Example of Implementation:
Turbulence Meets Active Matter

Michael Wilczek

Max Planck Institute for Dynamics and Self-Organization

Göttingen, Germany

Turbulence

I can do it!

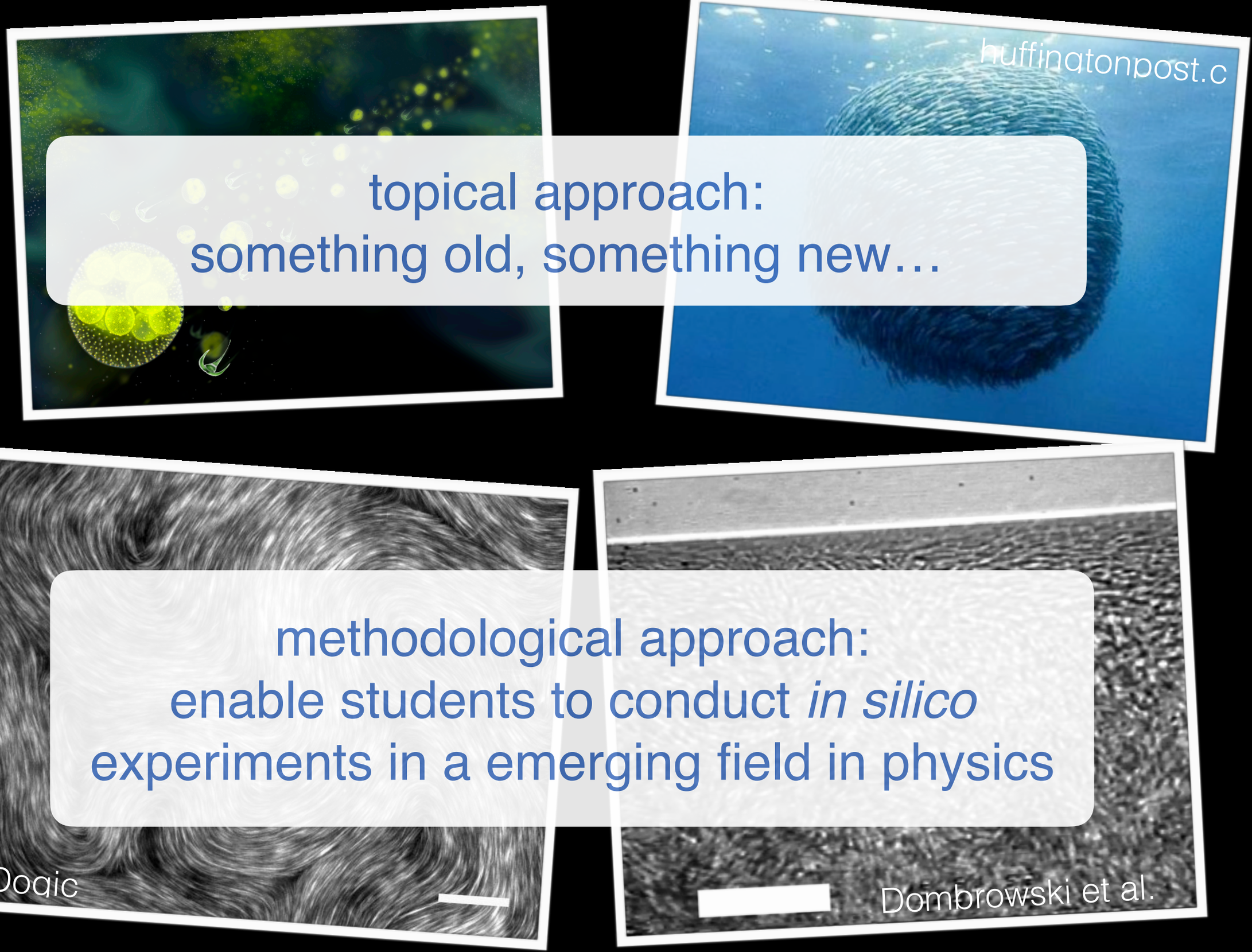
Werner Heisenberg

But it's the last grand problem of classical physics!

