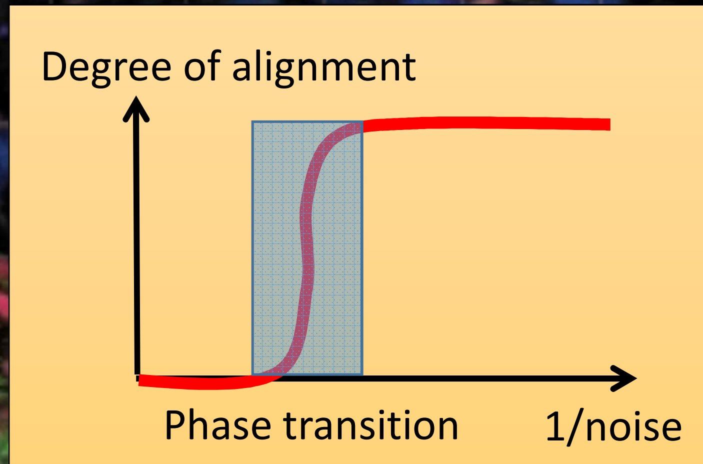


Depends on noise

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

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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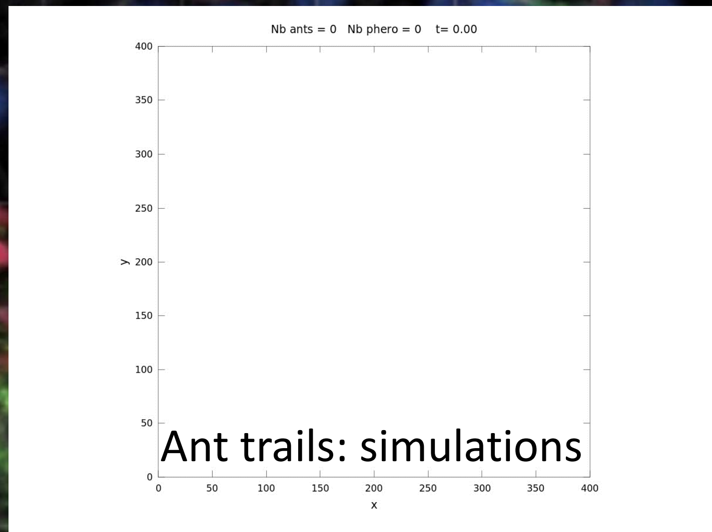
Different types of phase transitions

Symmetry breaking

Packing

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



Ant trails: simulations

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

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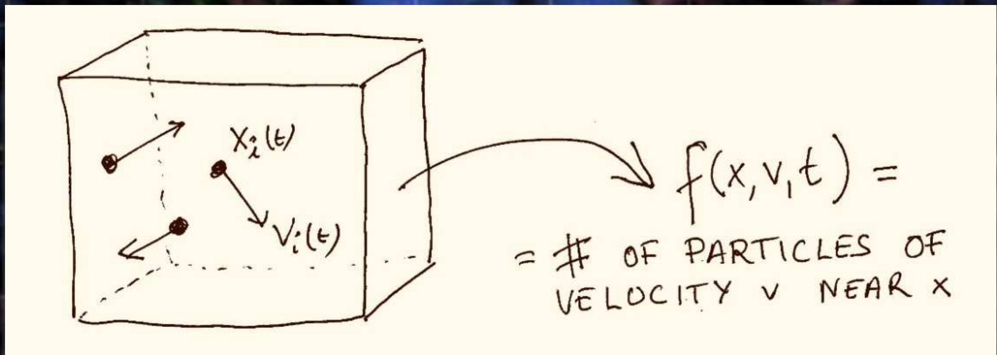
1st step: kinetic equation

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

Imperial College London

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 <v>) derived from conservations

In classical cases (gases):

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

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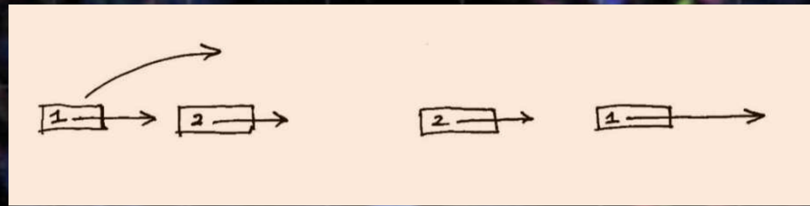
No conservations for "exotic" particles

Ex. vehicles:
no momentum conservation



How to obtain macroscopic equations ?

