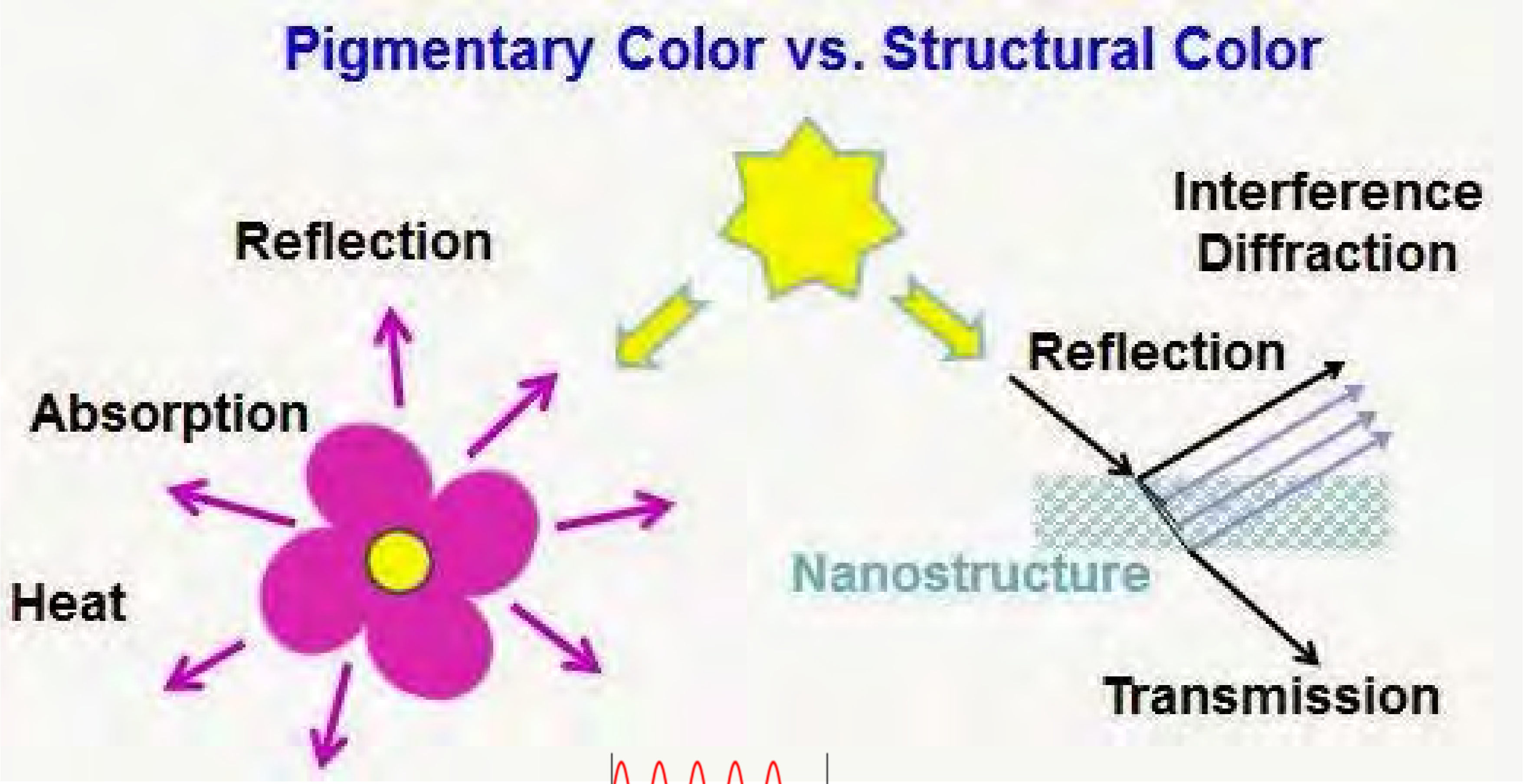
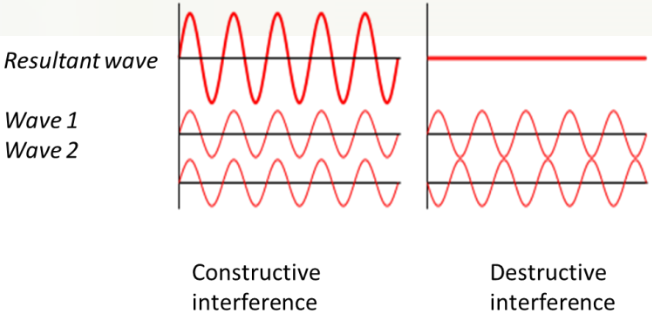
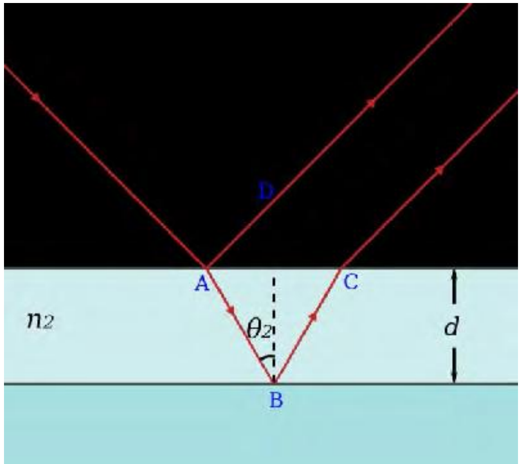
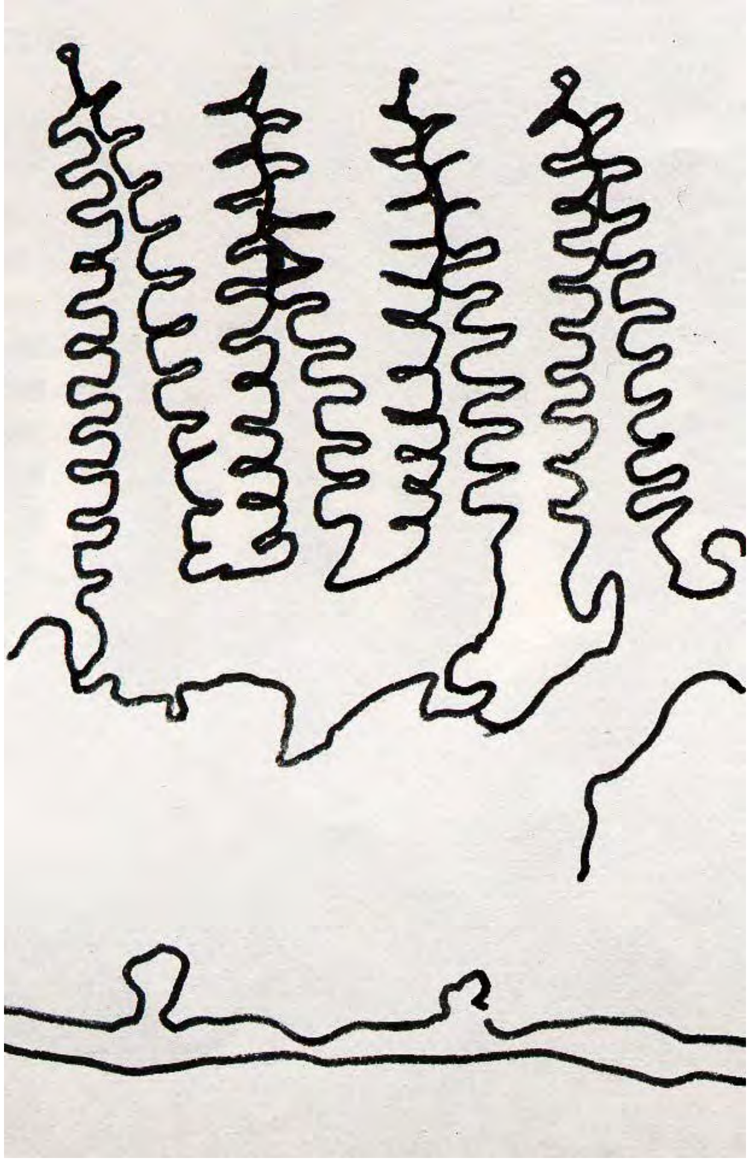






When light falls on a thin film, the waves reflected from the upper and lower surfaces travel different distances depending on the angle, so they interfere.

Butterfly wing at different magnifications reveals mesostructured chitin acting as a diffraction grating



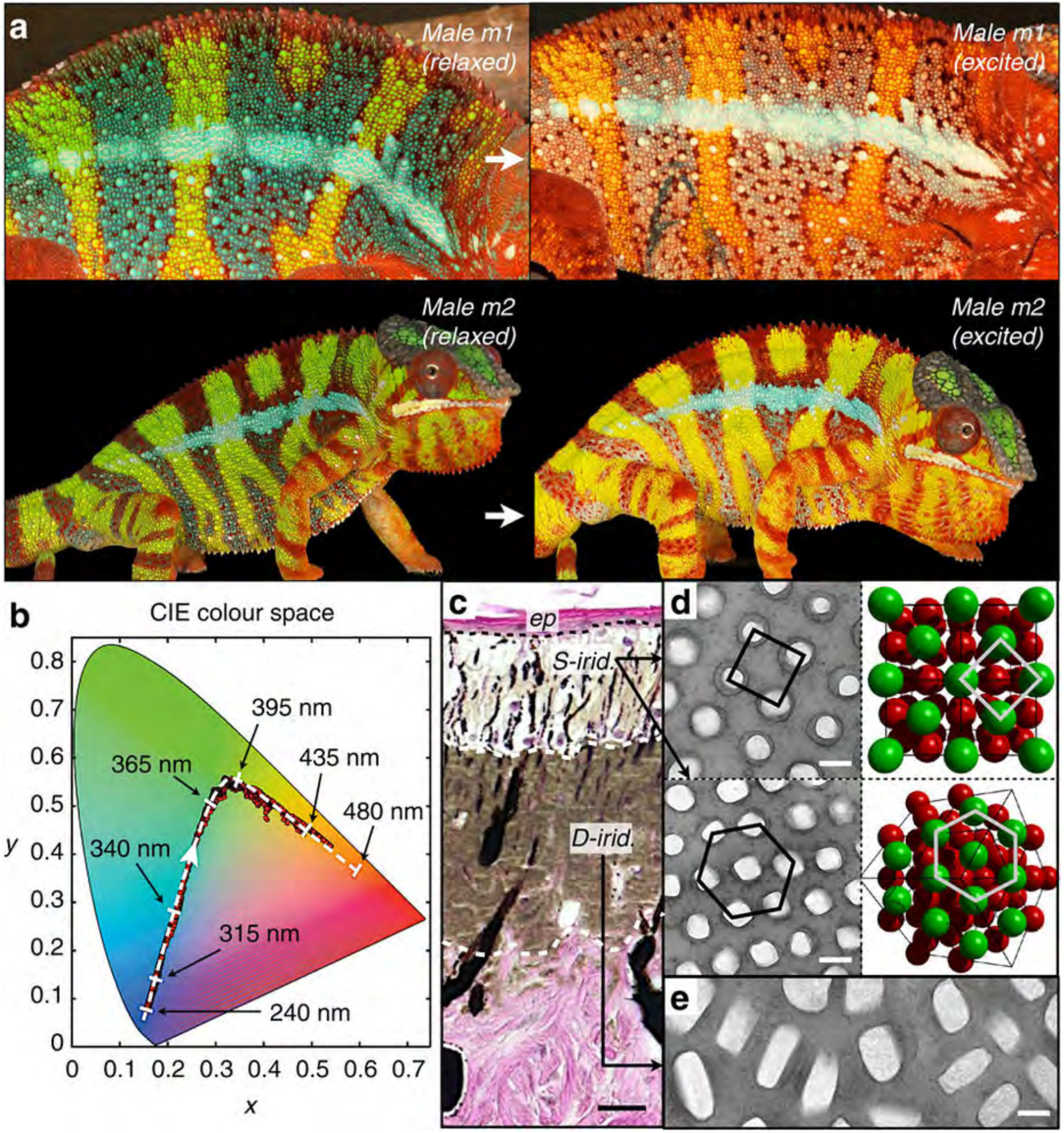
Article | OPEN

Photonic crystals cause active colour change in chameleons

Jérémie Teyssier, Suzanne V. Saenko, Dirk van der Marel & Michel C. Milinkovitch

Nature Communications **6**,
Article number: 6368 (2015)
doi:10.1038/ncomms7368
Download Citation
Photonic crystals

Received: 16 June 2014
Accepted: 22 January 2015



Chameleons can change their color in less than 1 second

Examples from wikipedia:

European bee-eaters owe their brilliant colours partly to diffraction grating microstructures in their feathers

In Morpho butterflies such as *Morpho helena* the brilliant colours are produced by intricate firtree-shaped microstructures too small for optical microscopes.

The male *Parotia lawesii* bird of paradise signals to the female with his breast feathers that switch from blue to yellow.

Brilliant green of emerald swallowtail, *Papilio palinurus*, is created by arrays of microscopic bowls that reflect yellow directly and blue from the sides.

Emerald-patched cattleheart butterfly, *Parides sesostris*, creates its brilliant green using photonic crystals.

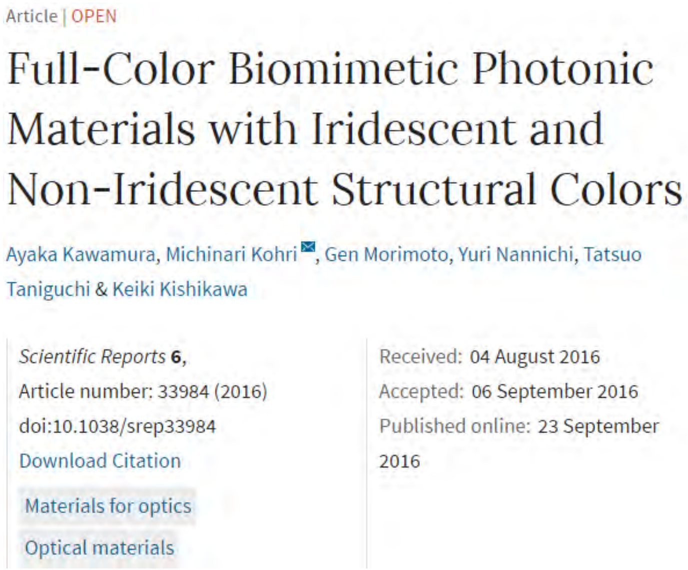
Iridescent scales of *Lamprocyphus augustus* weevil contain diamond-based crystal lattices oriented in all directions to give almost uniform green.

Hollow nanofibre bristles of *Aphrodita aculeata* (a species of sea mouse) reflect light in yellows, reds and greens to warn off predators.

Longfin inshore squid, *Doryteuthis pealeii*, has been studied for its ability to change colour.

Thin-film interference in a soap bubble. Colour varies with film thickness.

Smoked pork loin showing iridescence due to the fine arrangement of the muscle fibrils.



Article | OPEN

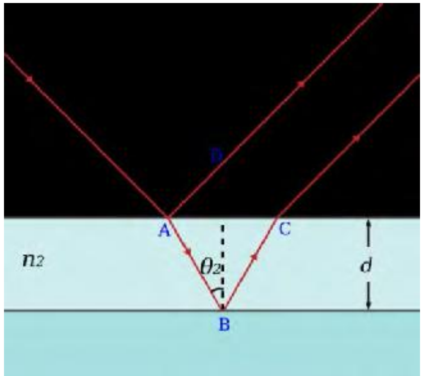
Full-Color Biomimetic Photonic Materials with Iridescent and Non-Iridescent Structural Colors

Ayaka Kawamura, Michinari Kohri, Gen Morimoto, Yuri Nannichi, Tatsuo Taniguchi & Keiki Kishikawa

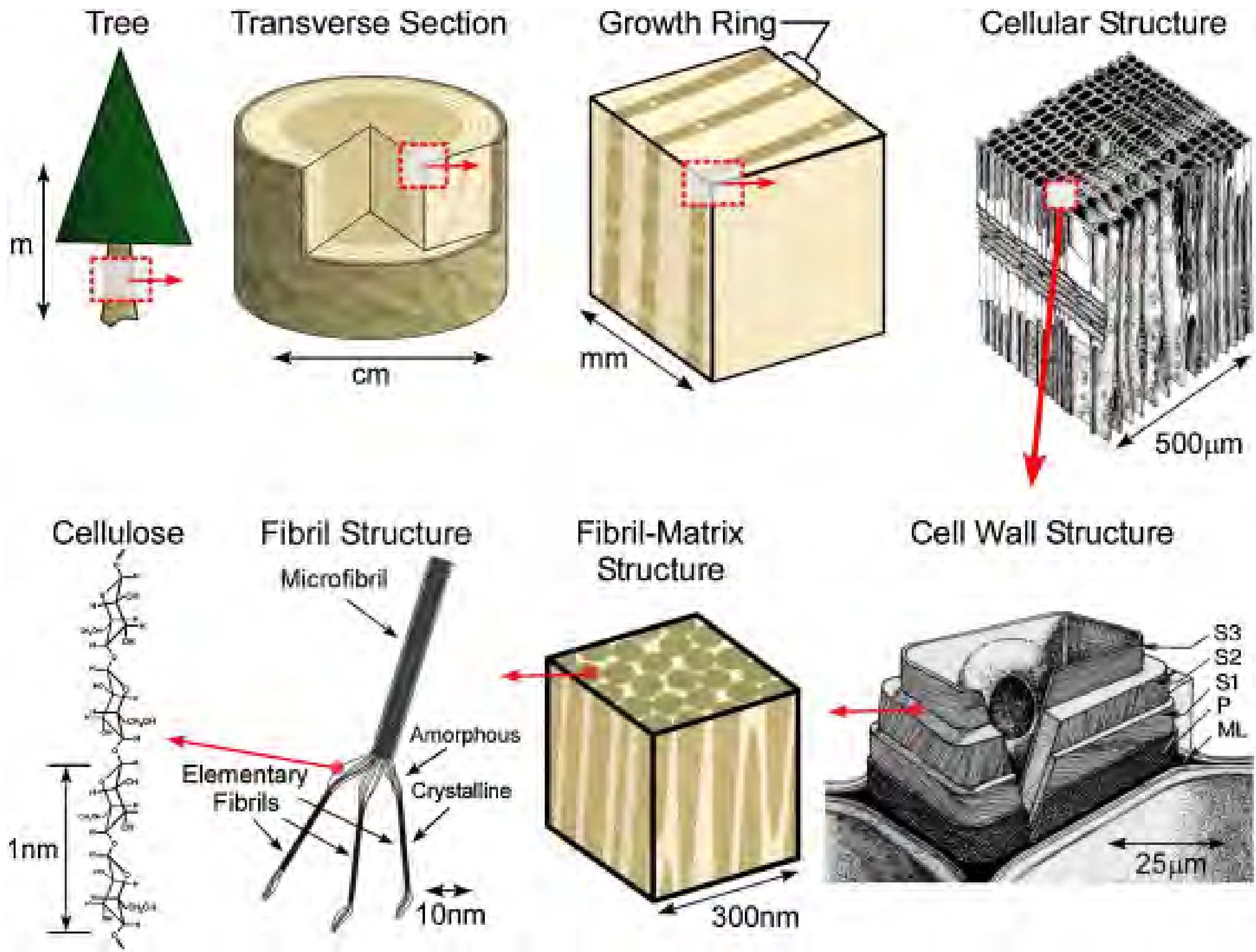
Scientific Reports **6**,
Article number: 33984 (2016)
doi:10.1038/srep33984
Download Citation

Materials for optics
Optical materials

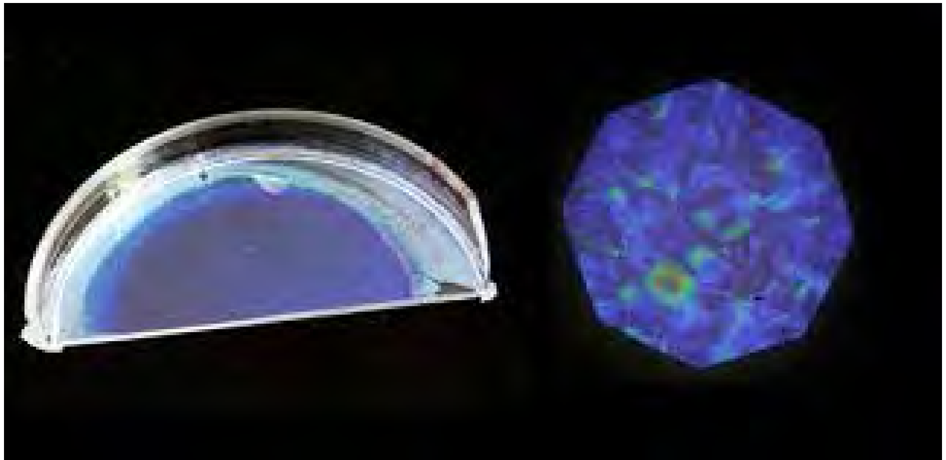
Received: 04 August 2016
Accepted: 06 September 2016