Richard Feynman

Plankton (aka Active Matter)

Turbulence Meets Active Matter



topical approach:
something old, something new…

methodological approach:
enable students to conduct *in silico*
experiments in a emerging field in physics

Intended Outcome: Bringing Research Experience to the Classroom

Topics:

- fluid dynamics
- turbulence theory
- soft matter physics: agent-based & continuum models
- statistical mechanics

Methods:

- theory: dynamical & complex systems
- computational aspects: programming, numerical solution of differential equations

Challenges:

- broad, multi-disciplinary range of topics
- theoretically & computationally demanding course material

Teaching Plan Implementation

Lecture:

- draw bigger picture
- motivate & define problems for student projects
- provide theoretical background

Tutorial:

- support student projects
- introduce computational methods
- group discussions of outcome of “numerical experiments”

Things I wanted to try out:

- active learning
- just-in-time teaching
- …

Interactive Elements

polleverywhere.com

Student Projects

- Generalized Vicsek models
- Modelling of pedestrian dynamics: Can you escape?
- Generalized Navier-Stokes equations as models for active flows
- Collective dynamics of force dipoles in a Stokes flow
- Active swimmers in a flow

ordinary differential equations

difficulty

partial differential equations

Getting up to Speed

Life at low Reynolds number

E. M. Purcell
Lyman Laboratory, Harvard University, Cambridge, Massach
(Received 12 June 1976)

Vorticity, defects a

al of Physics
urnal for physics

ation in

roswimmer suspensions

ich[2]
Germany
eig und Berlin,

Meso-sca

Henr - H. Wensink
Har n of a hydrody

[a]In
Ph
C

ng Reinken,[1,*] Sab
ical Physics, Techni
delling and Data Ana
Abbestr. 2-12,

December 2017

oire de

ny;
tre for

Novel Type of Phase Transition in a System of Self-Driven Particles

Tamás Vicsek,[1,2] András Czirók,[1] Eshel Ben-Jacob,[3] Inon Cohen,[3] and Ofer Shochet[3]
[1]Department of Atomic Physics, Eötvös University, Budapest, Puskin u 5-7, 1088 Hungary
[2]Institute for Technical Physics, Budapest, P.O.B. 76, 1325 Hungary
[3]School of Physics, Tel-Aviv University, 69978 Tel-Aviv, Israel
(Received 25 April 1994)

amical XY Model: How Birds Fly Together

ai Tu[1]
own Heights, New York 10598
Oregon 97403-1274*

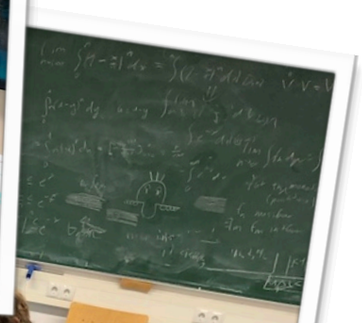
dom
te, France
m

SZOV[3,*]

Long-Range Ord

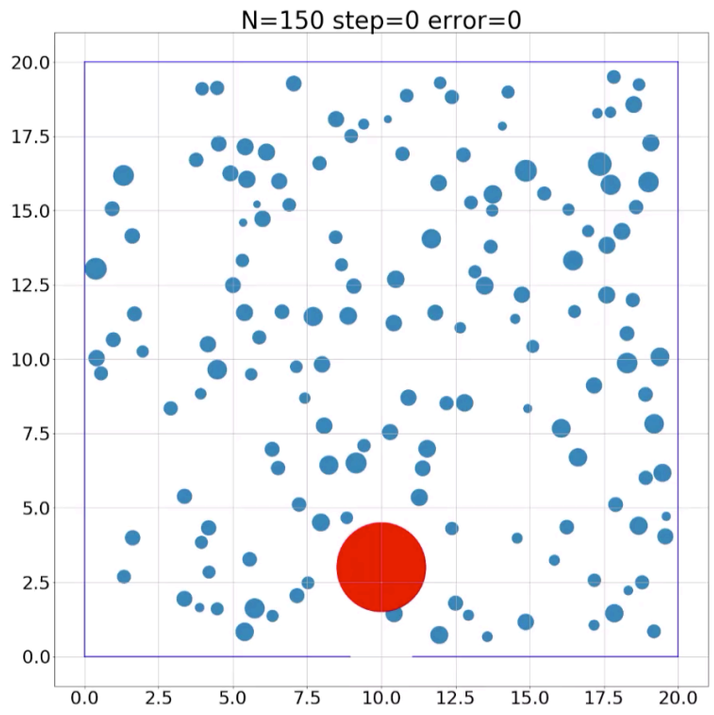
[1]IBM T. J. Watso
[2]Department of

Coding is Fun…Isn't it?