"weaker" conservation:
"generalized collision invariant"

Application: Vicsek

Self propulsion + alignment + noise

Macroscopic model is

$$\partial_t \rho + c_1 \nabla_x (\rho u) = 0$$

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

$$|u| = 1$$

Self-Organized Hydrodynamics (SOH)

S. Motsch

PD, Motsch, M3AS 18 Suppl (2008) 1193

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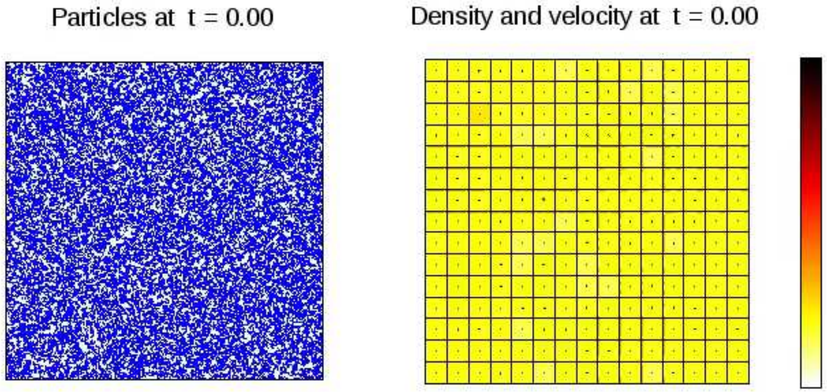
Vicsek (micro) vs SOH (macro)

Micro model (Vicsek)

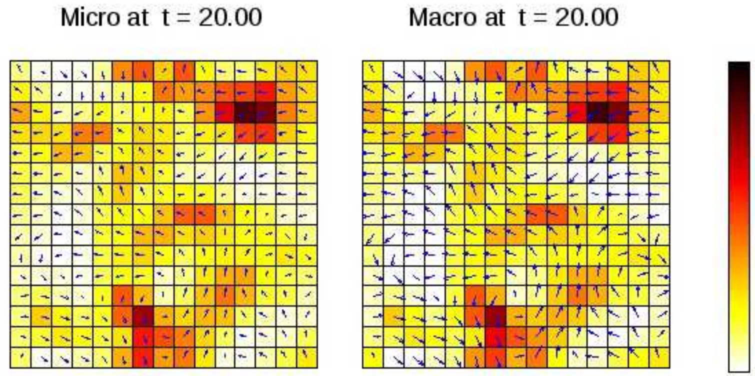
Self propulsion + alignment + noise



Particles

Density (color)
Velocity (arrows)

Micro (Vicsek) Macro (SOH)



Density (color)
Velocity (arrows)

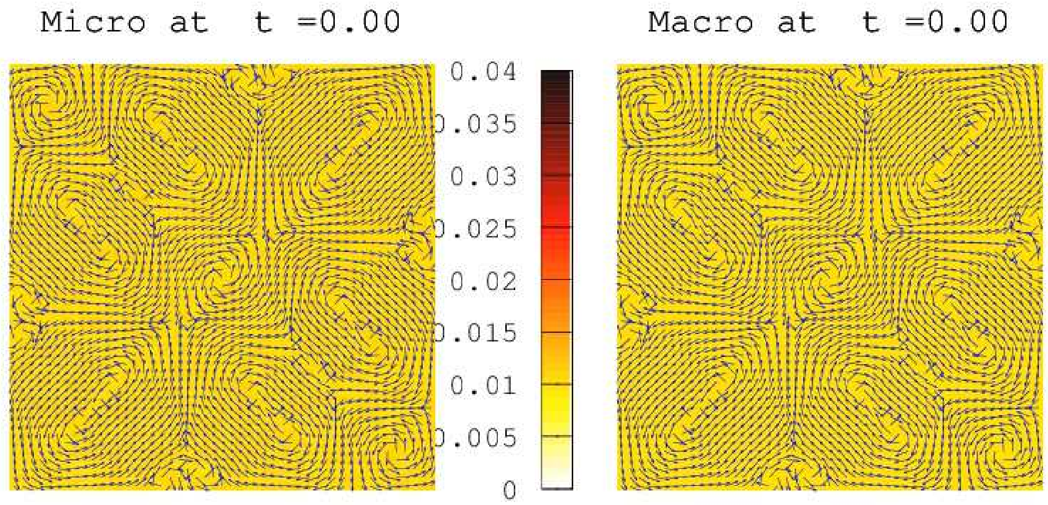
Simulations by S. Motsch

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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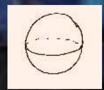
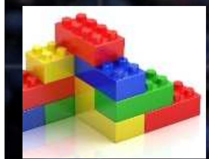
Tissue self-organization