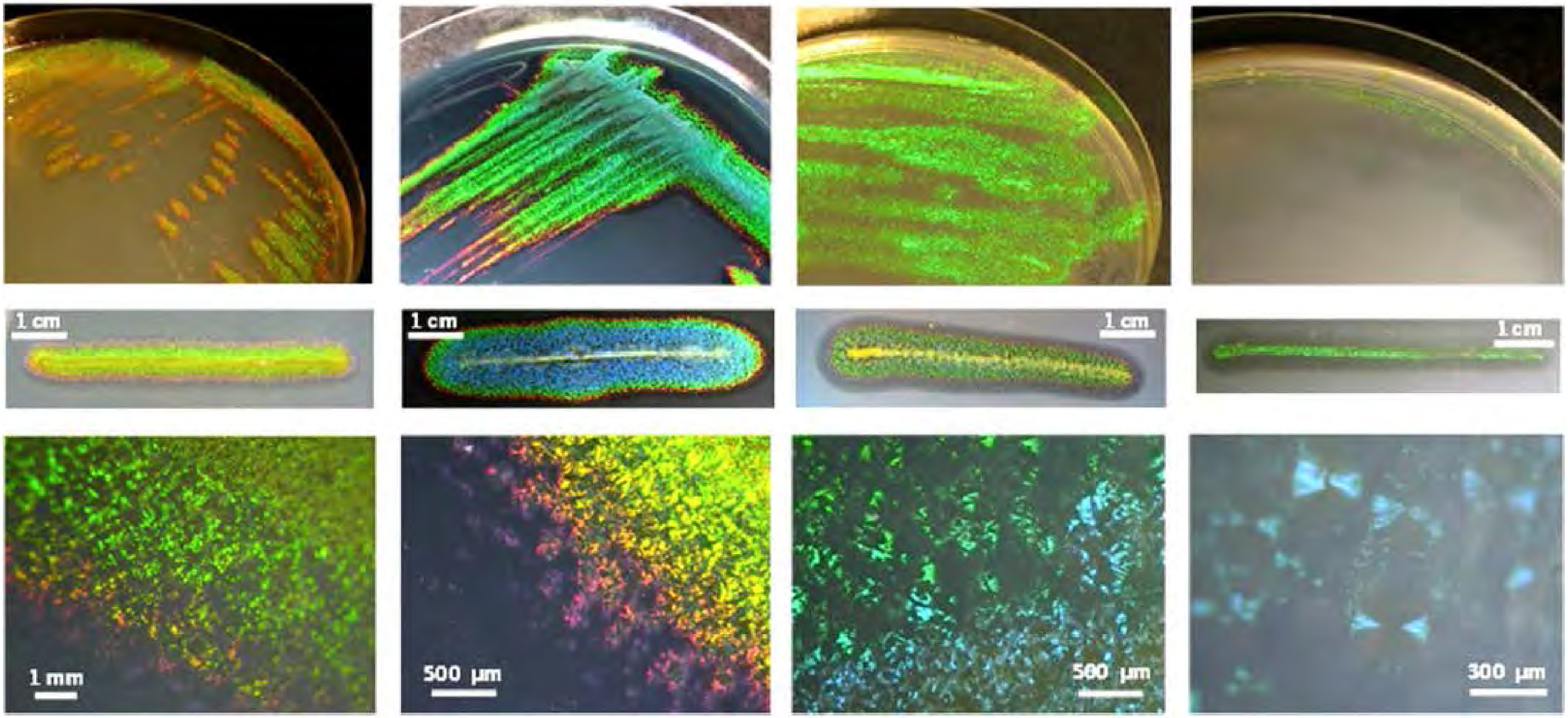
Polydopamine (PDA) shell layers
+ core polystyrene (PSt) particles

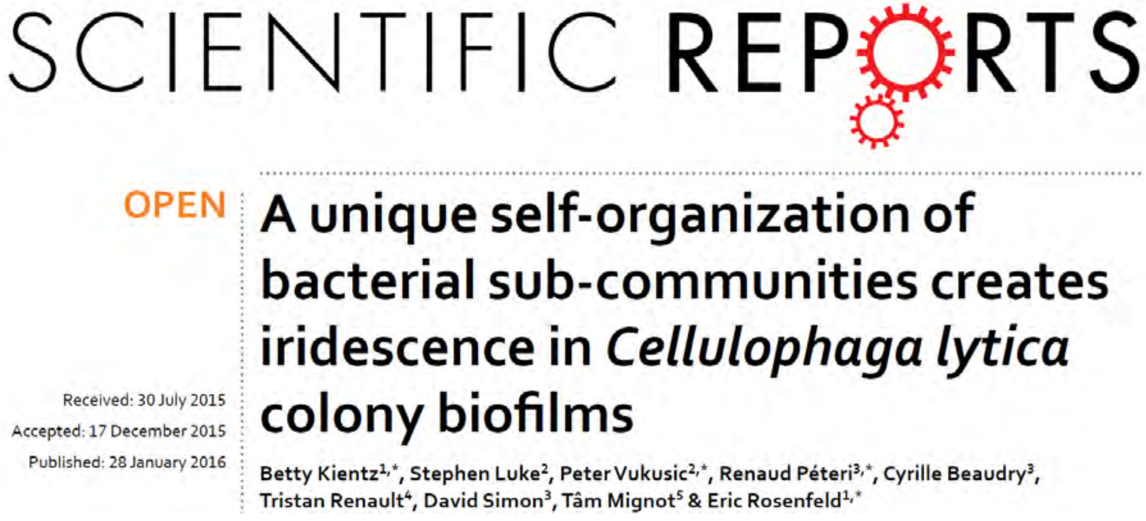


The most intense blue known in nature: African Pollia condensata berries



Dumanli, A. G., Kamita, G., Landman, J., van der Kooij, H., Glover, B. J., Baumberg, J. J., Steiner, U. and Vignolini, S. (2014), "Controlled, Bio-inspired Self-Assembly of Cellulose-Based Chiral Reflectors." Advanced Optical Materials. doi: 10.1002/adom.201400112




SCIENTIFIC REPORTS

OPEN

A unique self-organization of bacterial sub-communities creates iridescence in *Cellulophaga lytica* colony biofilms

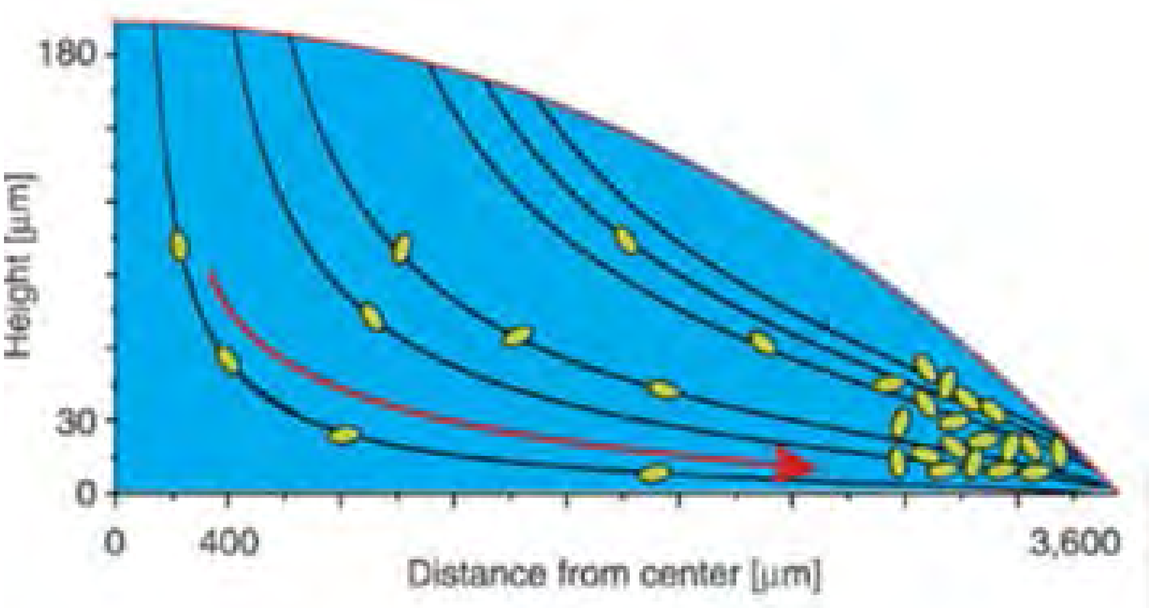
Received: 30 July 2015
Accepted: 17 December 2015
Published: 28 January 2016

Betty Kientz[1,*], Stephen Luke[2], Peter Vukusic[2,*], Renaud Péteri[3,*], Cyrille Beaudry[3], Tristan Renault[4], David Simon[3], Tâm Mignot[5] & Eric Rosenfeld[1,*]

Self-assembly:

Making a macroscopic sample (i.e. about 10^{20} nanoparticles) by physically picking up and moving nanoparticles into place, one by one, would take about 300 million years, even if the time for moving individual particles could be made as short as 1 millisecond.

One of many examples of self-assembly: The coffee stain effect:



NTNU – Trondheim
Norwegian University of
Science and Technology

Self-assembly: Emergent patterns, more is different

NTNU

Human made design:
Top-down assembly

How nature works:
Bottom-up Self-assembly

Scientific challenge of nanostructured self-assembly:
Combination of Top-down and Bottom-up:

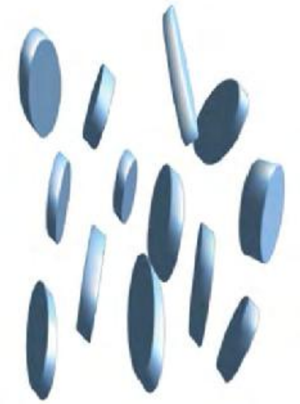
Another pile of rocks

Example of self-organization: Liquid Crystalline Phases

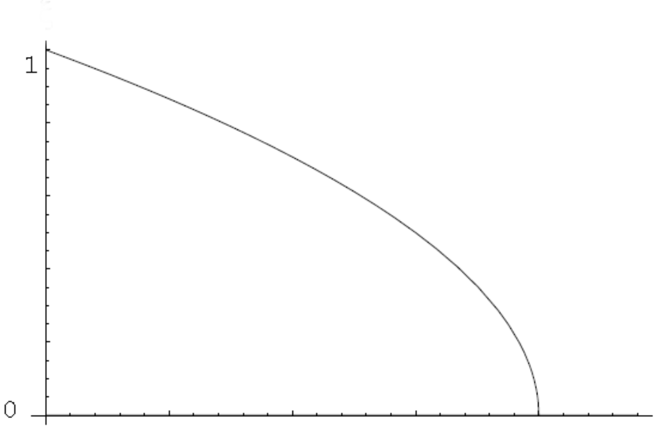
Order Parameter = O.P.
= Angular distribution function
= $S_2 = \frac{1}{2}\langle 3\cos^2\theta - 1 \rangle$

Isotropic Phase
(O.P. = 0) :
No orientational order,
no positional order

Nematic Phase
(O.P. ≠ 0):
Orientational order,
no positional order

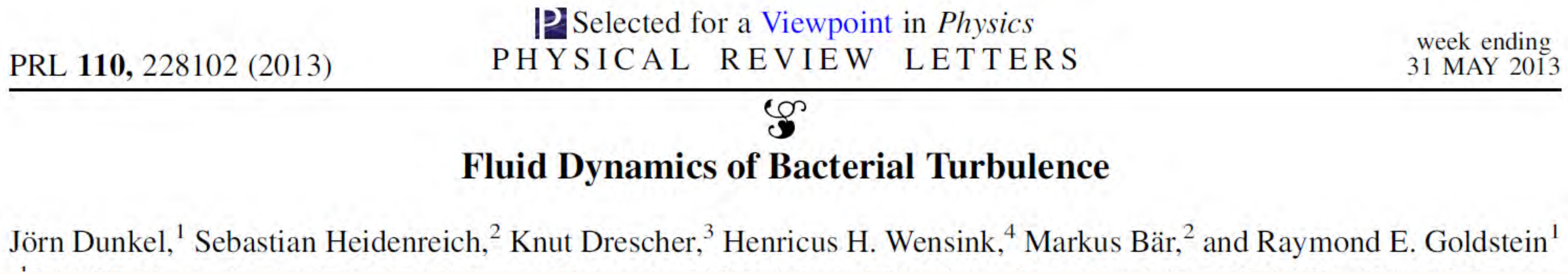


Order Parameter
(0<O.P.<1) = Angular
distribution function



Particle concentration, Electric fields, Magnetic fields, Etc.

Flocking and swarming



Selected for a Viewpoint in *Physics*

PRL **110,** 228102 (2013) PHYSICAL REVIEW LETTERS week ending 31 MAY 2013

Fluid Dynamics of Bacterial Turbulence

Jörn Dunkel,[1] Sebastian Heidenreich,[2] Knut Drescher,[3] Henricus H. Wensink,[4] Markus Bär,[2] and Raymond E. Goldstein[1]

exp_03_40xoil_40fps_flow.mov: Real-time low resolution movie (duration 50 s) of tracer motion as used for the PTV analysis (see main text for imaging parameters).

exp_03.mov (Real-time movie (duration 50 s) of the PIV flow field as extracted from "exp_03_40xoil_40fps_brightfield.mov"

Living Crystals of Light-Activated Colloidal Surfers

Jeremie Palacci *et al.*
Science **339**, 936 (2013);
DOI: 10.1126/science.1230020

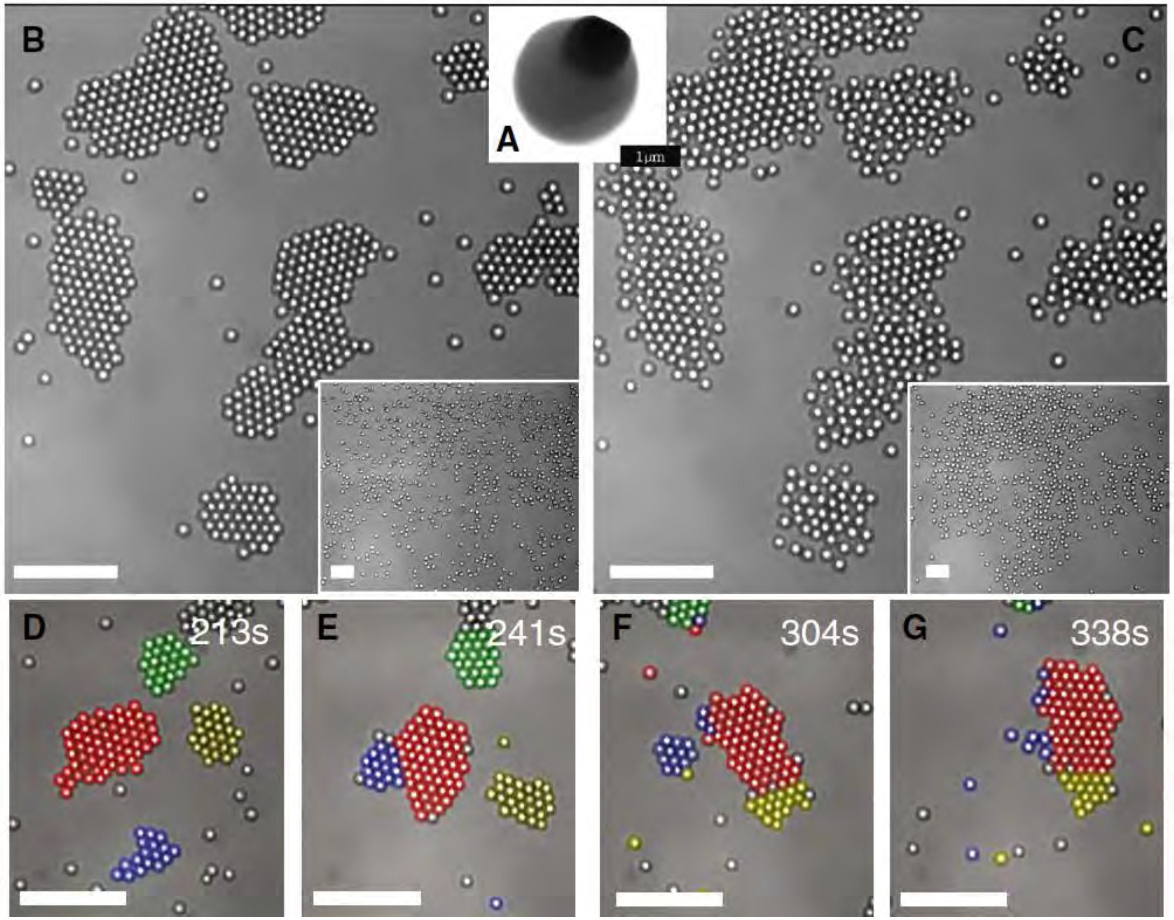
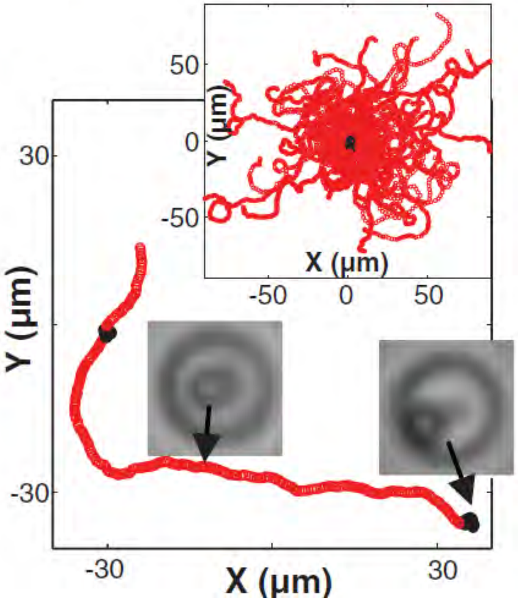


Fig. 1. (**A**) Scanning electron microscopy (SEM) of the bimaterial colloid: a TPM polymer colloidal sphere with protruding hematite cube (dark). (**B**) Living crystals assembled from a homogeneous distribution (inset) under illumination by blue light. (**C**) Living crystals melt by thermal diffusion when light is extinguished: Image shows system 10 s after blue light is turned off (inset, after 100 s). (**D** to **G**) The false colors show the time evolution of particles belonging to different clusters. The clusters are not static but rearrange, exchange particles, merge (D→F), break apart (E→F), or become unstable and explode (blue cluster, F→G). For (B) to (G), the scale bars indicate 10 µm. The solid area fraction is $\Phi_s \approx 0.14$.



A hematite cube protruding from a TPM polymer spheremoves on fixed glass substrate when exposed to blue light (red part of trace) and diffuses when the light is off (black part of trace). Initially, with no light, the hematite cube is oriented randomly (image, right) but rotates and faces downward toward the glass substrate when the light is turned on (image, left). The particle then surfs on the osmotic flow it induces between the substrate and itself. (Inset) A superposition of the trajectories of many particles with their origins aligned.

Living Crystals of Light-Activated Colloidal Surfers
Jeremie Palacci *et al.*
Science **339**, 936 (2013);
DOI: 10.1126/science.1230020

Phoretic and osmotic effects can conveniently be switched on and off by light.