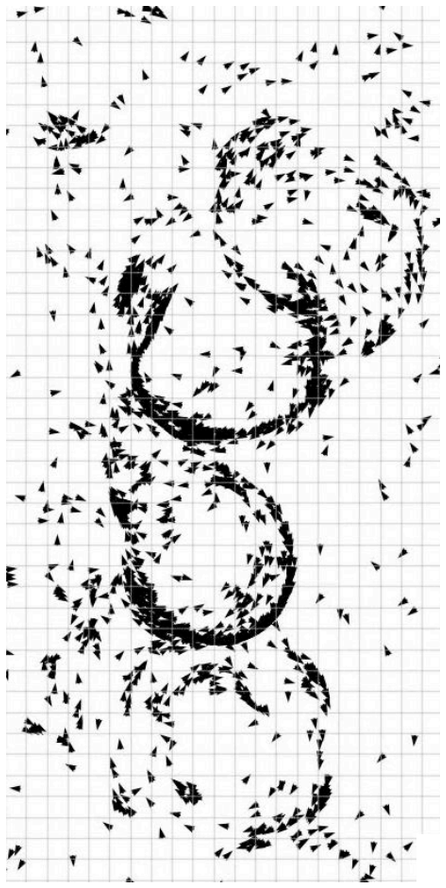


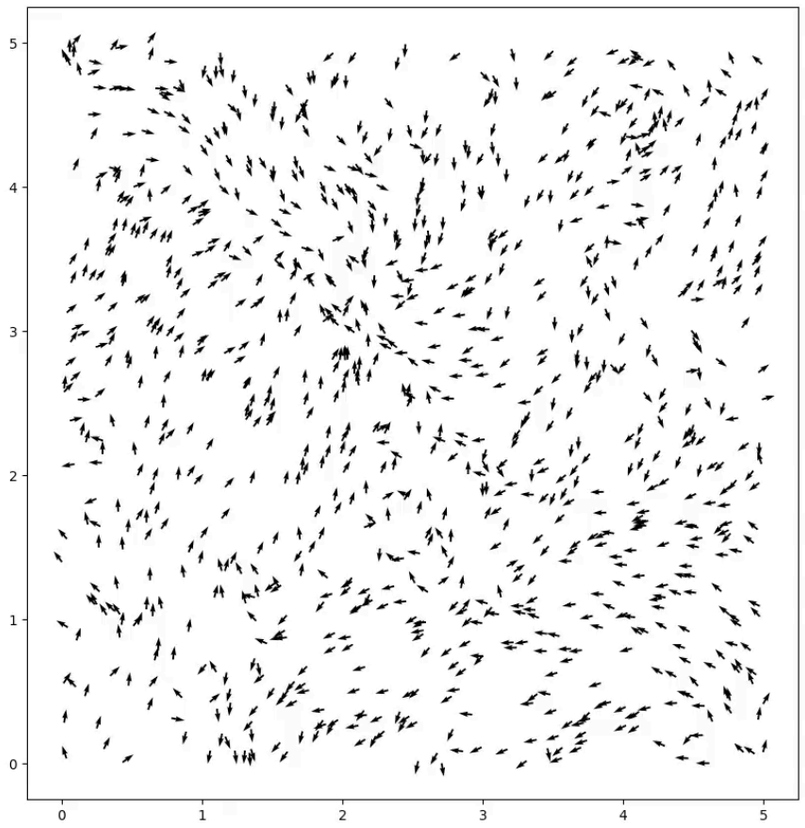
Results

pedestrian evacuation

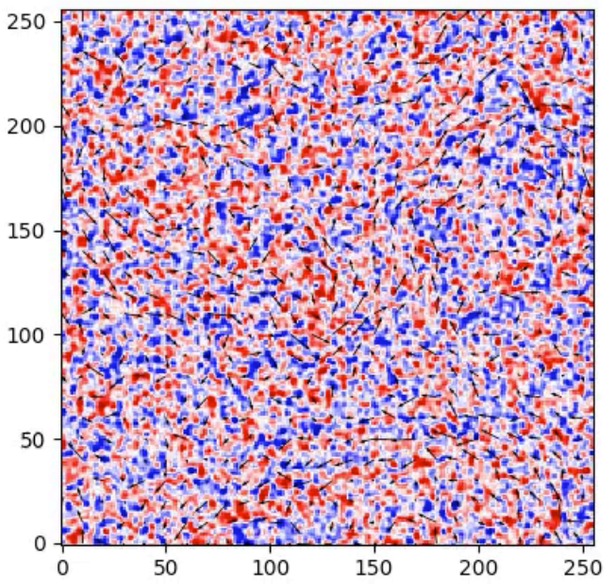


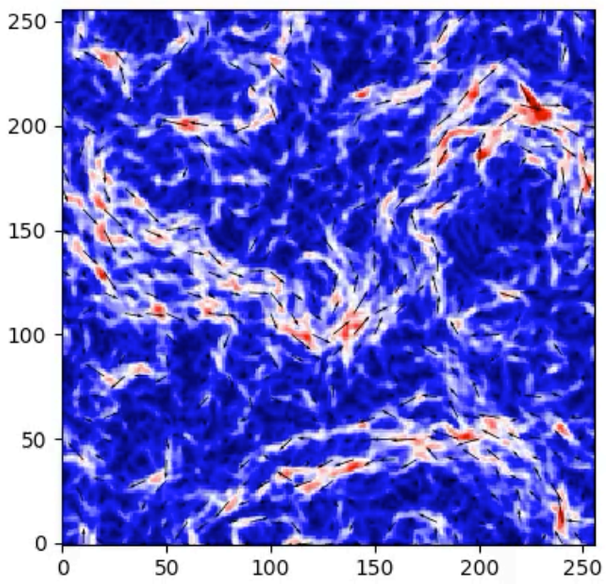