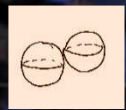
Cells: 2D spheres



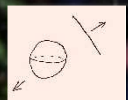
Fibers: line segments



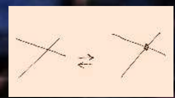
Cell-cell volume exclusion



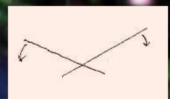
Cell-fiber repulsion

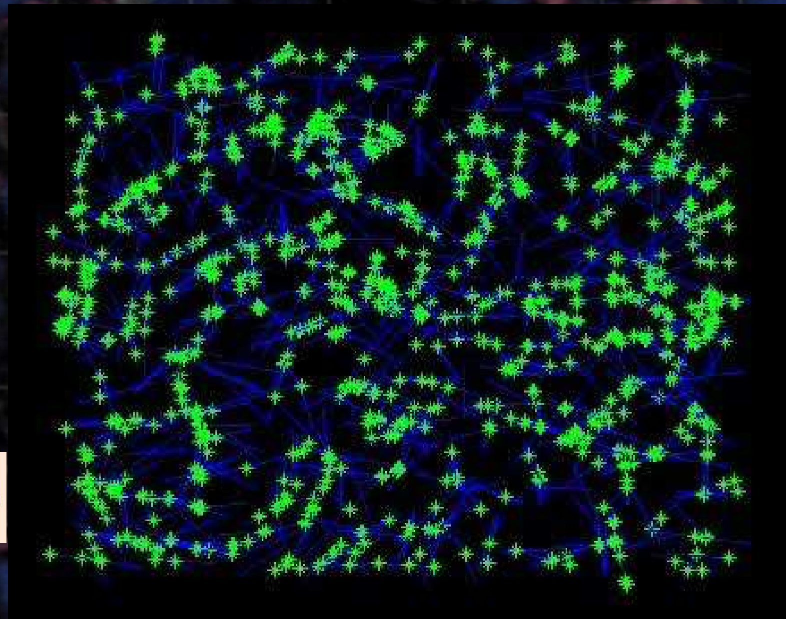


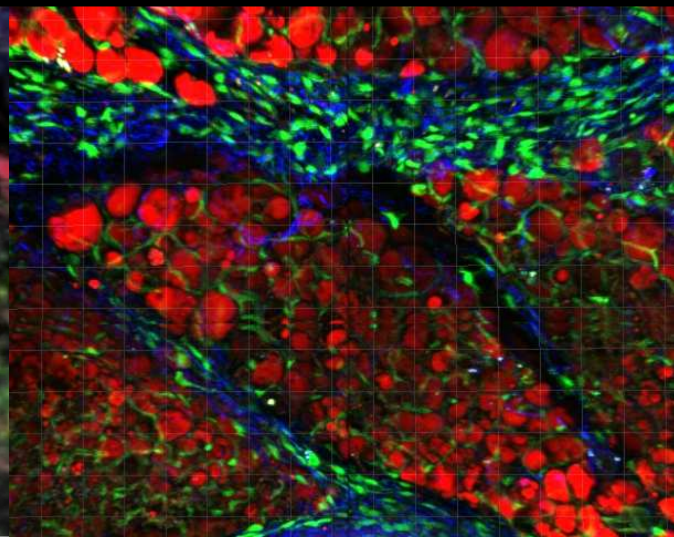
Fiber-fiber cross-linking



Fiber-fiber alignment







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

L. Casteilla

D. Peurichard

Blood capillary formation

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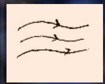
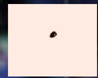
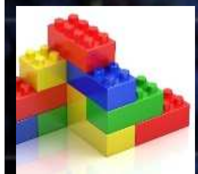
Blood: fluid 