Quincke rotation

1896. ANNALEN № 11.

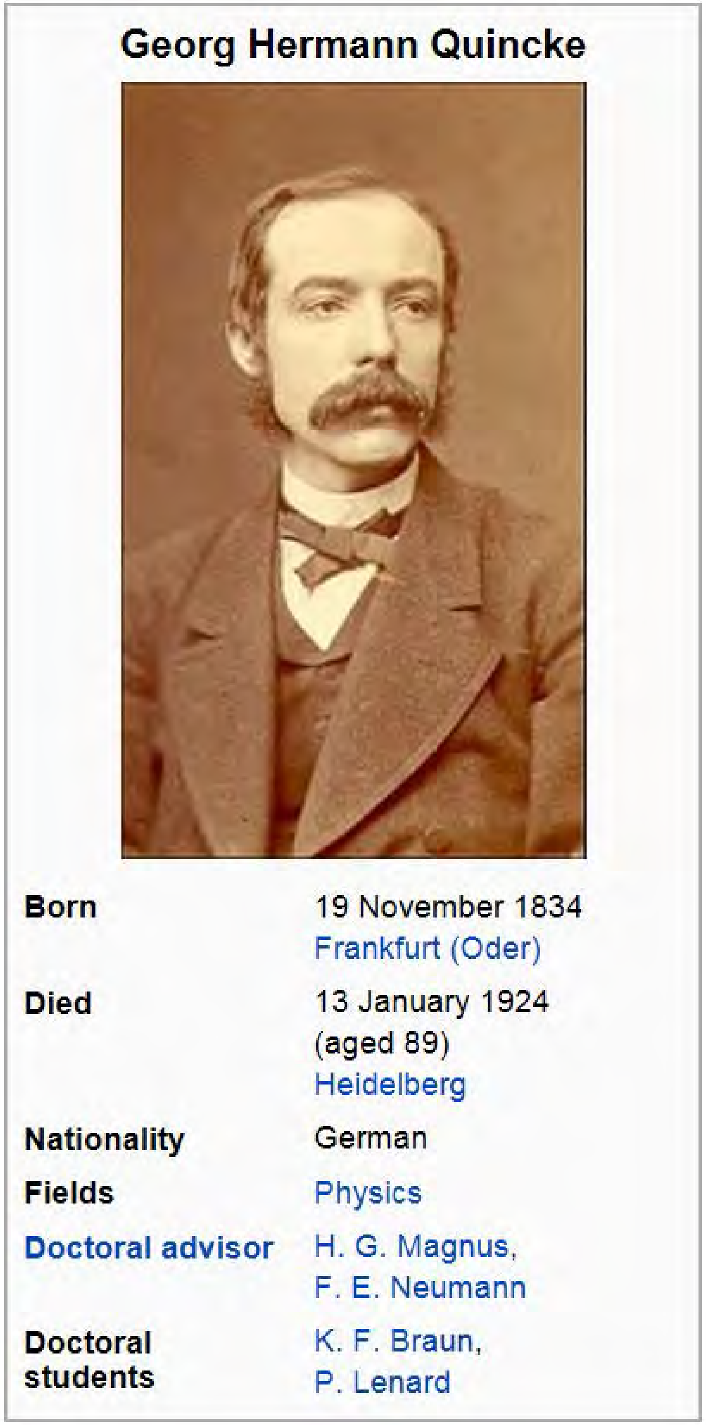
der

PHYSIK UND CHEMIE.

NEUE FOLGE. BAND 59.

1. Ueber Rotationen im constanten electrischen Felde; von G. Quincke.¹)

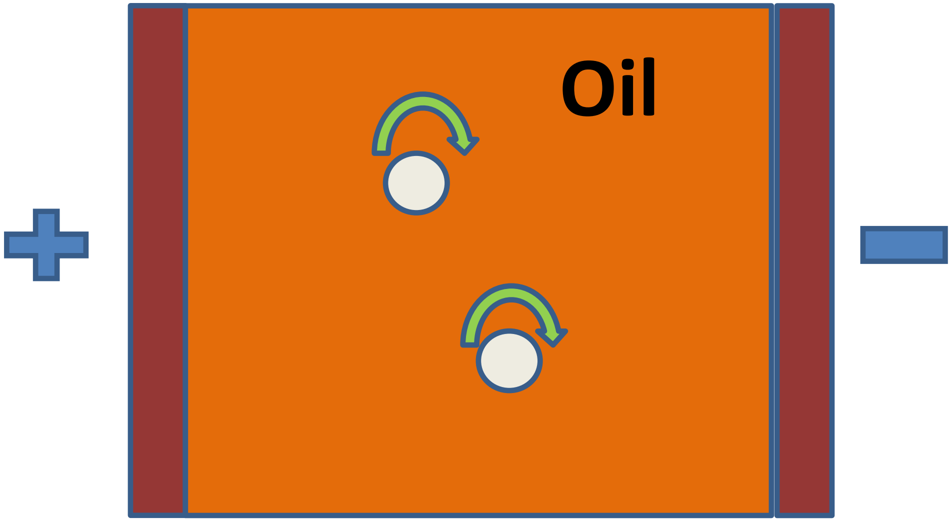
(Hierzu Taf. [illegible] Fig. 1—26.)



Georg Hermann Quincke

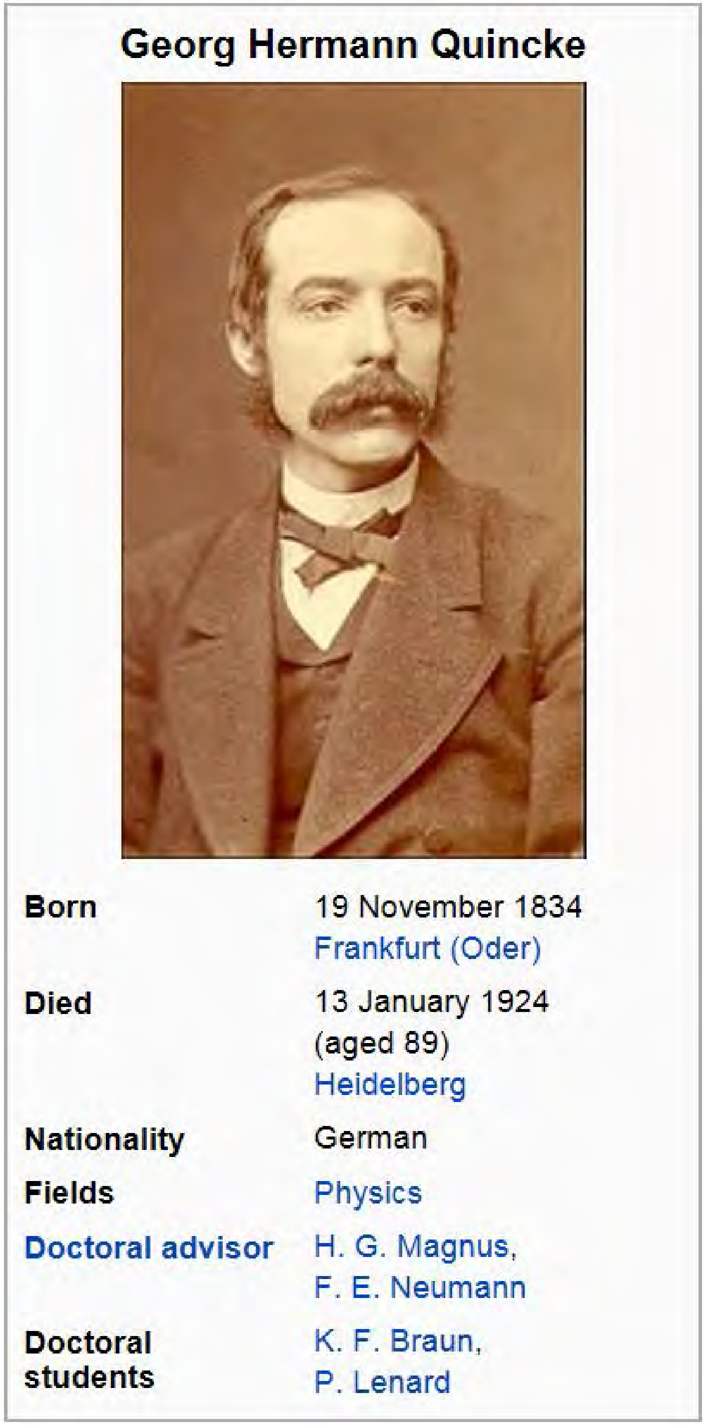
Born	19 November 1834 Frankfurt (Oder)
Died	13 January 1924 (aged 89) Heidelberg
Nationality	German
Fields	Physics
Doctoral advisor	H. G. Magnus, F. E. Neumann
Doctoral students	K. F. Braun, P. Lenard

Quincke rotation



Small glass beads rotate spontaneously when immersed in liquids and subject to an electrostatic field

1. Threshold electric field
2. Rotation axis normal to the applied E-field



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1896. ANNALEN №11.

DER

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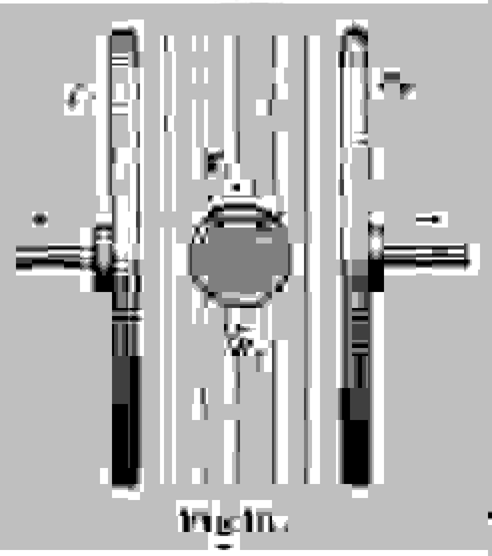
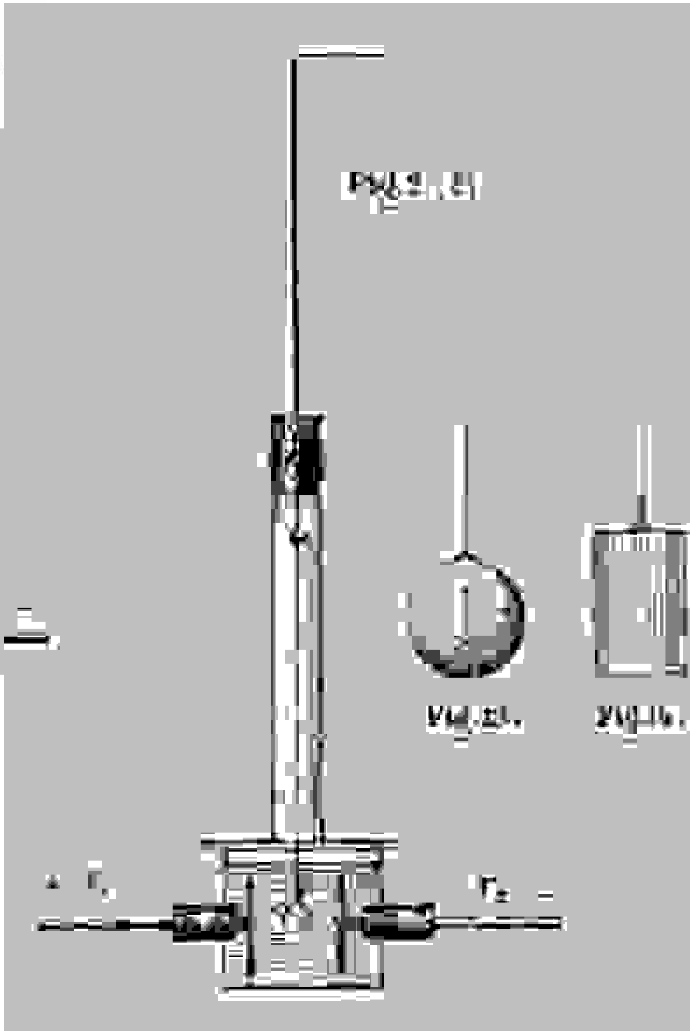
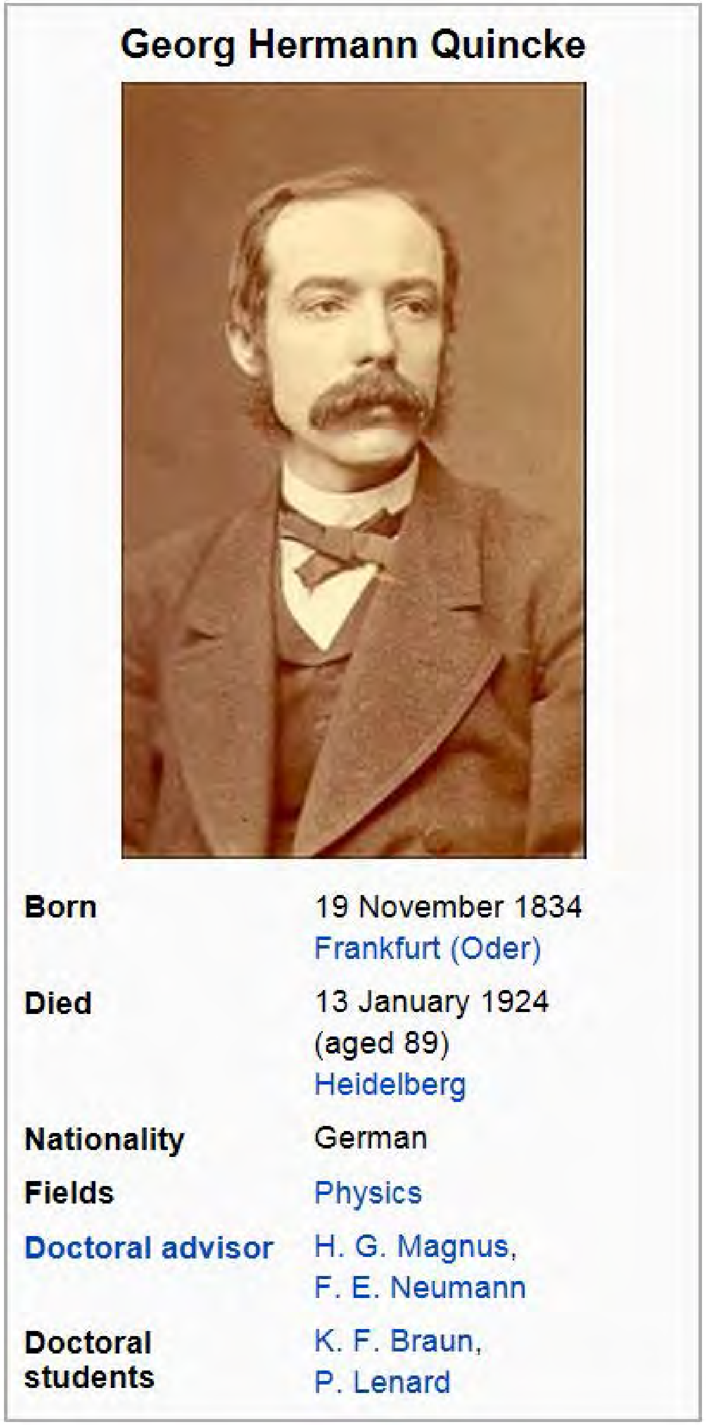
1. *Ueber Rotationen im constanten electrischen Felde; von G. Quincke.*[1])

(Hierzu Taf. V u. VI Fig. 1—38.)







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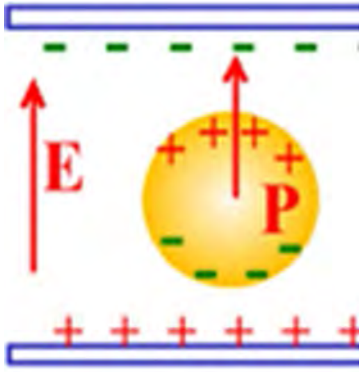
Quincke rotation

Quincke Rotation: Dynamic dipole instability

$$\tau_{fluid} = \frac{\varepsilon_{fluid}}{\sigma_{fluid}}$$

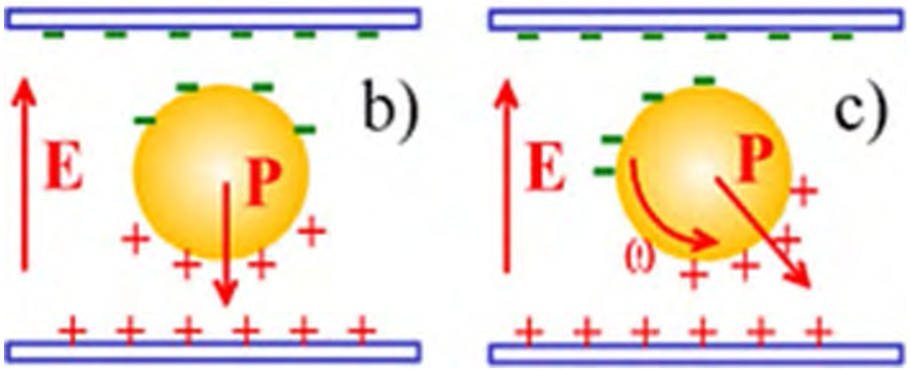
$$\tau_{particle} = \frac{\varepsilon_{particle}}{\sigma_{particle}}$$

$\tau_{fluid} > \tau_{particle}$



Polarization is parallell with the applied field

$\tau_{fluid} < \tau_{particle}$



Polarization is anti-parallell with the applied field, Unstable dipole.

T.B. Jones, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. IA-20, NO. 4, 1984

PHYSICAL REVIEW E **87**, 043014 (2013)

Electrohydrodynamic interaction of spherical particles under Quincke rotation

Debasish Das and David Saintillan*
Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

(Received 3 March 2013; published 29 April 2013)

$$\Omega = \pm \frac{1}{\tau_{\mathrm{MW}}}\sqrt{\left(\frac{E_e}{E_c}\right)^2 - 1}, \quad \text{with}$$

$$E_c = \sqrt{\frac{2\eta}{\varepsilon_1 \tau_{\mathrm{MW}}(\varepsilon_{21} - \sigma_{21})}}.$$

No radius dependence !

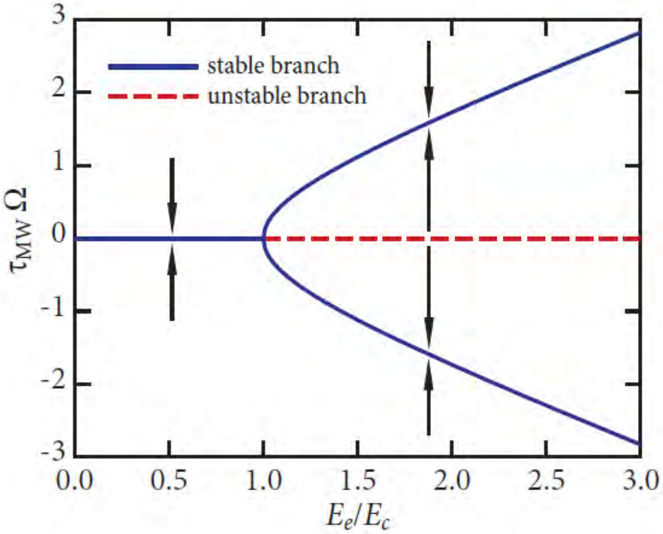
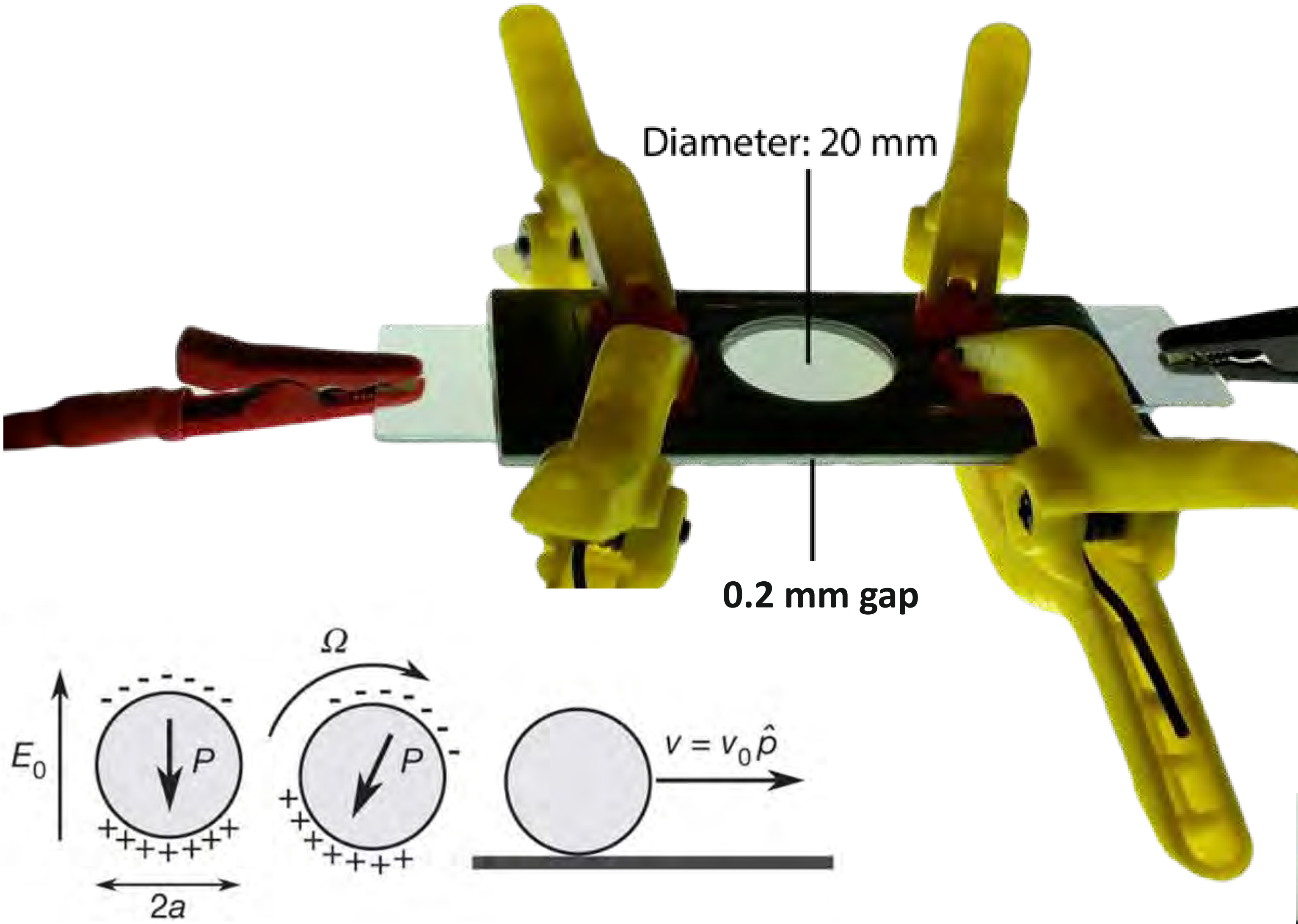


FIG. 3. (Color online) Stability diagram for the angular velocity magnitude of a single sphere. A supercritical pitchfork bifurcation occurs at $E_e = E_c$; above this value, the solution $\Omega = 0$ becomes unstable and spontaneous rotation occurs with an angular velocity given by Eq. (33).