active particles

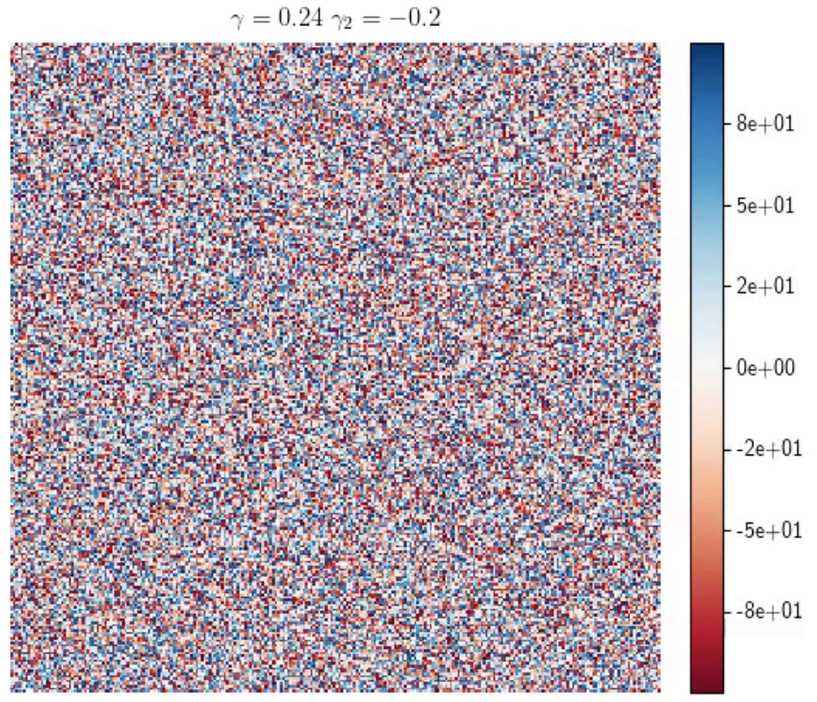




active fluids



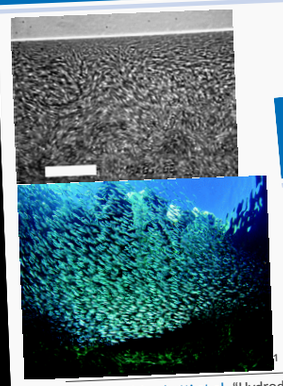




Final Presentations

Why active fluids?