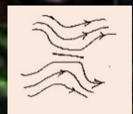
Oxygen (O2): point particles 

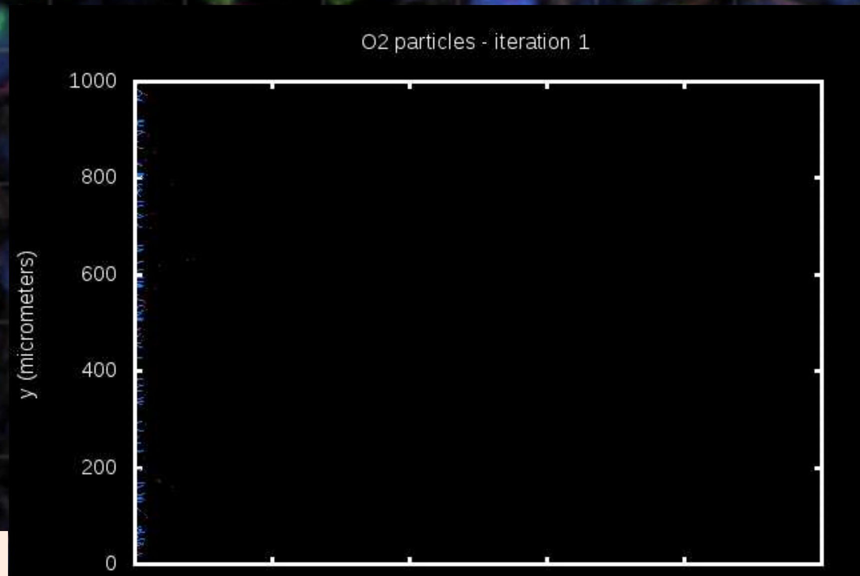
Capillaries: line segments 

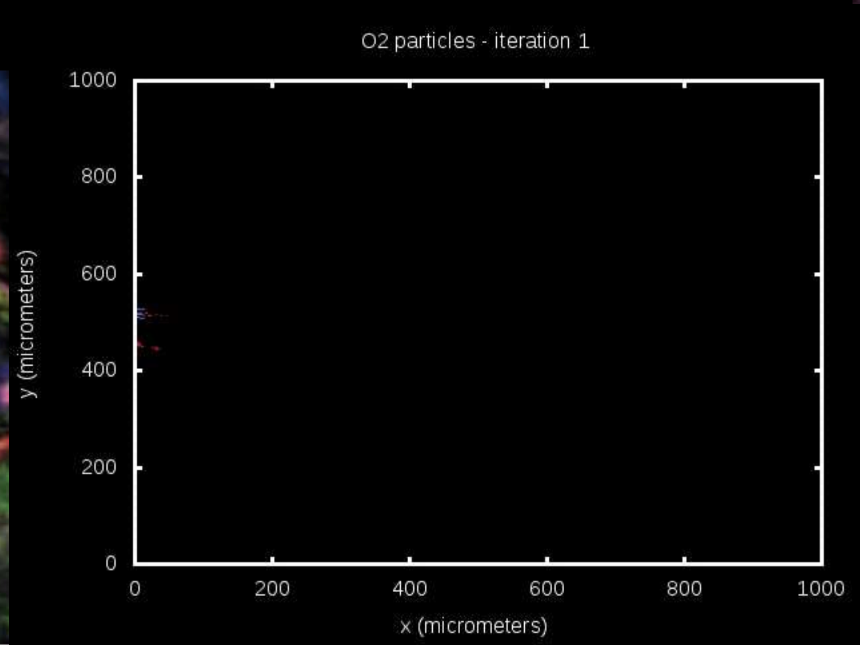


Oxygen transport by blood 

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

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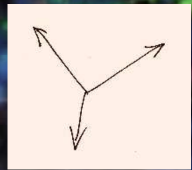
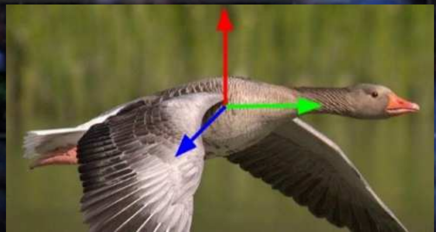
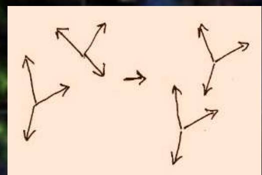
Body attitude coordination