Hele-Shaw cell with ITO glass covers: suspension containg 30micron PS beads



Experiments at NTNU Trondheim: Tommy Kristiansen

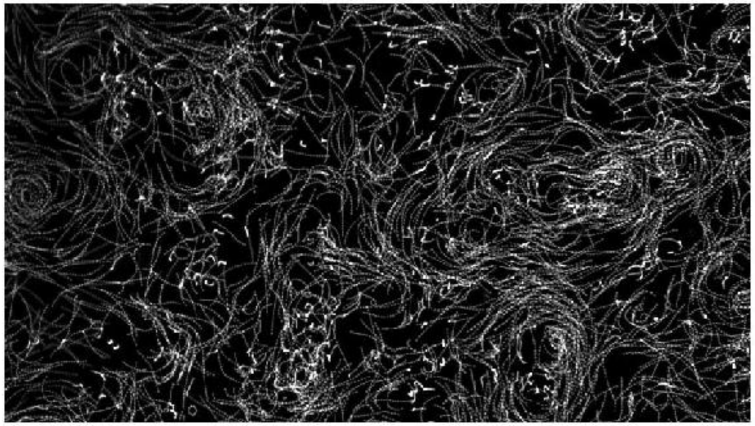
40µm 2250V/mm

Fast moving quincke rollers

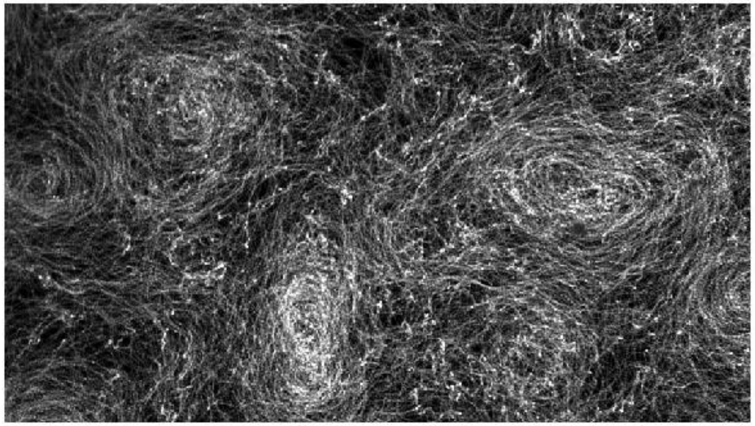
Experiments at NTNU Trondheim: Tommy Kristiansen

Streak photography night sky

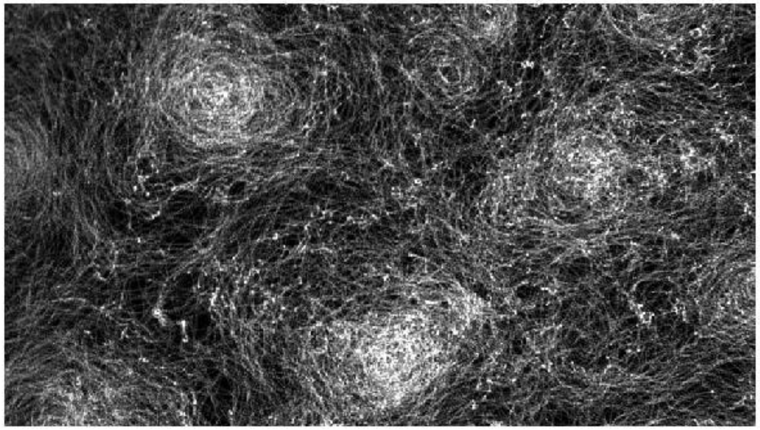
Streak photos of fast moving Quincke rollers: «Vortices»



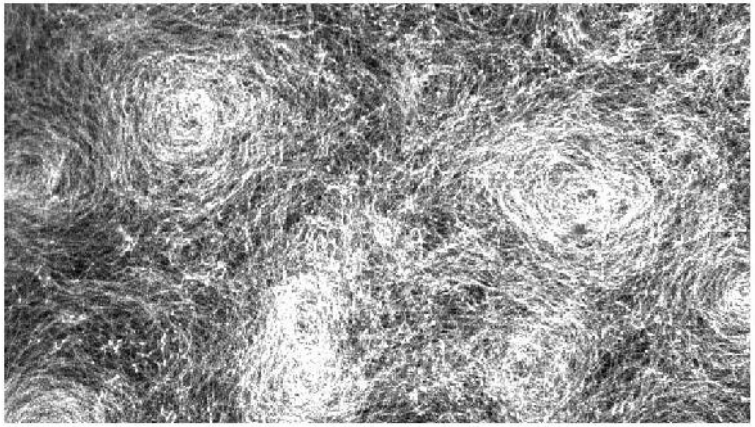
15 frames after 0 secs



100 frames after 3 secs



100 frames after 6 secs



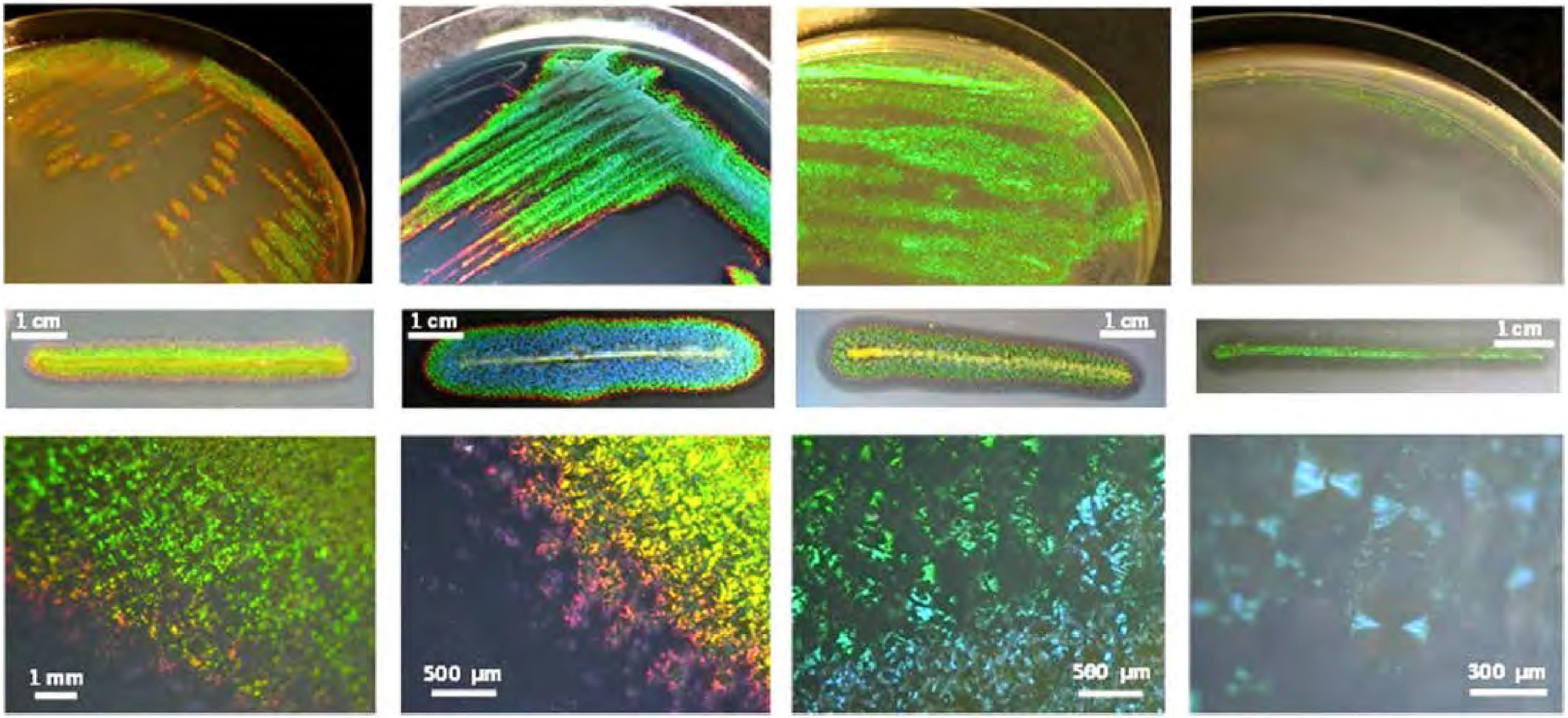
100 frames after 9 secs

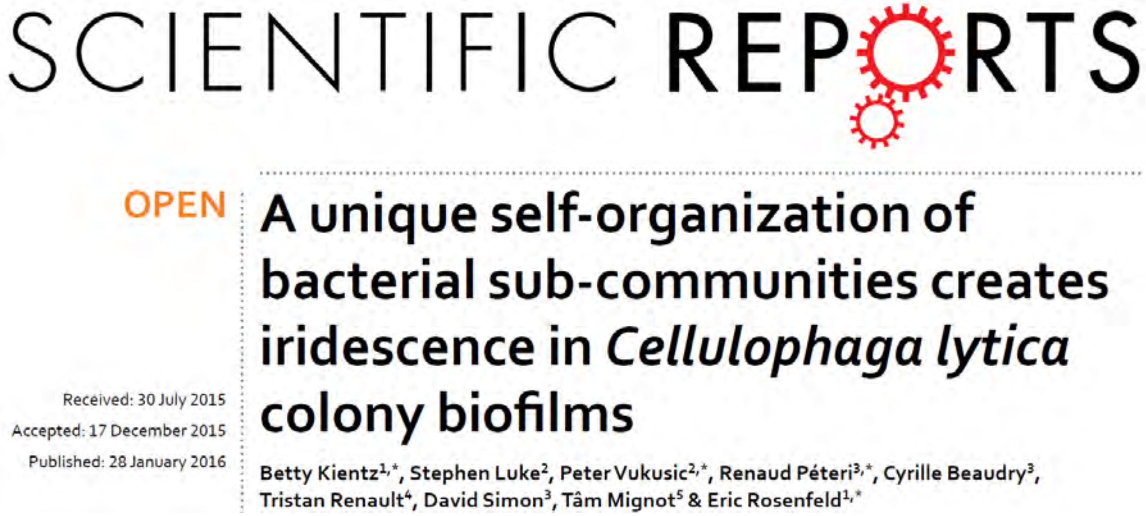
Experiments at NTNU Trondheim: Tommy Kristiansen

30µm   1375V/mm   60fps

«Living crystals «or active «entangled matter»

Experiments at NTNU Trondheim: Tommy Kristiansen




SCIENTIFIC REPORTS

OPEN

A unique self-organization of bacterial sub-communities creates iridescence in *Cellulophaga lytica* colony biofilms

Received: 30 July 2015
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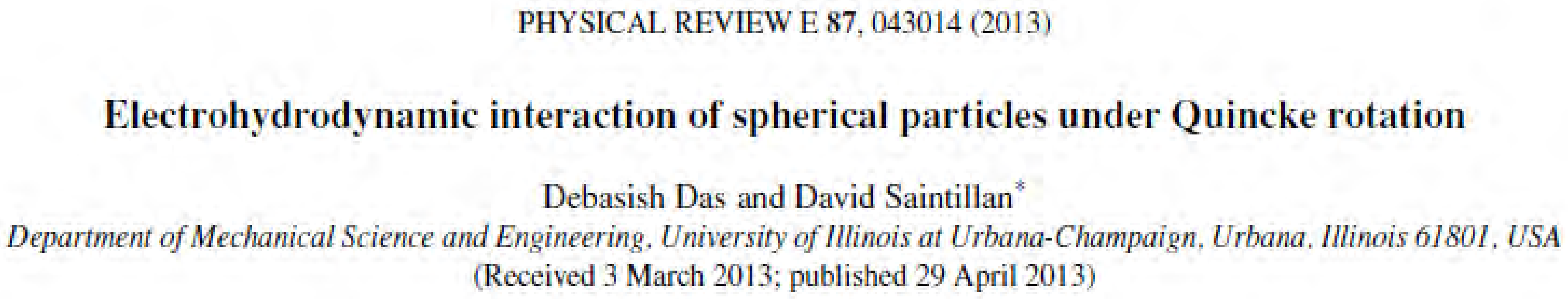
Betty Kientz[1,*], Stephen Luke[2], Peter Vukusic[2,*], Renaud Péteri[3,*], Cyrille Beaudry[3], Tristan Renault[4], David Simon[3], Tâm Mignot[5] & Eric Rosenfeld[1,*]



PHYSICAL REVIEW E 87, 043014 (2013)

Electrohydrodynamic interaction of spherical particles under Quincke rotation

Debasish Das and David Saintillan*

Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

(Received 3 March 2013; published 29 April 2013)

Interaction of Quincke rotating beads

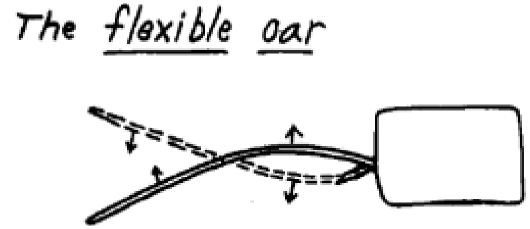
Life at low Reynolds number American Journal of Physics, Vol. 45, No. 1, January 1977

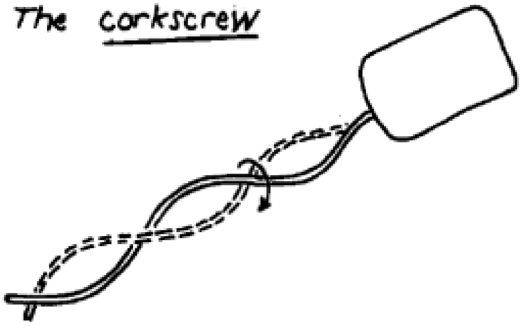
E. M. Purcell

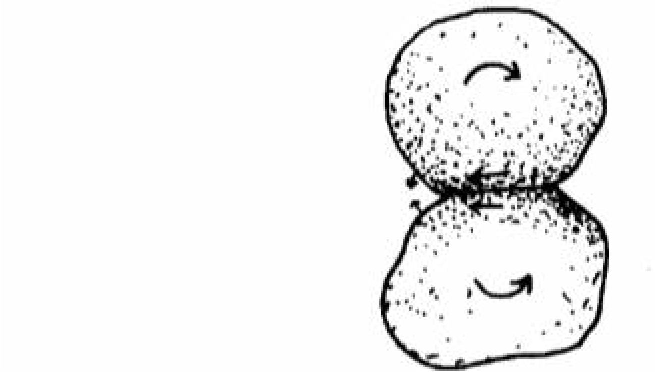
Lyman Laboratory, Harvard University, Cambridge, Massachusetts 02138

(Received 12 June 1976)

Another animal might consist of two cells which were stuck together and were able to roll on one another by having some kind of attraction here while releasing there. That thing will "roll" along.







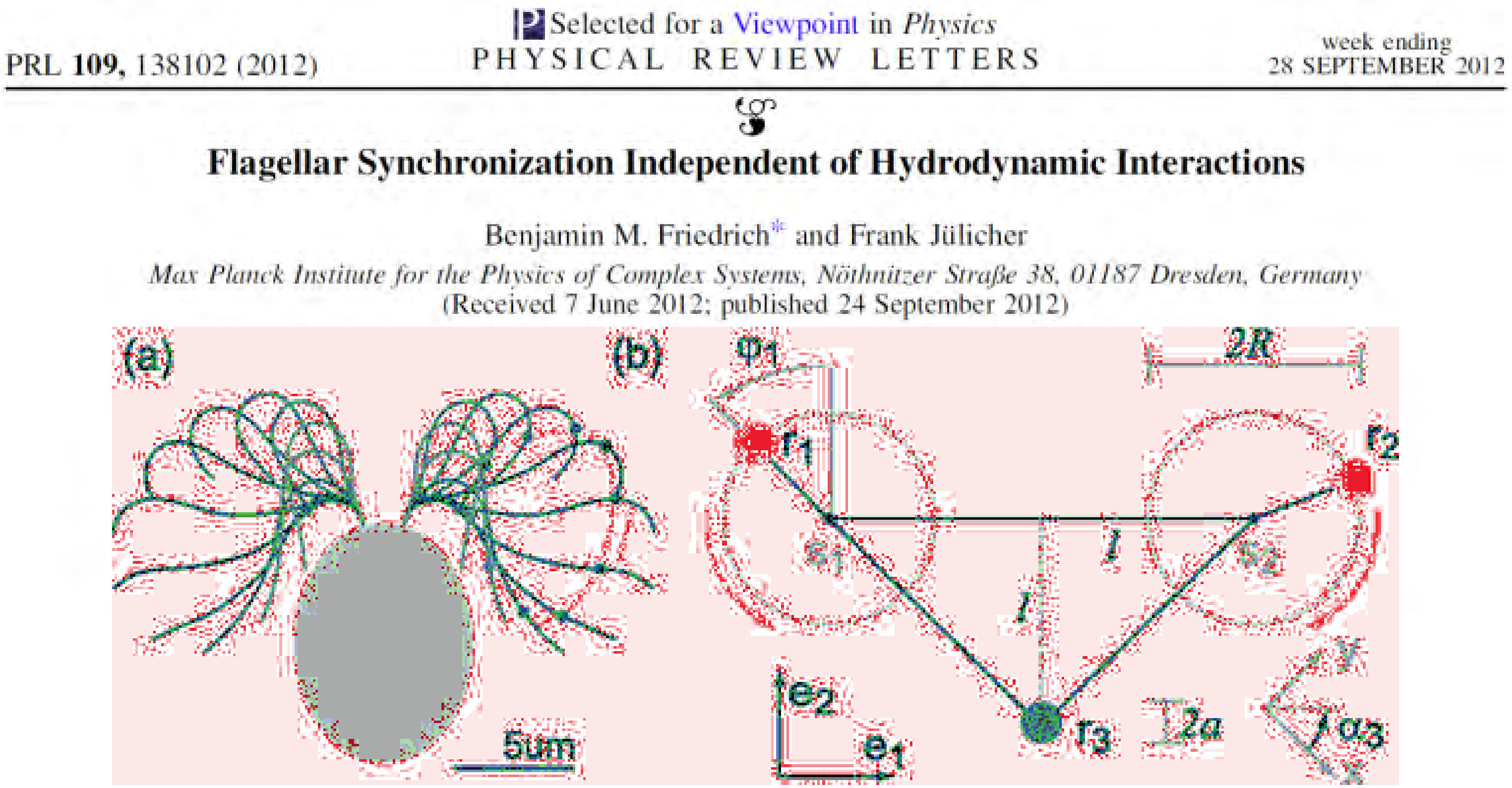
Counter-rotating rotors

Swimmers

Chlamydomonas is a single-cell green alga about 10 micrometres in diameter that swims with two flagella.