A short introduction to active fluids

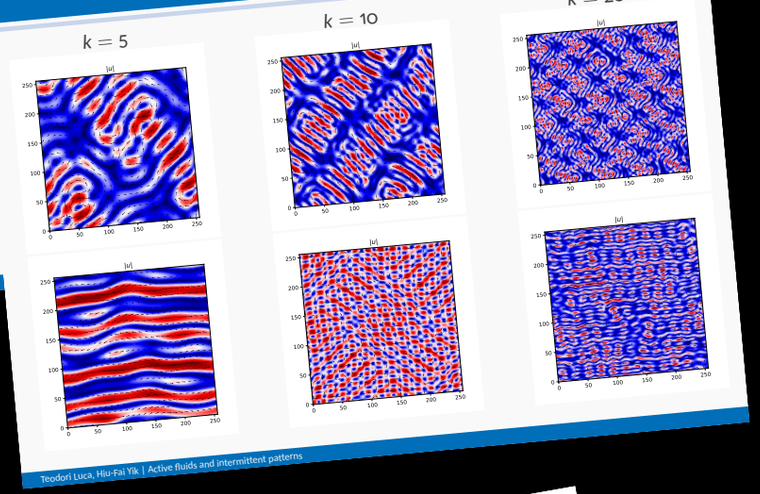


[1]M. C. Marchetti et al. "Hydrodyn
Physics (2013).

Teodori Luca, Hiu-Fai Yik | Active fluids and intermittent patterns

Intermittent pattern forming system

Snapshots of patterns



Teodori Luca, Hiu-Fai Yik | Active fluids and intermittent patterns

Introduction

DGL

Theoretical Background
Equations

- acceleration equation

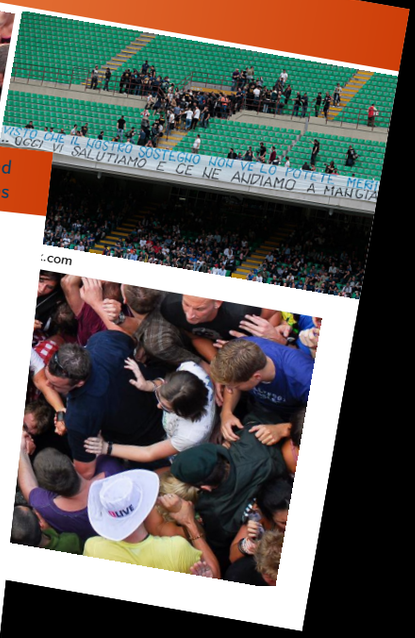
$$\frac{d\boldsymbol{v}_i}{dt} = \underbrace{\frac{v_i^0(t)\,\boldsymbol{e}_i^0(t) - \boldsymbol{v}_i(t)}{\tau_i}}_{\text{velocity difference without interactions}} + \underbrace{\frac{1}{m_i}\sum_{j(\neq i)} \boldsymbol{f}_{ij}}_{\text{interaction pedestrians}} + \underbrace{\frac{1}{m_i}\sum_{W} \boldsymbol{f}_{iW}}_{\text{interaction with walls}}$$

- change of position

$$\frac{d\boldsymbol{r}_i}{dt} = \boldsymbol{v}_i(t)$$

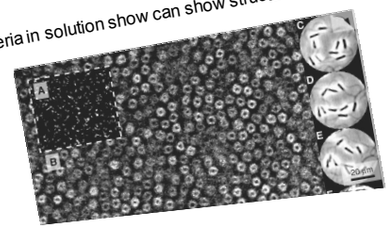
$\boldsymbol{v}$ velocity, v^0 desired velocity, $\boldsymbol{e}$ direction, τ characteristic time, m_i mass, $\boldsymbol{f}_{ij}$ person interaction force, $\boldsymbol{f}_{iW}$ wall interaction force, $\boldsymbol{r}$ position

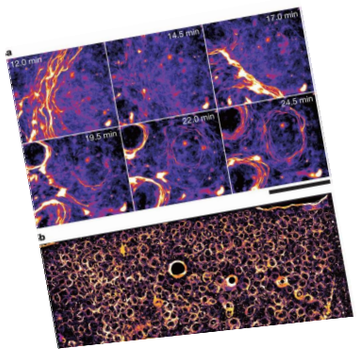
Helbing, Farkas, and Vicsek in *Nature*



Introduction

Bacteria in solution show can show structured behavior:





What are we trying to model?