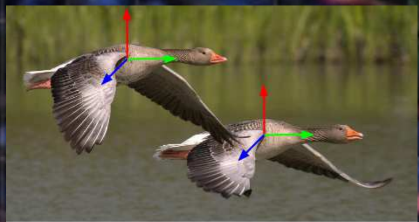
Birds, fish: frames



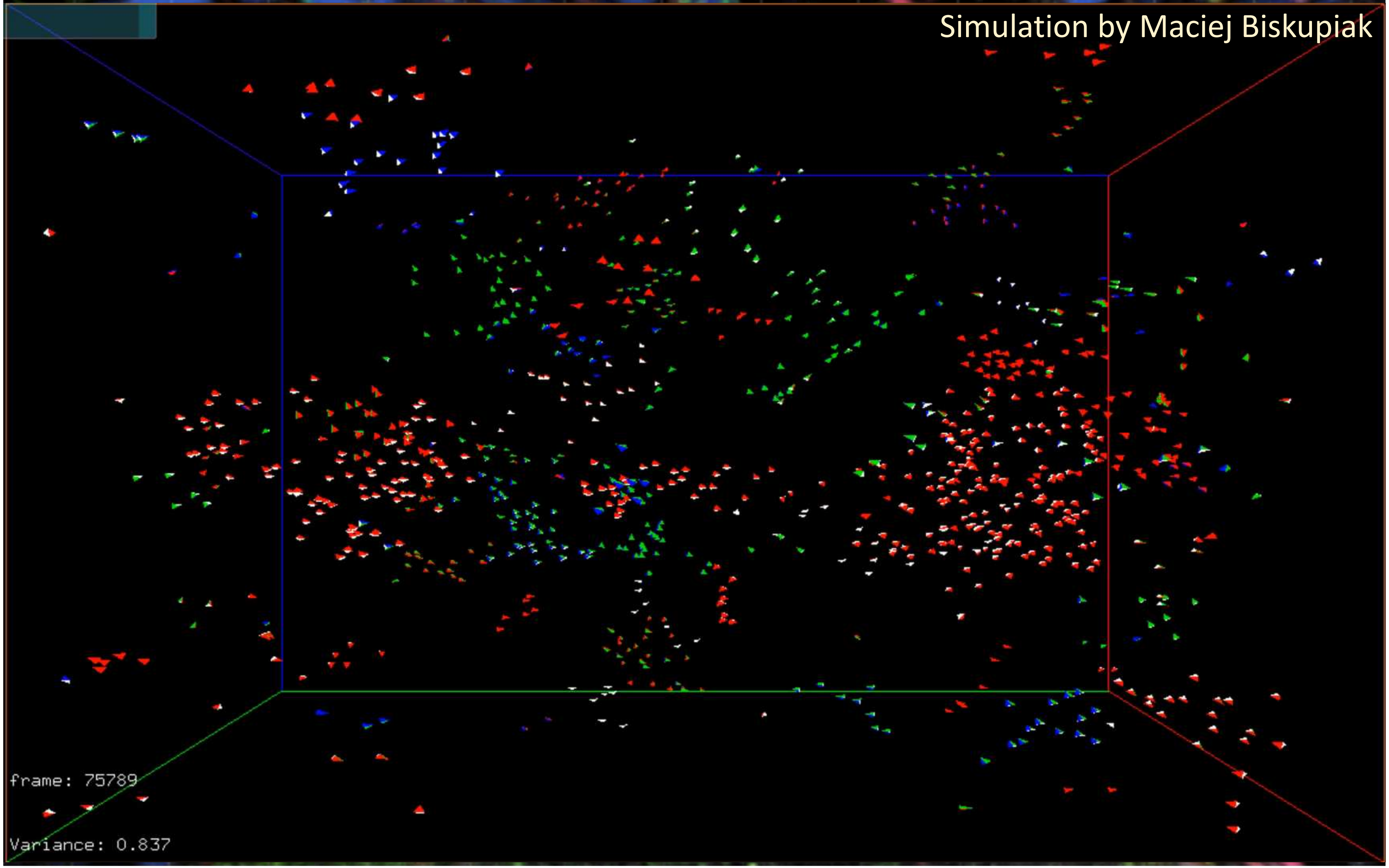


Frame alignment





Body attitude coordination



Body attitude coordination

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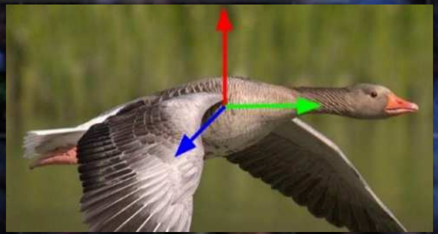
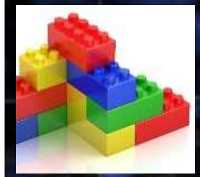
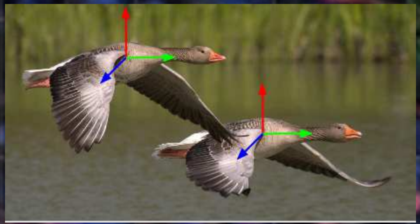




Frame alignment



Macroscopic model:

$$
\partial_t \rho + c_1 \nabla_x \cdot (\rho\, \Lambda \mathbf{e_1}) = 0,
$$

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

A. Frouvelle

S. Merino-Aceituno

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

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Conclusion

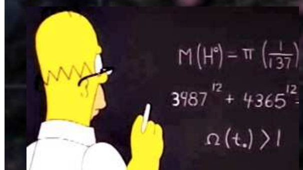
Emergence: Property of systems that develop patterns on scales larger than those of their individual components

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

$f(x,v,t)$

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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