Two-rotor bifilament swimmer: Chlamydomonas

Two-rotor model of bifilament swimmer



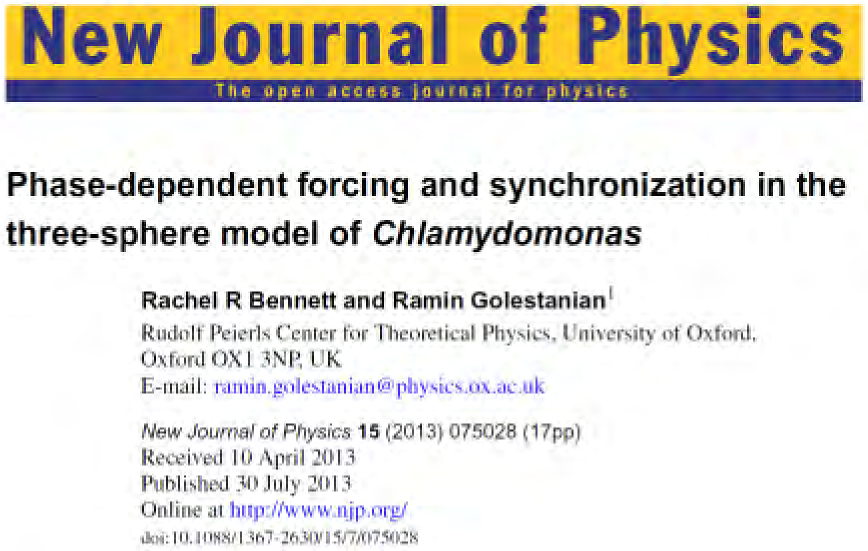
PRL **109,** 138102 (2012)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
28 SEPTEMBER 2012

Flagellar Synchronization Independent of Hydrodynamic Interactions

Benjamin M. Friedrich* and Frank Jülicher
Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Straße 38, 01187 Dresden, Germany
(Received 7 June 2012; published 24 September 2012)



New Journal of Physics
The open access journal for physics

Phase-dependent forcing and synchronization in the three-sphere model of *Chlamydomonas*

Rachel R Bennett and Ramin Golestanian[1]
Rudolf Peierls Center for Theoretical Physics, University of Oxford, Oxford OX1 3NP, UK
E-mail: ramin.golestanian@physics.ox.ac.uk

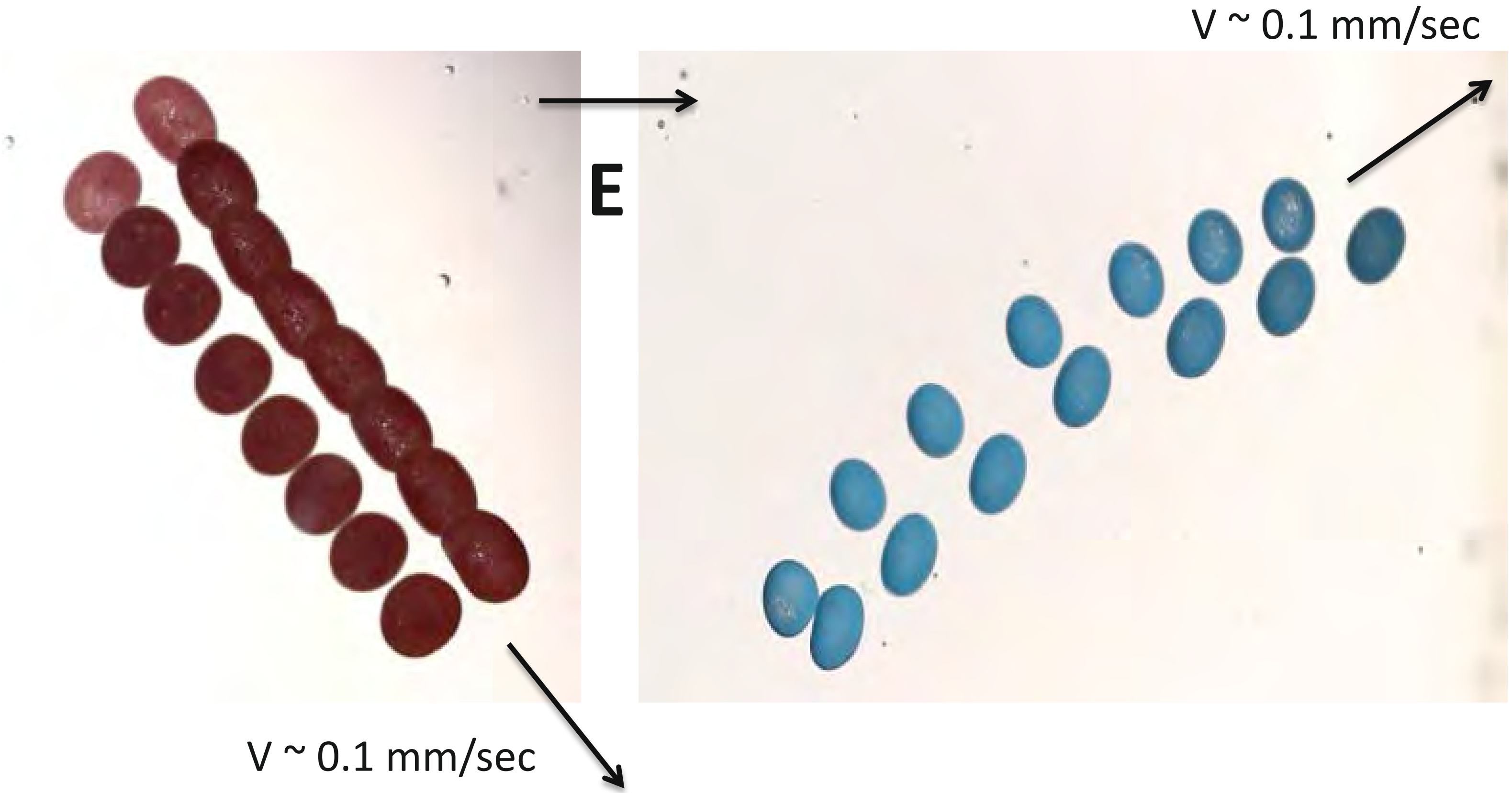
New Journal of Physics **15** (2013) 075028 (17pp)
Received 10 April 2013
Published 30 July 2013
Online at http://www.njp.org/
doi:10.1088/1367-2630/15/7/075028

Swimming upwards

- E

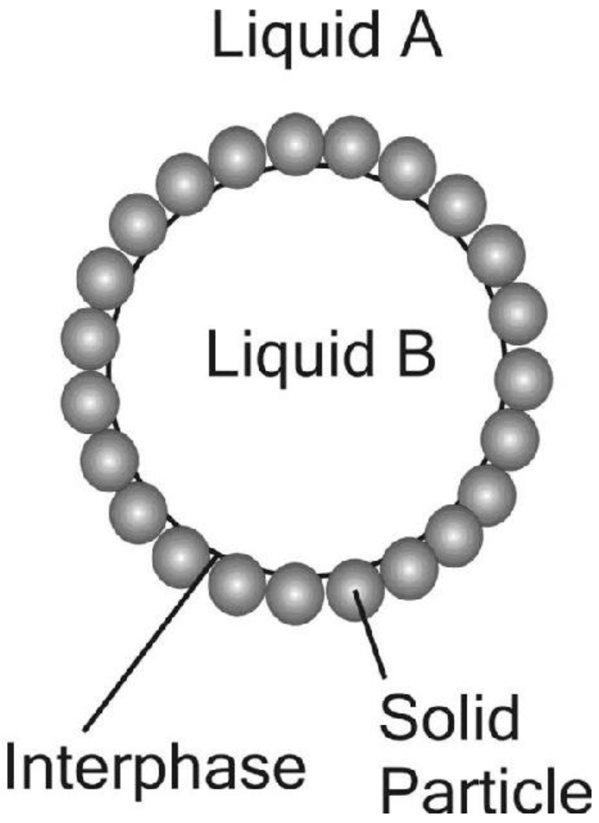
Experiments at NTNU Trondheim

Pair swimming of tank treading capsules



Experiments at NTNU Trondheim

Electro-hydrodynamic propulsion of counter-rotating Pickering drops P. Dommersnes, A. Mikkelsen & J. O. Fossum EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS 225, 699-705 (2016)



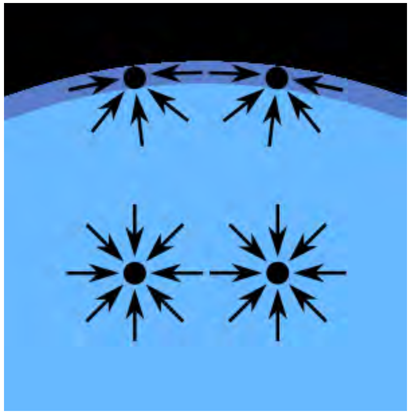
Surface Energy: $E = \gamma A$

A = Surface area $\gamma_{WA} = 0.0073\,\text{N/m}$

Capillary binding: A particle at the interface is trapped in a capillary barrier with a substantial energy cost of moving to either side of the liquid interface.

Origin of capillary binding:
Surface tension:

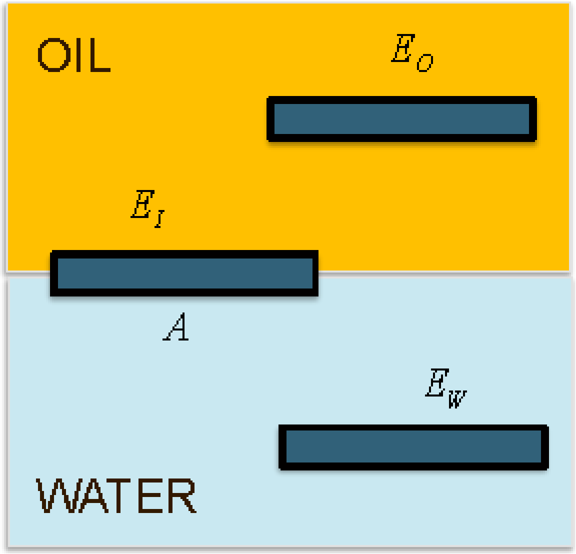
The forces on molecules of a liquid:



Surface tension preventing a paper clip from submerging

Capillary binding

Capillary binding of a flat solid particle at a liquid interface



Particle surface energy :

$$E_O = 2A\gamma_{SO}$$

$$E_W = 2A\gamma_{SW}$$

$$E_I = A\gamma_{SO} + A\gamma_{SW} - A\gamma_{OW}$$

Energy gain :

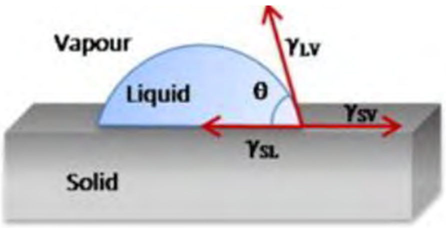
$$E_I - E_O = -A\gamma_{OW}(1+\cos\theta)$$

$$E_I - E_W = -A\gamma_{OW}(1-\cos\theta)$$

Wetting angle Young's relation:

$$\gamma_{SO} = \gamma_{SW} + \gamma_{OW}\cos\theta$$

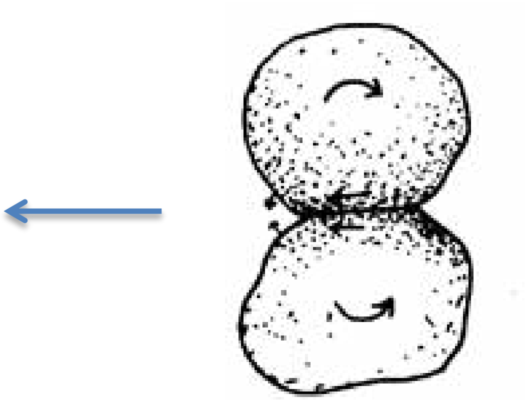
Energetically favorable to adsorb particles at the interface.



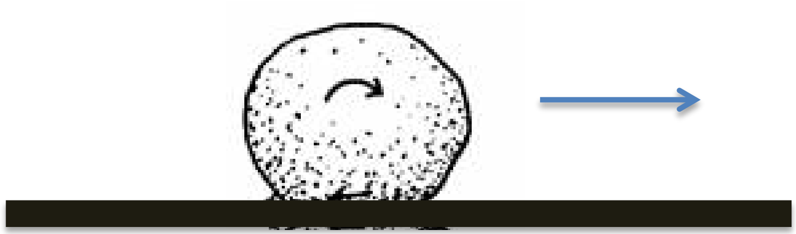
Typically:

$A_p\gamma_{OW}$ ~ 10000 kT for microparticles

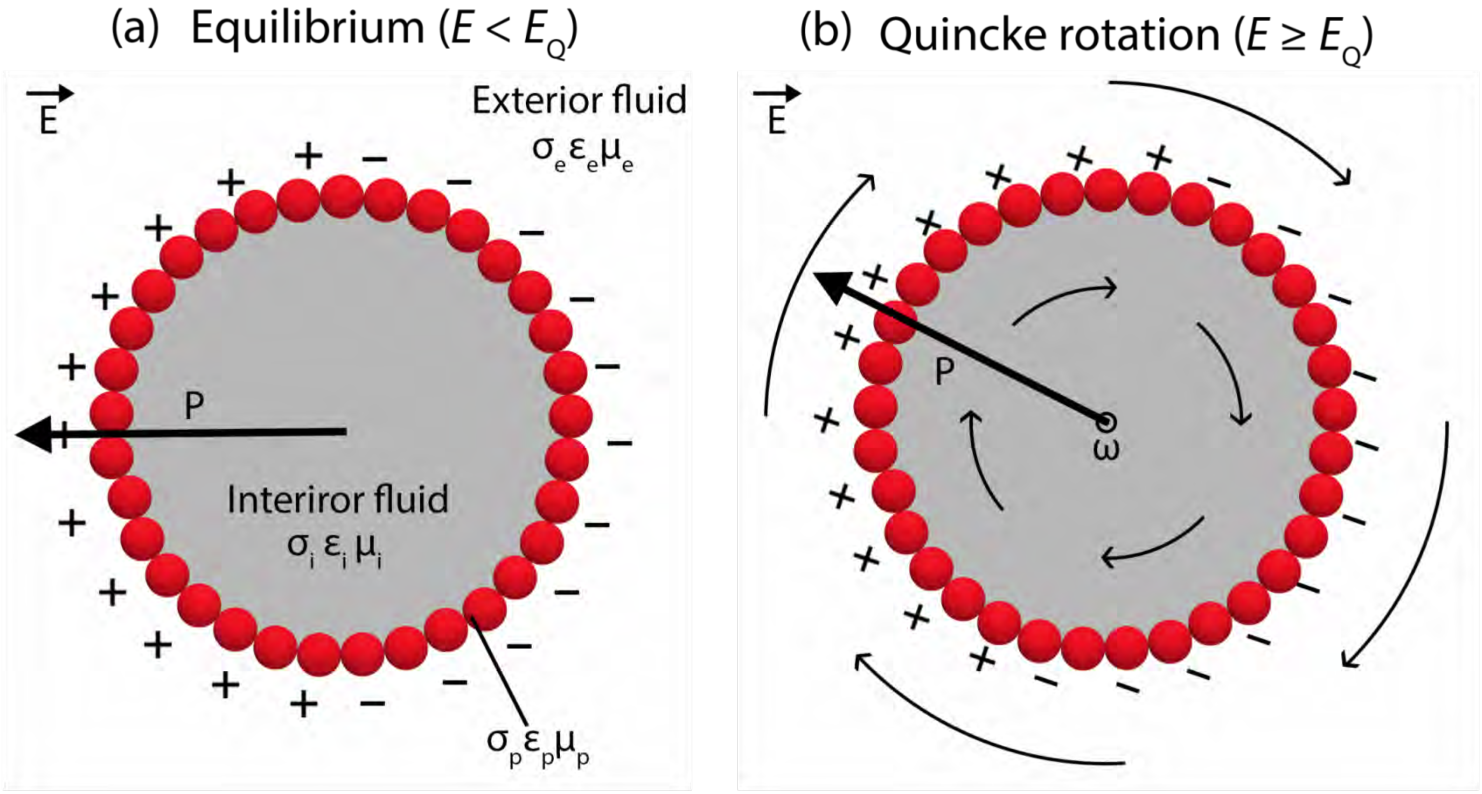
Pair rollers



Surface roller

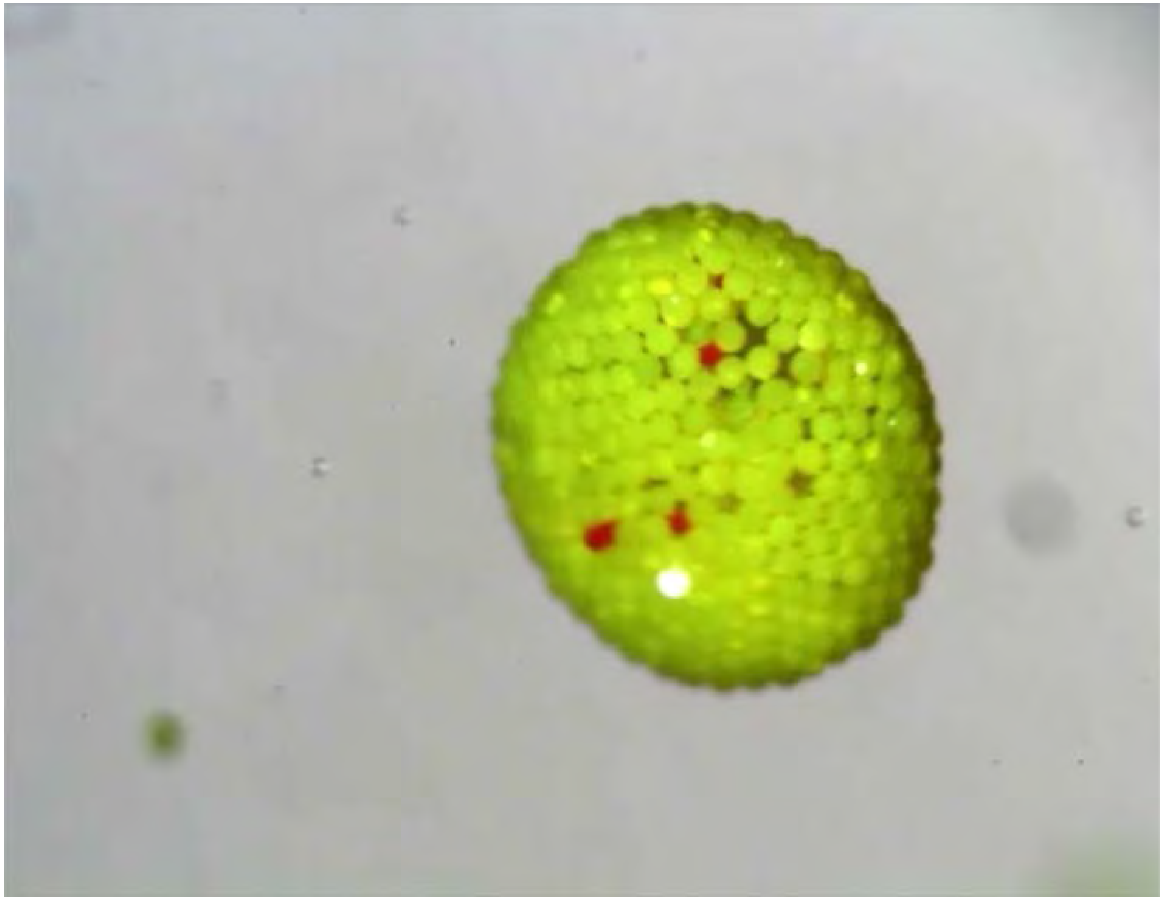


Kicking off one another, or rolling on a surface



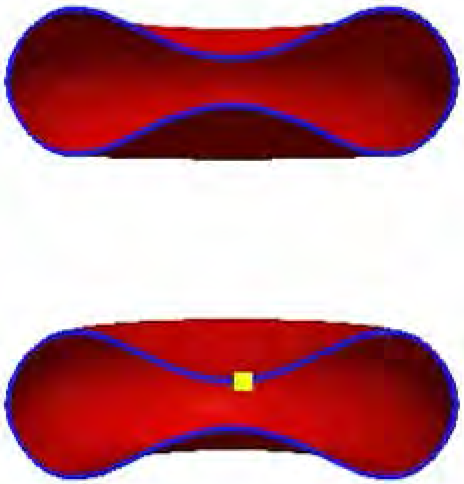
Quincke rotation of Pickering frops. Experiments at NTNU Trondheim