„…to describe the solvent flow in an active suspension…"

- Incompressible Navier-Stokes equations
- Model bacterial influence on the flow
- Dense suspension of bacteria

Collective dynamics of microswimmers in Stokes flow

…

Convergence of the field

$$\boldsymbol{u}(\boldsymbol{r}) = \int d\boldsymbol{r}' \boldsymbol{T}(\boldsymbol{r}-\boldsymbol{r}') F \sum_{\alpha\beta\gamma} \boldsymbol{p}^{\alpha\beta\gamma} \left[\delta\left(\boldsymbol{r}' - \left[\boldsymbol{r}^{\alpha\beta\gamma} + \frac{\ell}{2}\boldsymbol{p}^{\alpha\beta\gamma}\right]\right) - \delta\left(\boldsymbol{r}' - \left[\boldsymbol{r}^{\alpha\beta\gamma} - \frac{\ell}{2}\boldsymbol{p}^{\alpha\beta\gamma}\right]\right)\right]$$

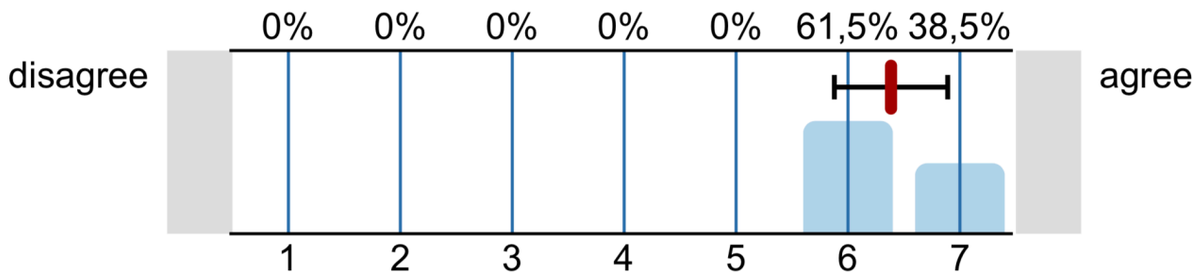
$$\boldsymbol{u}(0) = \frac{1}{8\pi\mu}\sum_{\alpha\beta\gamma}\left[\left(\frac{1}{r_\prime} - \frac{1}{r_{\prime\prime}}\right)\boldsymbol{I} + \frac{1}{r_\prime^3}\boldsymbol{r}_\prime \otimes \boldsymbol{r}_\prime - \frac{1}{r_{\prime\prime}^3}\boldsymbol{r}_{\prime\prime} \otimes \boldsymbol{r}_{\prime\prime}\right].\boldsymbol{p}^{\alpha\beta\gamma}$$

$$\boldsymbol{u}(0) = \frac{1}{8\pi\mu}\sum_{\alpha\beta\gamma}\left[\left(-\frac{d\cos\theta}{r^{\alpha\beta\gamma 2}}\right)\boldsymbol{p}^{\alpha\beta\gamma}\left(-\frac{3d\cos\theta(\boldsymbol{p}^{\alpha\beta\gamma}.\boldsymbol{r}^{\alpha\beta\gamma})}{r^{\alpha\beta\gamma 4}}\right)\boldsymbol{r}^{\alpha\beta\gamma} + \frac{\boldsymbol{r}^{\alpha\beta\gamma}}{r^{\alpha\beta\gamma 3}} + \frac{(\boldsymbol{p}^{\alpha\beta\gamma}.\boldsymbol{r}^{\alpha\beta\gamma})}{r^{\alpha\beta\gamma 3}}\boldsymbol{p}^{\alpha\beta\gamma}\right]$$

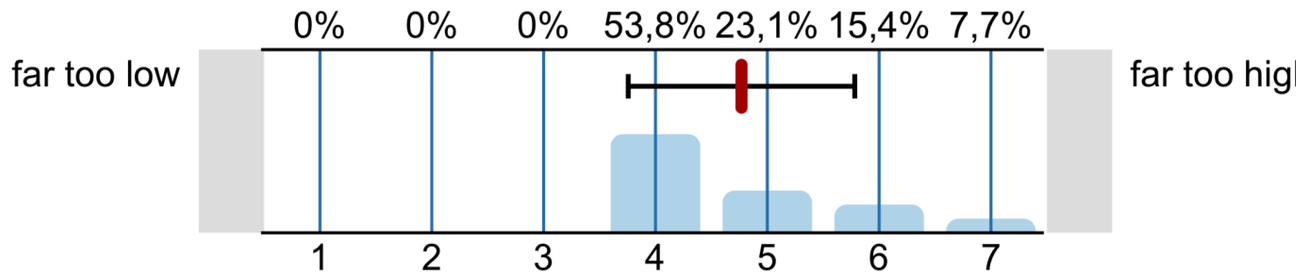
$$\boldsymbol{r}' = \boldsymbol{r}^{\alpha\beta\gamma} + \frac{l}{2}\boldsymbol{p}^{\alpha\beta\gamma} \qquad \boldsymbol{r}'' = \boldsymbol{r}^{\alpha\beta\gamma} - \frac{l}{2}\boldsymbol{p}^{\alpha\beta\gamma}$$