Movie of single Quincke rotating Pickering drop



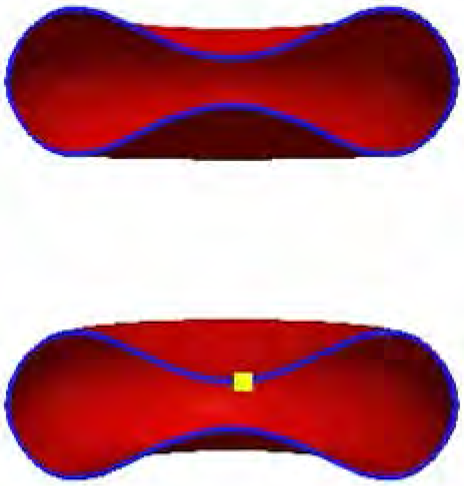
Quincke rotation of Pickering drops. Experiments at NTNU Trondheim

Tank treading and tumbling motion

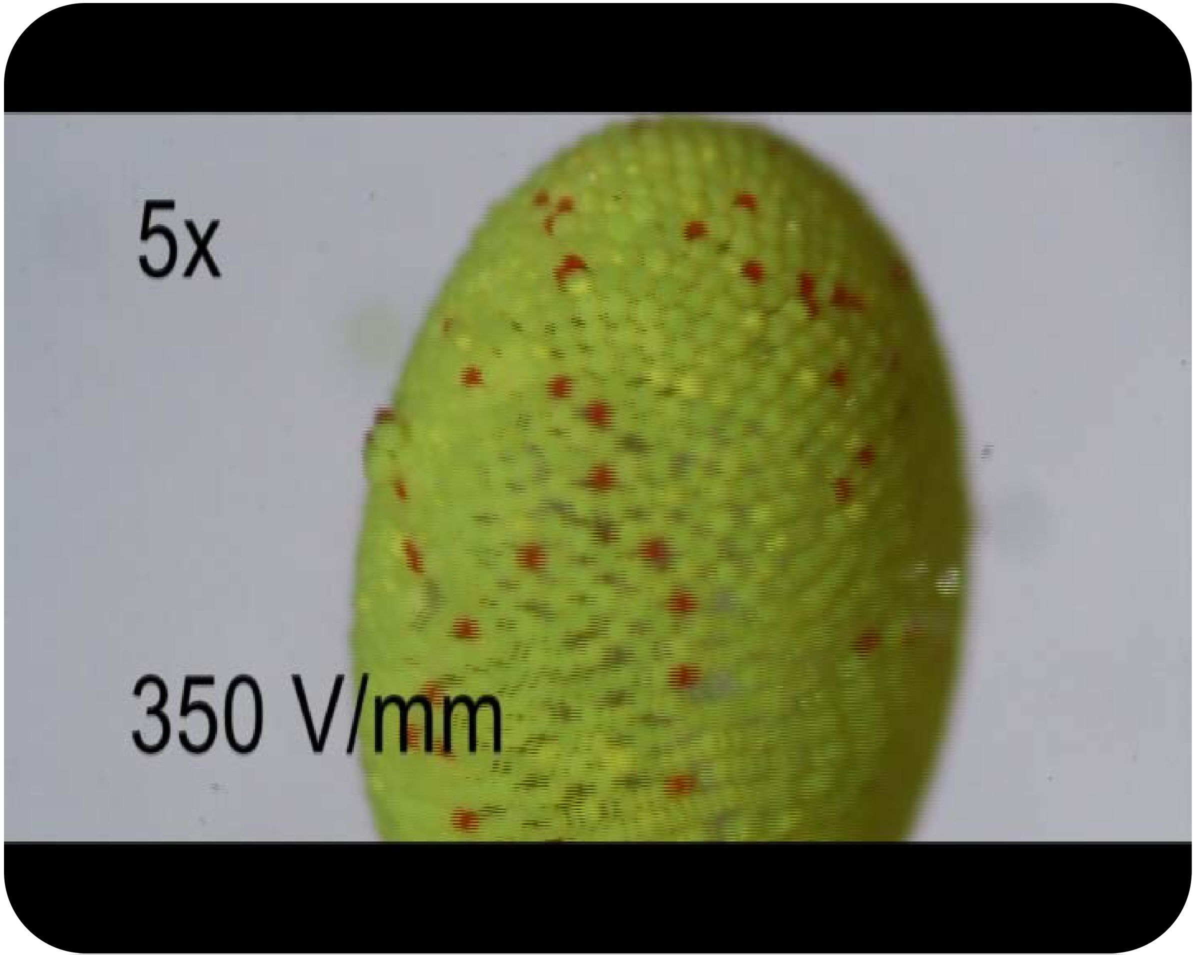


Video from: http://www.youtube.com/watch?v=mKLhfb5csr4

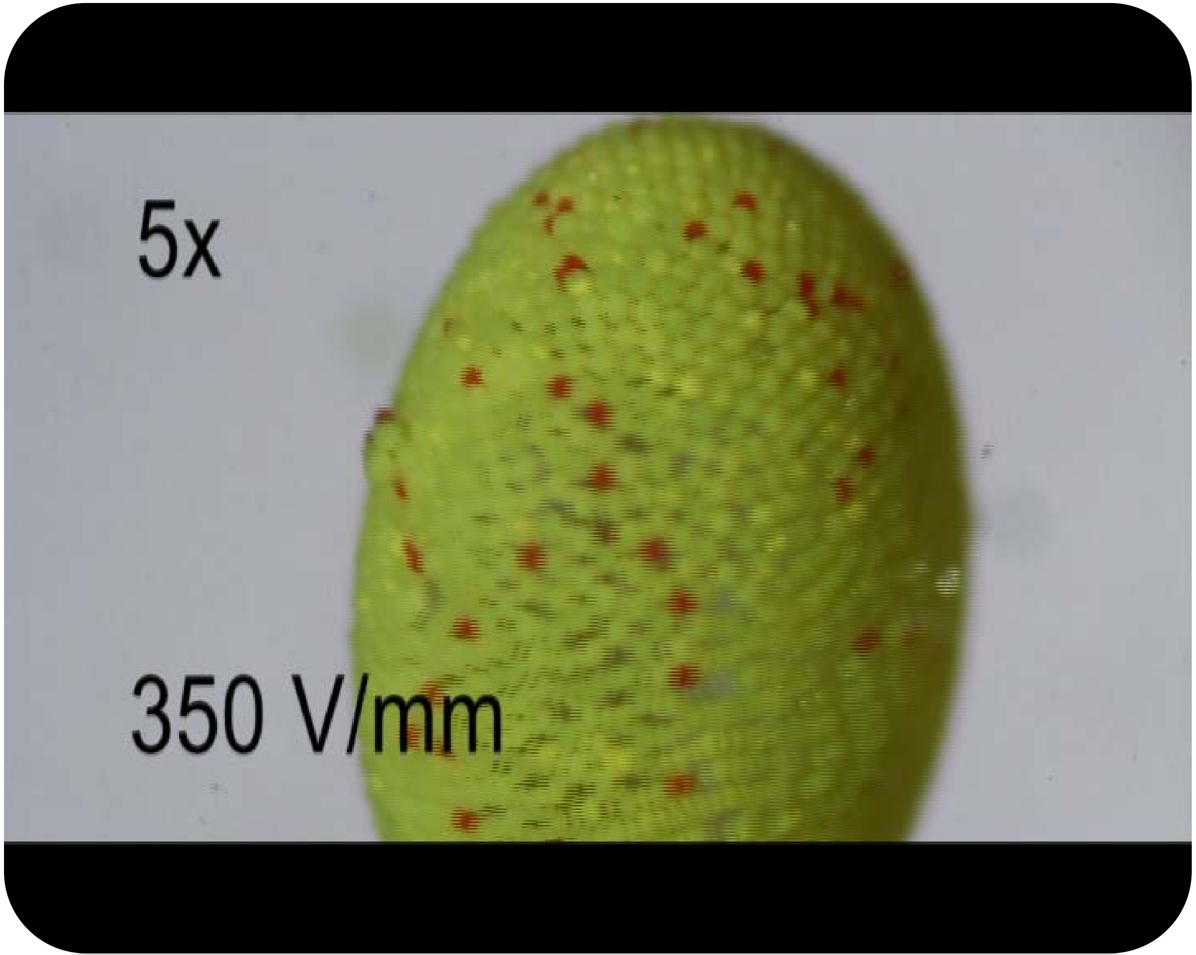
Tumbling and tank treading motion



Video from: http://www.youtube.com/watch?v=mKLhfb5csr4

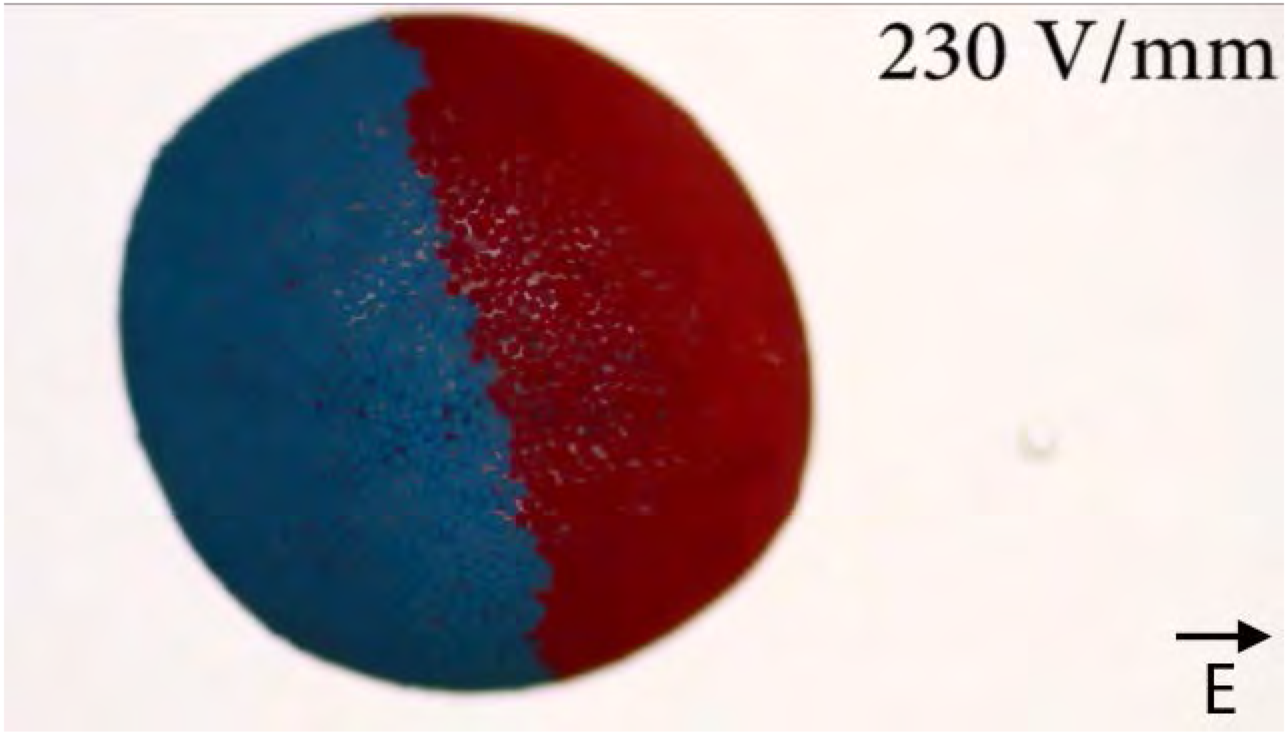


Transition from solid shell rotation to **tank treading:**
Experiments at NTNU Trondheim



Transition from solid shell rotation to **tank treading:**
Experiments at NTNU Trondheim

Solid to liquid transition of the particle layer occurs when we increase the E-field



MUD

is Soft Matter

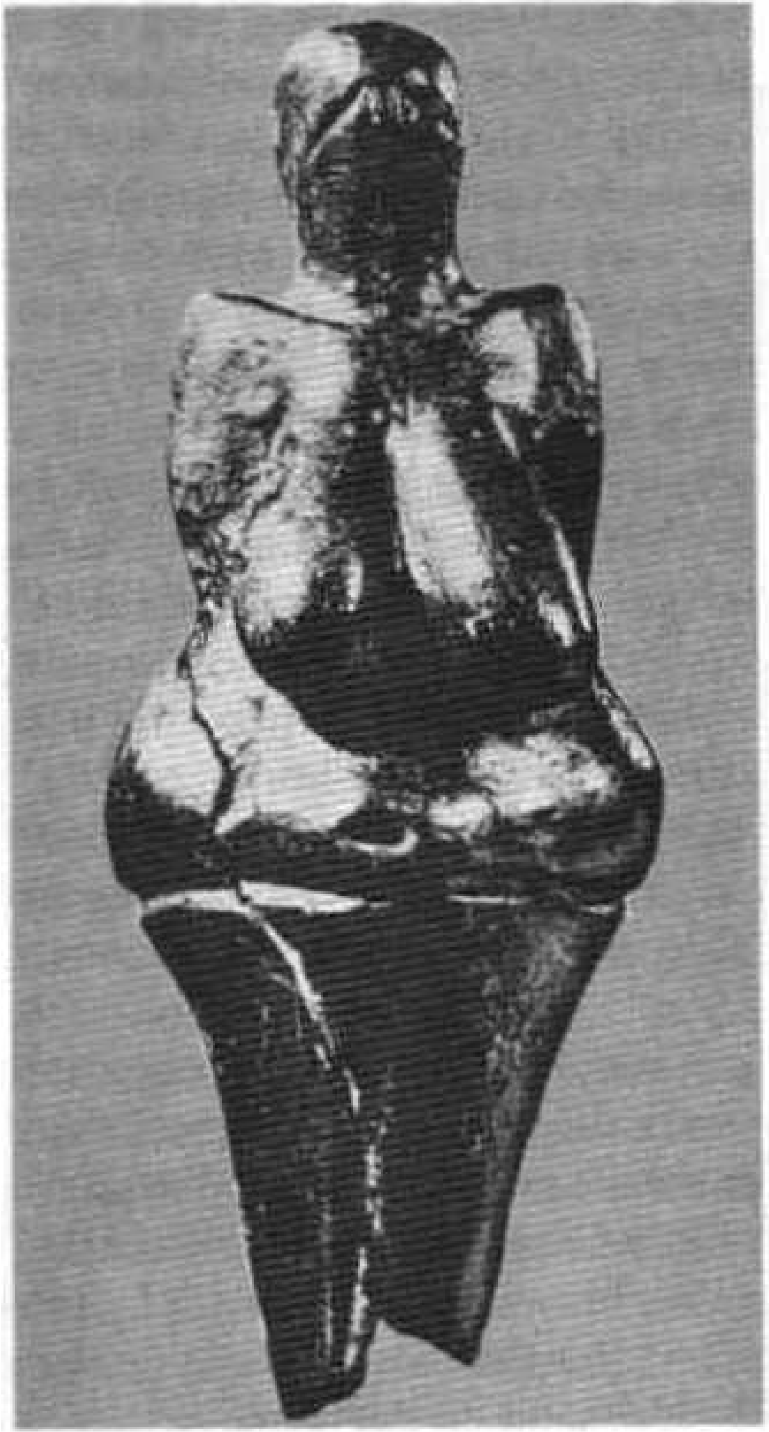
Soft (rheology),
sticky (adhesion),
slippery (friction)

Health and
well-being

Soft in processing,
can be hard in use

Soft matter =
Liquid + Solid

Complex materials
buildt from 2 or more
components



Clays in ART

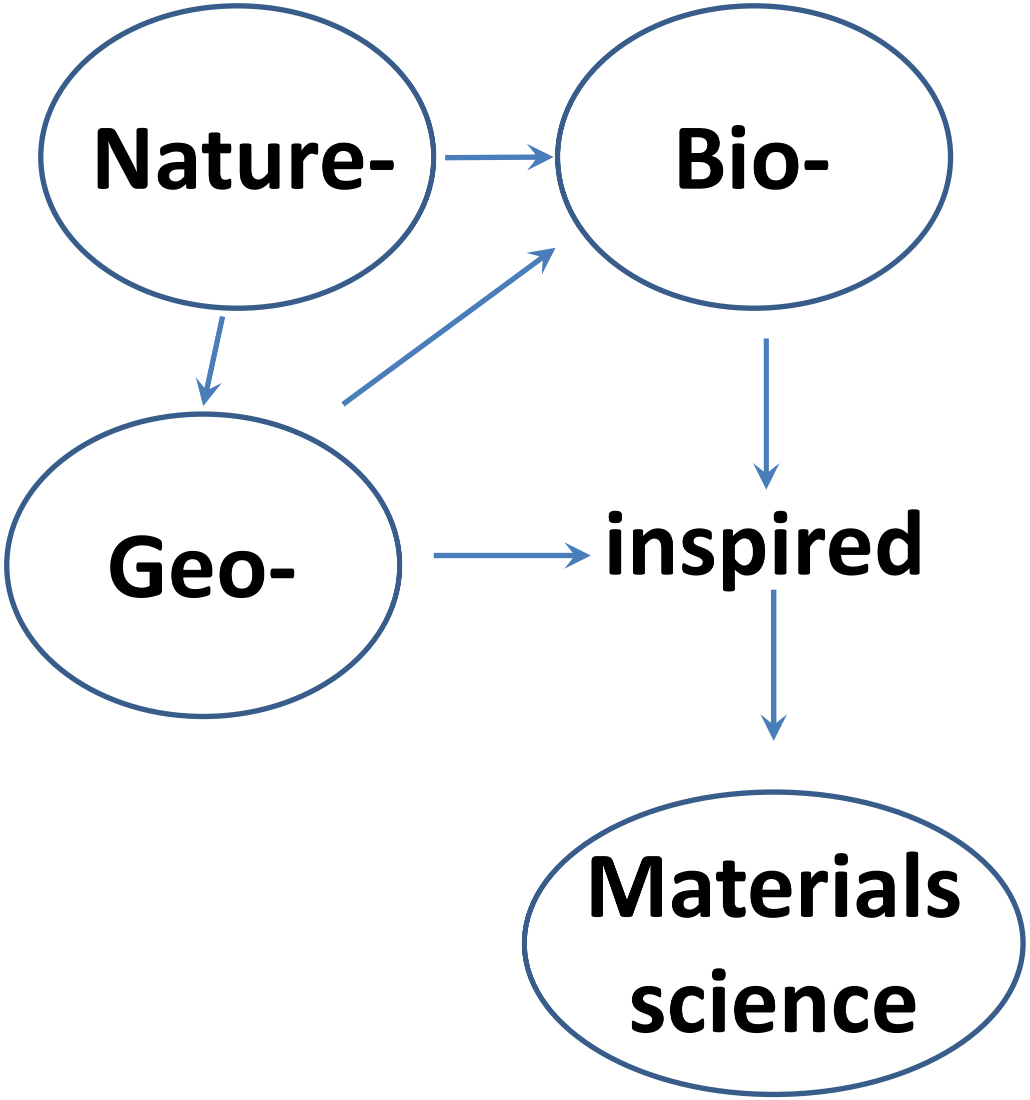
The oldest surviving piece of art:

The oldest sample known of baked clay:

Figurine: "Venus of Vestonice"

Found in 1920 in the Czech Republic.

Approximate age: 23000 B.C.
(Dated from mammoth bone ash in the clay)



Nature-

Bio-

Geo-

inspired

Materials science

2017 MRS® FALL MEETING & EXHIBIT

November 26–December 1, 2017 | Boston, Massachusetts

BM01—Multiscale Mechanobiology and Biomechanics—Theory, Experiments, Computations
BM02—Multiphase Fluids for Materials Science—Droplets, Bubbles and Emulsions
BM03—Biological and Bioinspired Materials for Photonics and Electronics—From Living Organisms to Devices
BM04—Biomaterials for Regenerative Engineering
BM05—Polymer Gels in Materials Science—3D/4D Printing, Fundamentals and Applications
BM06—2D Nanomaterials in Health Care
BM07—Emerging Materials and Devices for Engineering Biological Function and Dynamics
BM08—Materials Design for Neural Interfaces
BM09—Stretchable Bioelectronics—From Sensor Skins to Implants and Soft Robots
BM10—Bioinspired Interfacial Materials with Superwettability
BM11—Modeling, Characterization, Fabrication and Applications of Advanced Biopolymers—Where Form Meets Function
BM12—Biomolecular Self-Assembly for Materials Design

Our main motivation for studying clays is that clays may be viewed as good representative model systems for soft condensed matter and complex materials, with ”near” applications.

Question to ask:

How does nano-scale physics (fex. clay nanostructures) translate into macroscopic (fex. clay flow) behaviors?

http://www.folk.ntnu.no/fossumj
http://www.ntnu.edu/physics/complexmaterials/softcomplex

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Some of our interconnected clay activities:

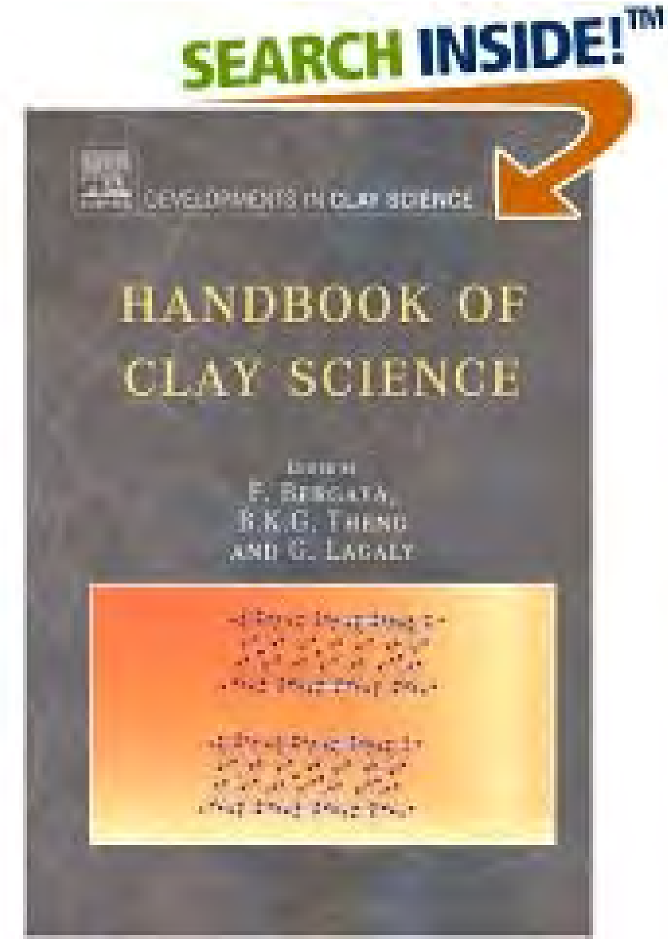
http://www.ntnu.edu/physics/complexmaterials/softcomplex

Macroscopic properties of (clay) gels: Elasticity, flow, fracture processes.

Molecular transport and capture in clays and related porous media: Capture /release of molecules. Diffusive processes.

Self-organization from nanoparticles: Spontaneous and guided self-organization. Smart materials. Composite materials.

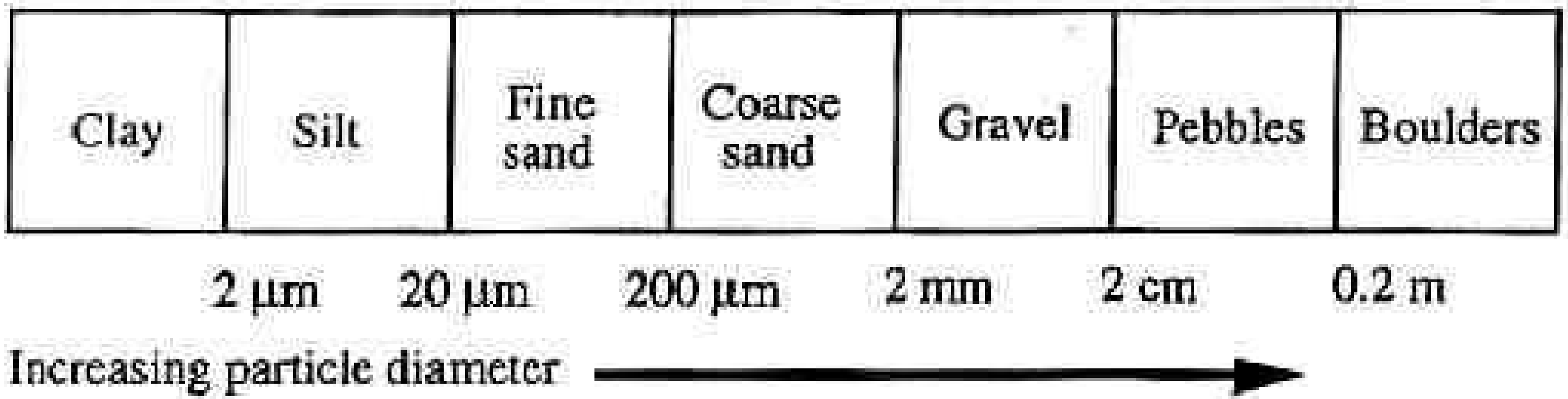
Clays have a remarkable multitude of practical uses and relevances:



F. Bergaya, B. K. G. Theng, and G. Lagaly, editors. Handbook of Clay Science. Elsevier, 2006

As clays and clay materials are abundant, inexpensive and environmentally friendly, they will most likely be known as the materials of the 21st century.

Clays are the smallest mineral particles around:



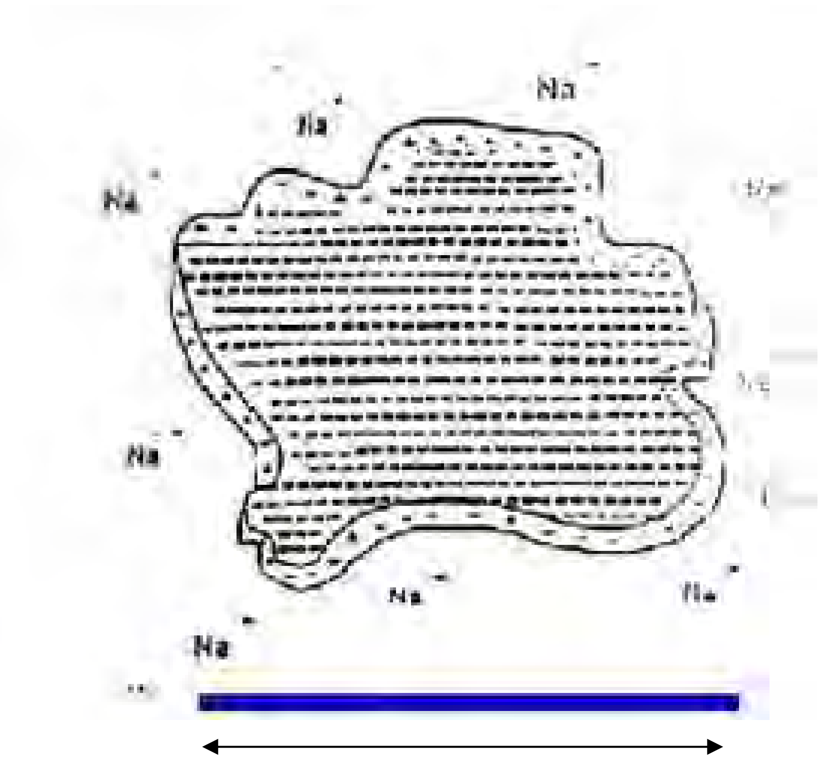
Grain size classification. [This system is the one used by the International Society of Soil Science.]

Figure 1 *The left panel above is from a natural clay deposit, and it illustrates on a macroscopic scale that clays are anisotropic materials. The right panel is an electron microscope image of vermiculite clay demonstrating its lamellar structure on the nano-scale, reminiscent of graphene, which is one of the main characteristics of clay minerals.*

Clays are nano-/micro-particles:

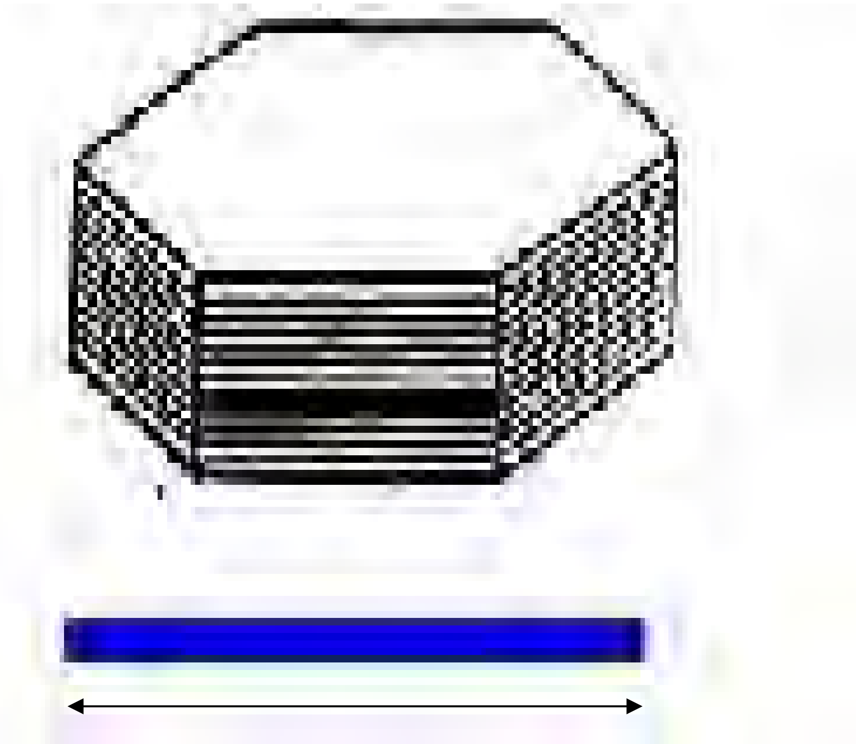
Two basic forms at nano-/micro-scale:

1 nm thick ”nanocards”



~ µm

100 nm thick nanolayered particles ”decks of nanocards”



~ µm

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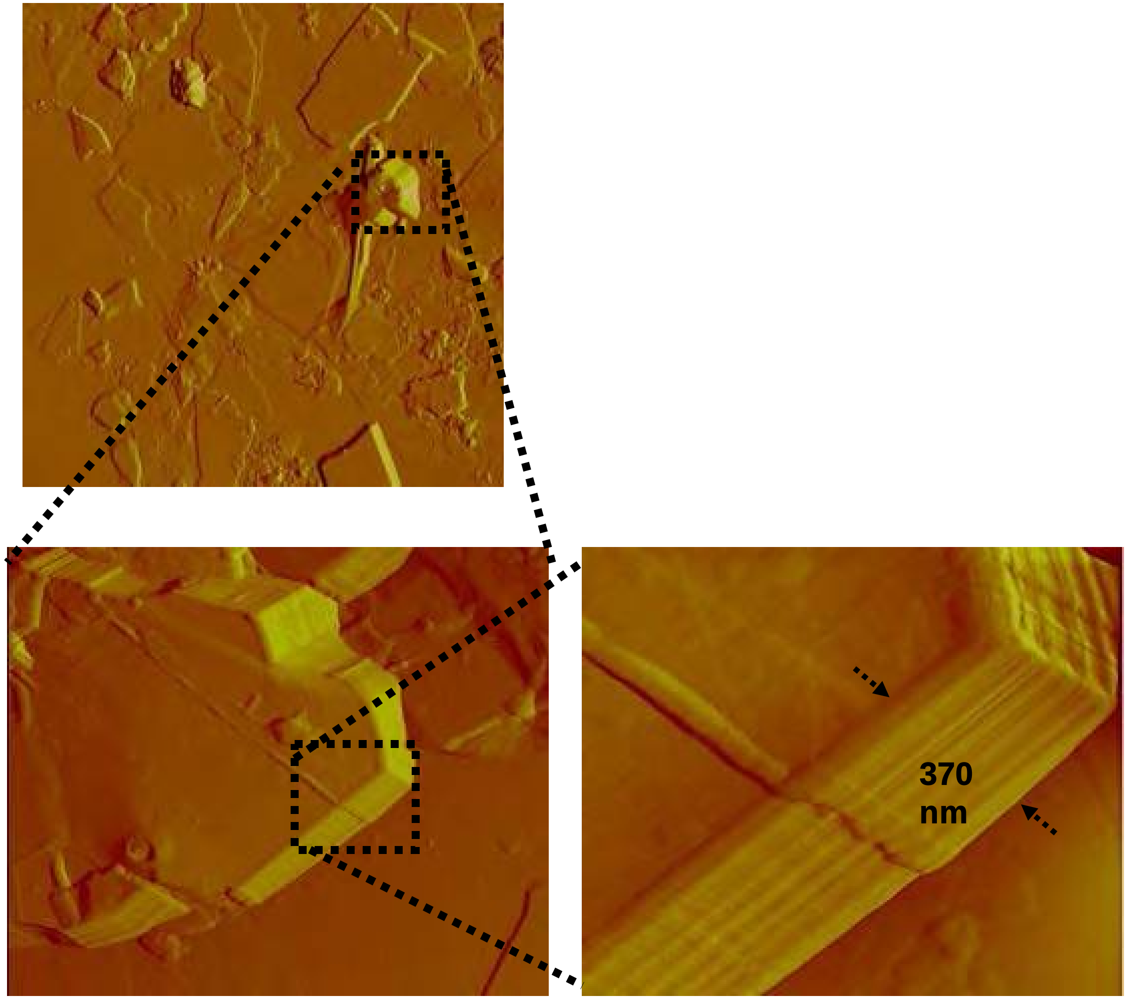
AFM images of clay stack:

Scan size
25µm x 25µm



5µm x 5µm

1.2µm x 1.2µm

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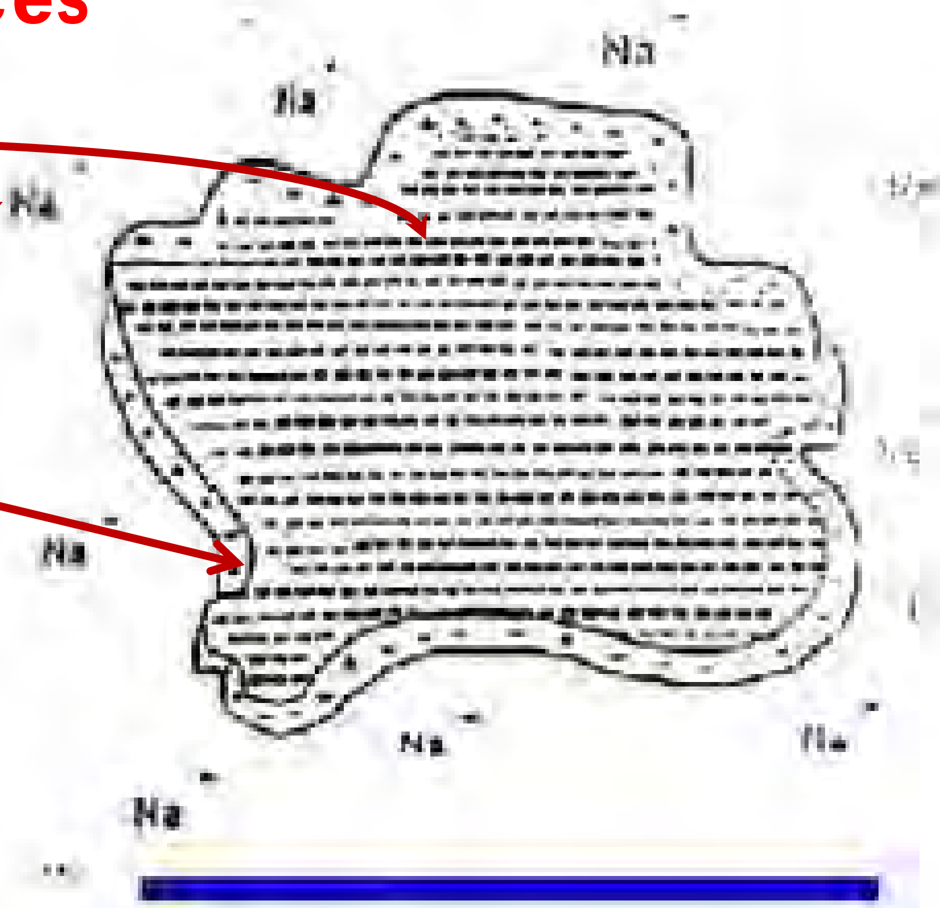
http://www.ntnu.edu/physics/complexmaterials/softcomplex

Important for structures and behaviors:

Clay particle platelet shape

Charged clay surfaces



Negative surface charge compensated by cations

Small positive edge charge

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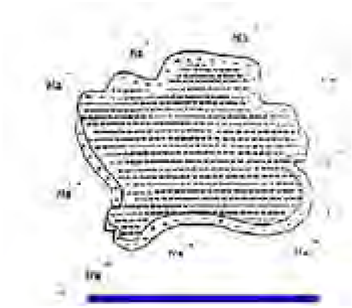
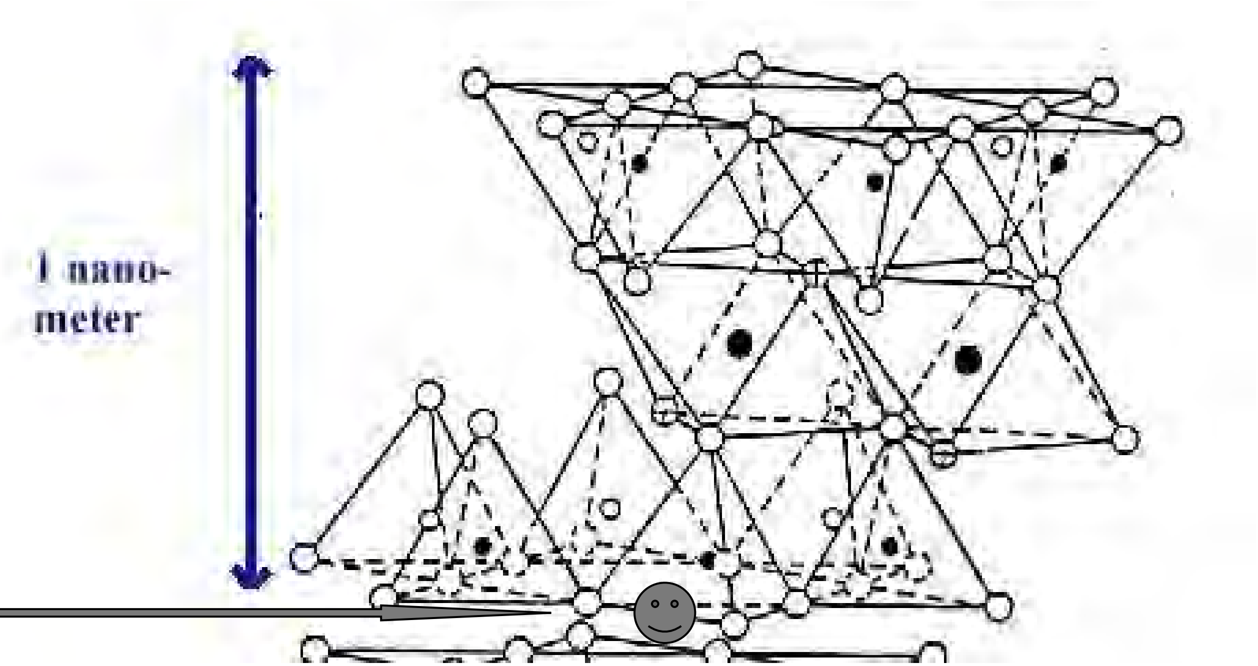
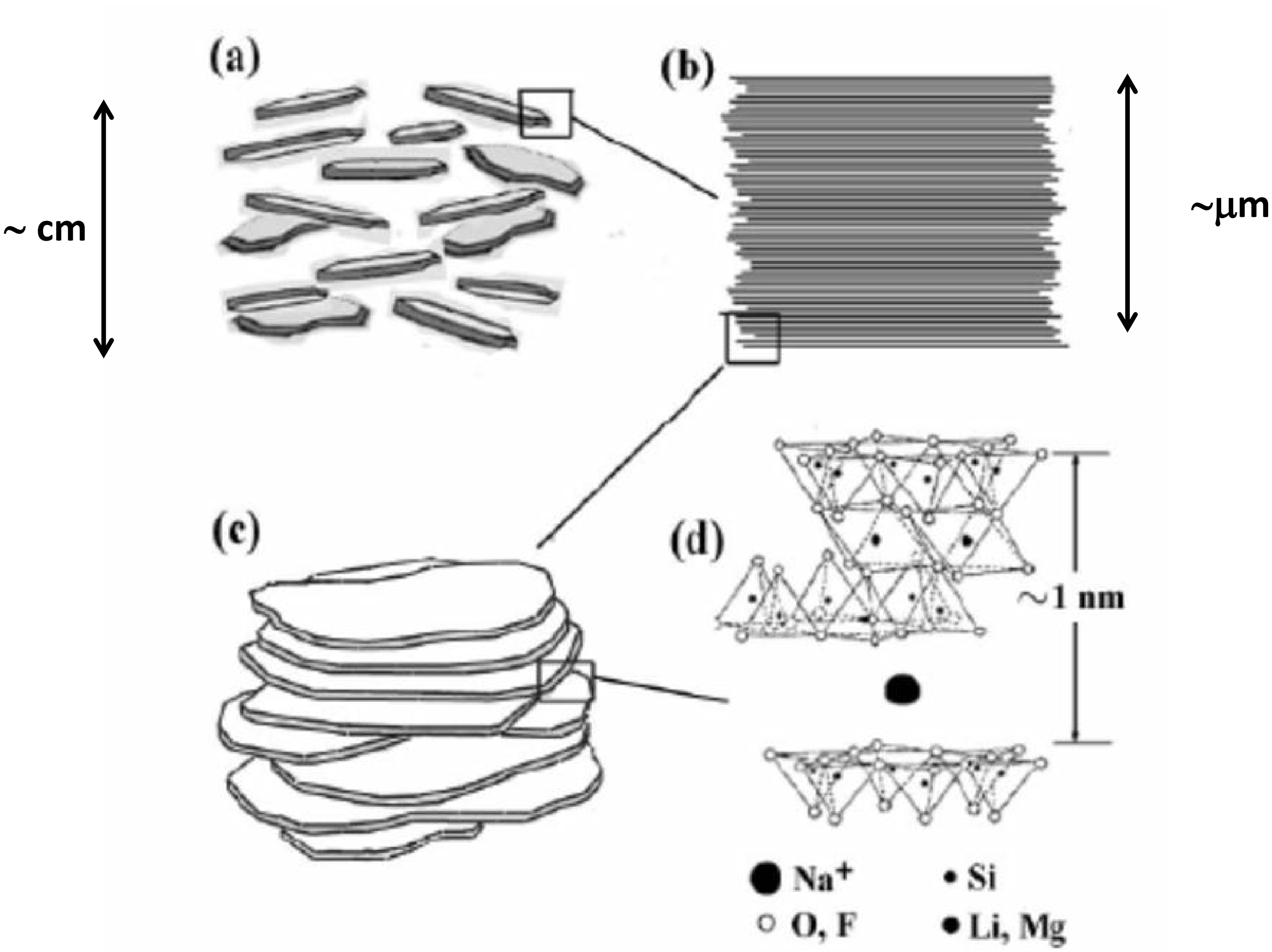