Feedback (from 10 MSc, 1 BSc, 2 PhD students)

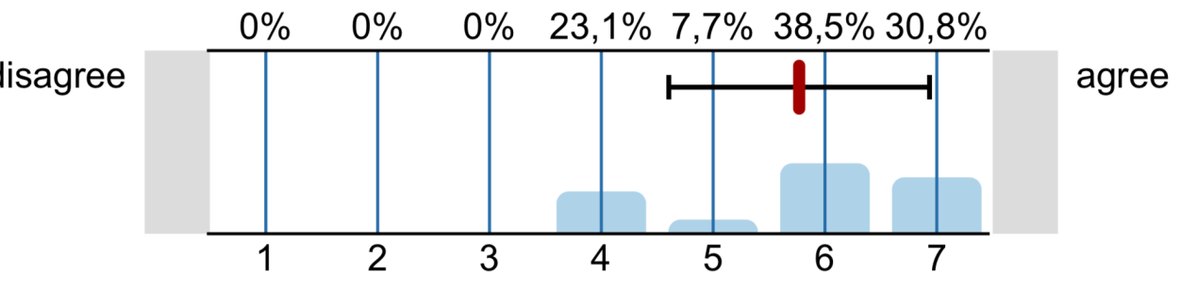
The course increased my interest in the topic.



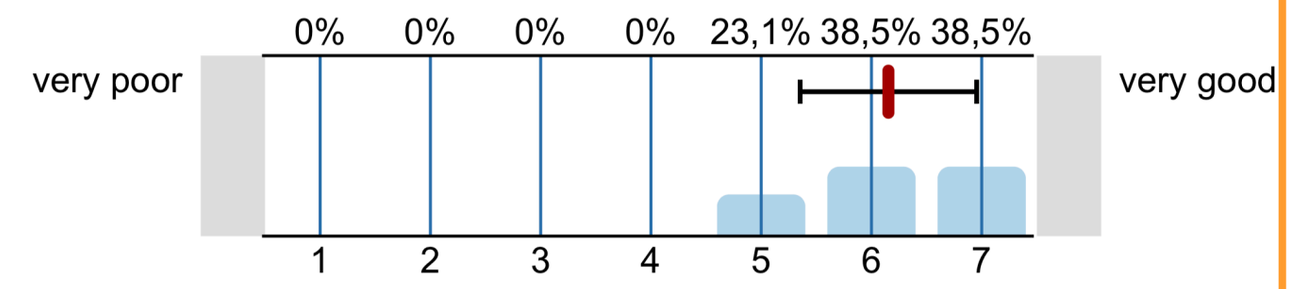
The workload is…



I learn a lot in this course.



overall rating



“I really like the hybrid-lecture type of classes and projects”

“The project really increased my interest — very nice approach!”

“The structure of the course combined with the tutorials was very good. I learned a lot about programming, which will certainly be useful for my future studies”

Teaching Evaluation Team

Acknowledgements

Jose Agustín Arguedas-Leíva
Lukas Bentkamp
Tobias Bätge
Debarghya Banerjee
Jan Cammann
Gerrit Green
Gregor Ibbeken
Martin James
Colin Koch
Kim Kreienkamp
Cristian Lalescu
Laura Lukassen (now Univ. Oldenburg)
Leonhard A. Leppin
Niklas Schnierstein
Dominik Suchla
Birte Thiede
Dimitar Vlaykov (now Univ. Exceter)

FULBRIGHT GERMANY

Bundesministerium für Bildung und Forschung

RESEARCH CORPORATION for SCIENCE ADVANCEMENT

MAX-PLANCK-GESELLSCHAFT