Each individual swelling (smectite) clay card is a mesoscopic single crystal with a well defined crystal structure, consisting of three atomic layers, two identical outer layers (Si + O), and a single middle layer (metals + OH), thus the name 2:1 clays:



Cation

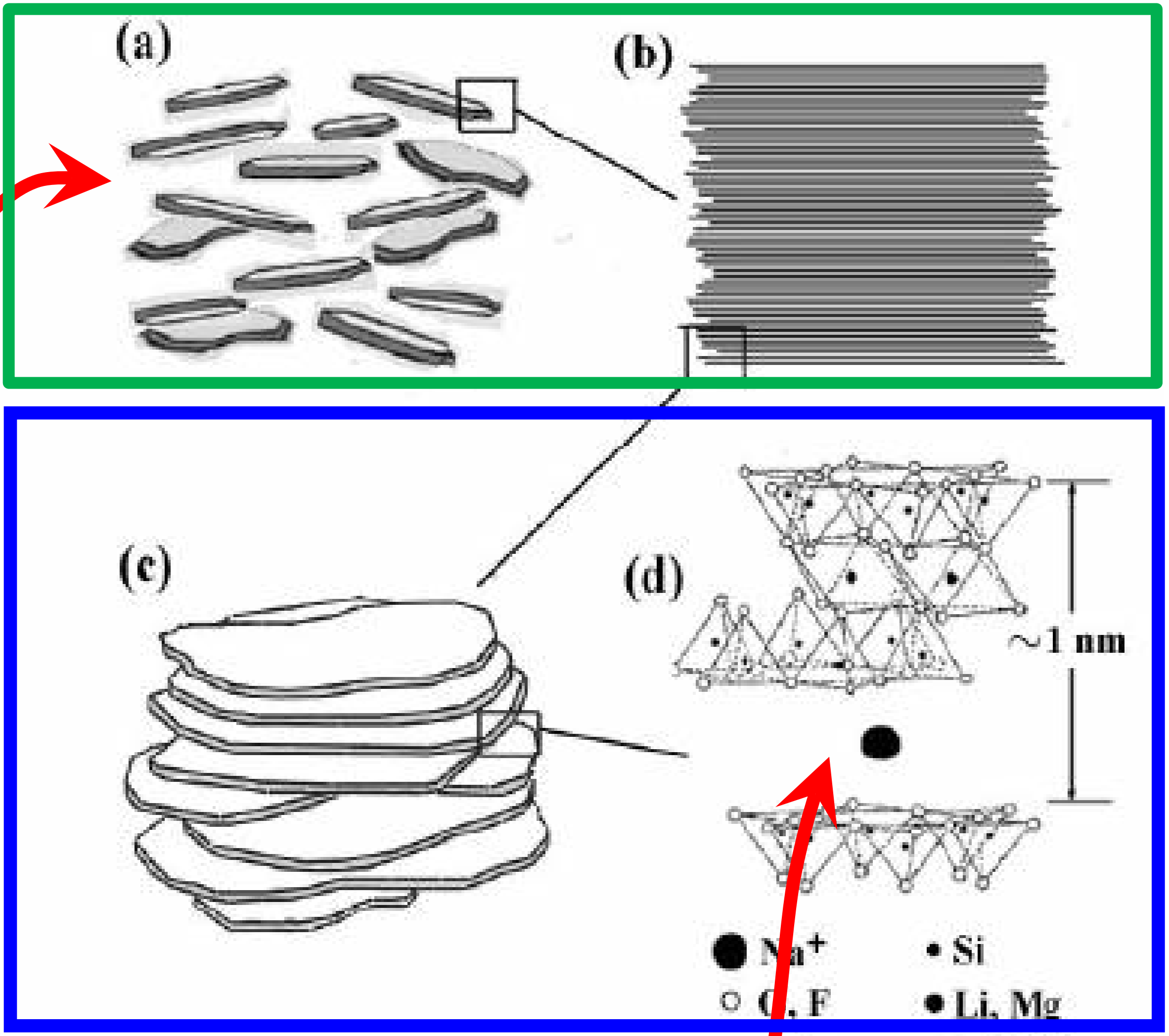
The nano-/meso- structures behind clayey behaviour



Levles of description:

Nanoparticle aggregates

Nanoparticles



Atoms or molecules

SELF-ORGANIZATION OF CLAY PARTICLES

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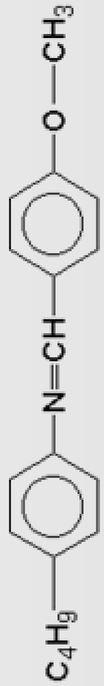
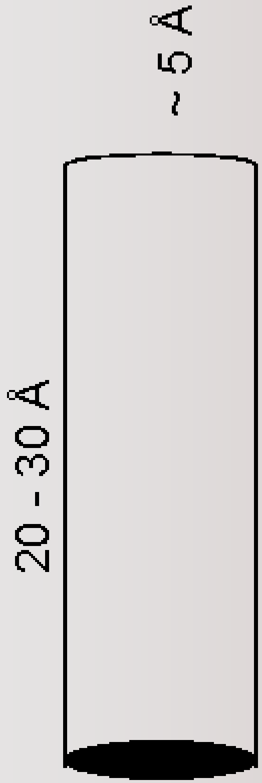
LCP = Liquid Crystalline Phases

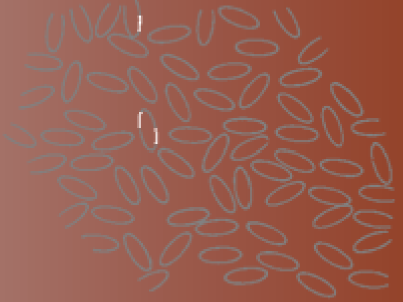
Chemistry Physics



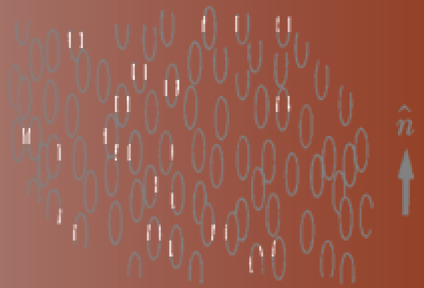


from particles with shape, fex. rods:

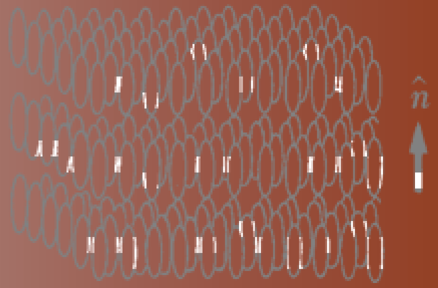
Isotropic Phase



Nematic Phase



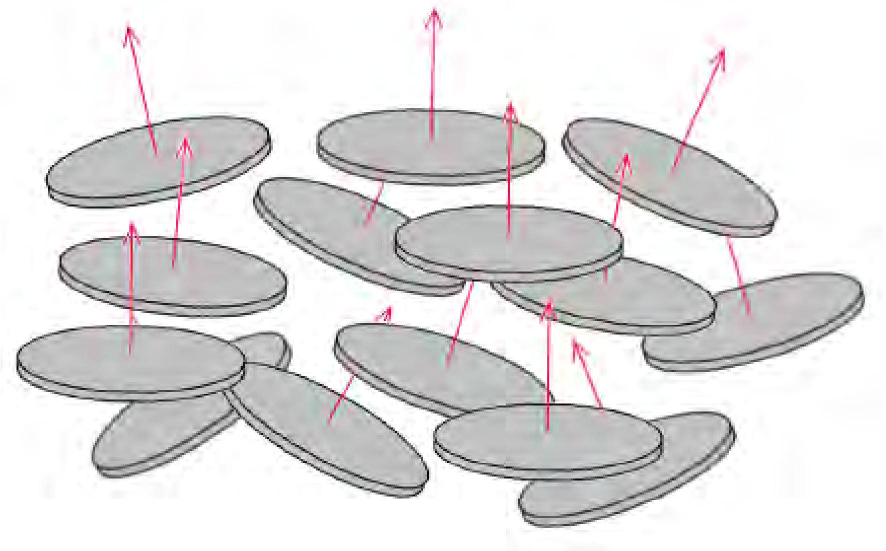
Crystalline Phase



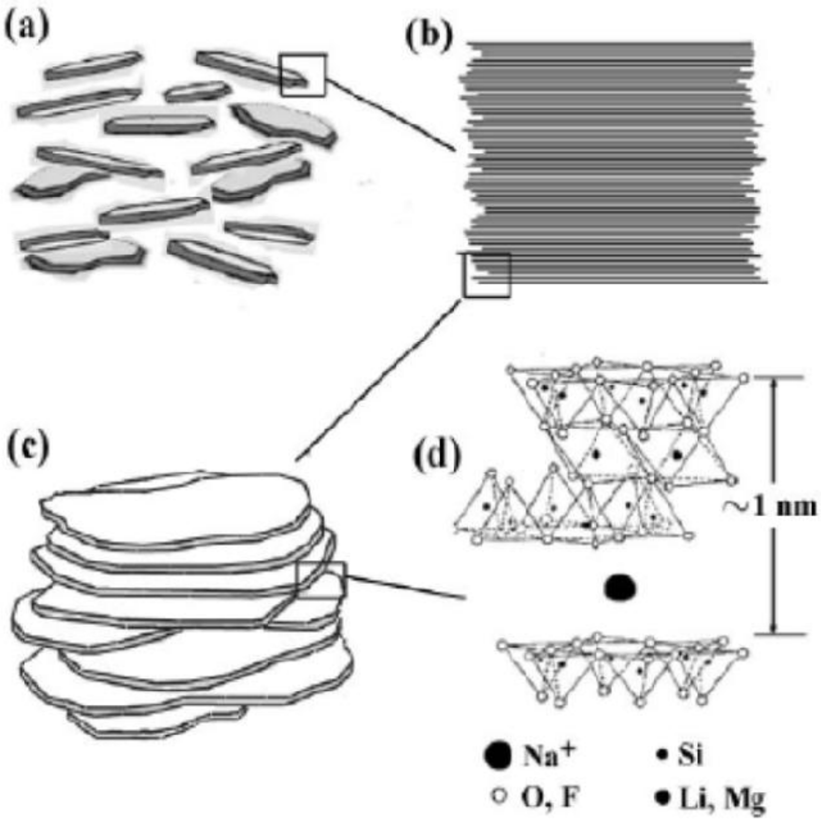
LCD technology

LCP = Self-Organized Liquid Crystalline Phases

Nematic order of discs:



Clays are disc-like nano-/micro- particles:



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Alignement of particles with shape (i.e. not spherical) has been of basic scientific interest to physicists and chemists for a long time:

Irving Langmuir: Nobel Prize in Chemistry 1932

Langmuir did pioneering experimental work in 1938 on finding liquid crystal structures in a clay.

J. Chem Phys. 6, 873 (1938)

One of our experiments:

http://www.ntnu.edu/physics/complexmaterials/softcomplex

Pure Water

Clay
powder
About 3 % in weight

NaCl

About 10^{-3} M

Basic clay particle

~100nm

~μm

Liquid

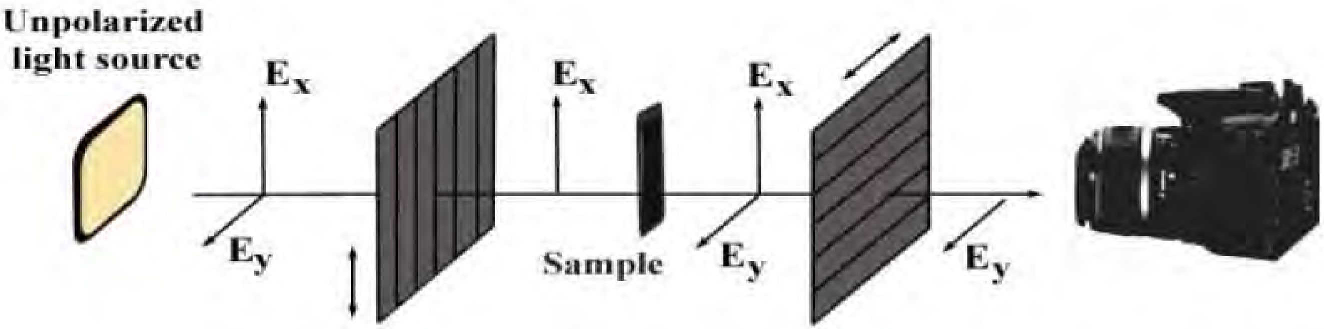
Isotropic gel or glass?

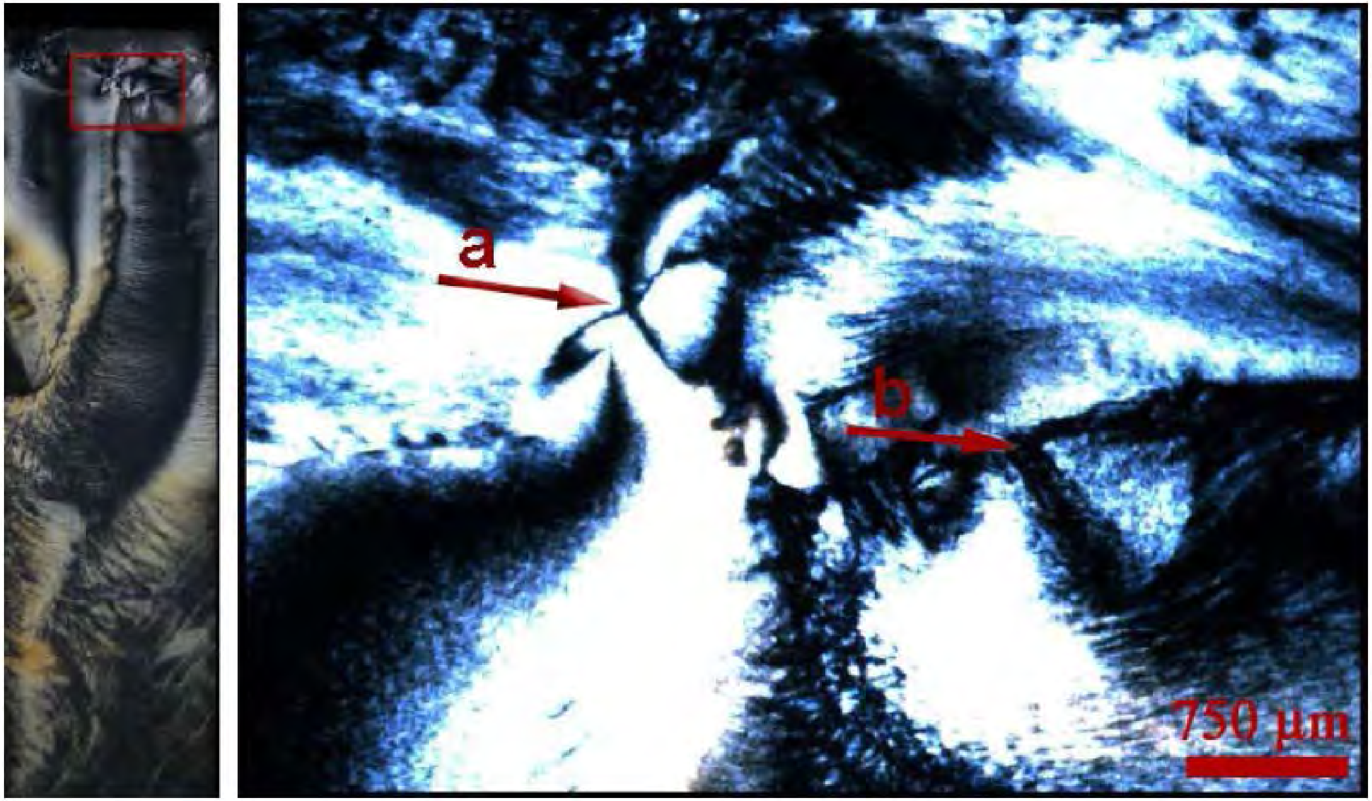
Nematic like gel or glass?

Sediment

4 ”Phases” in same Sample Tube

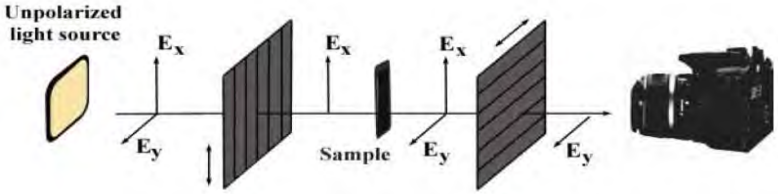
Orientational order in gravity dispersed clay colloids: A synchrotron x-ray scattering study of Na-fluorohectorite suspensions. E. DiMasi, J.O. Fossum, T. Gog, and C. Venkataraman. **Phys.Rev. E 64, 061704 (2001)**





a and **b**
are ”typical” nematic defect signatures: Disclinations ("discontinuity" in the "inclination" of the director)

Nematic textures in colloidal dispersions of Na-fluorohectorite synthetic clay. N.I. Ringdal, D.M. Fonseca, E.L. Hansen, H. Hemmen, and J.O. Fossum. **Phys.Rev. E 81, 041702 (2010)**



Self-organization by sedimentation clay particles in H_2O:

complex @ © NTNU - Norwegian University of Science and Technology

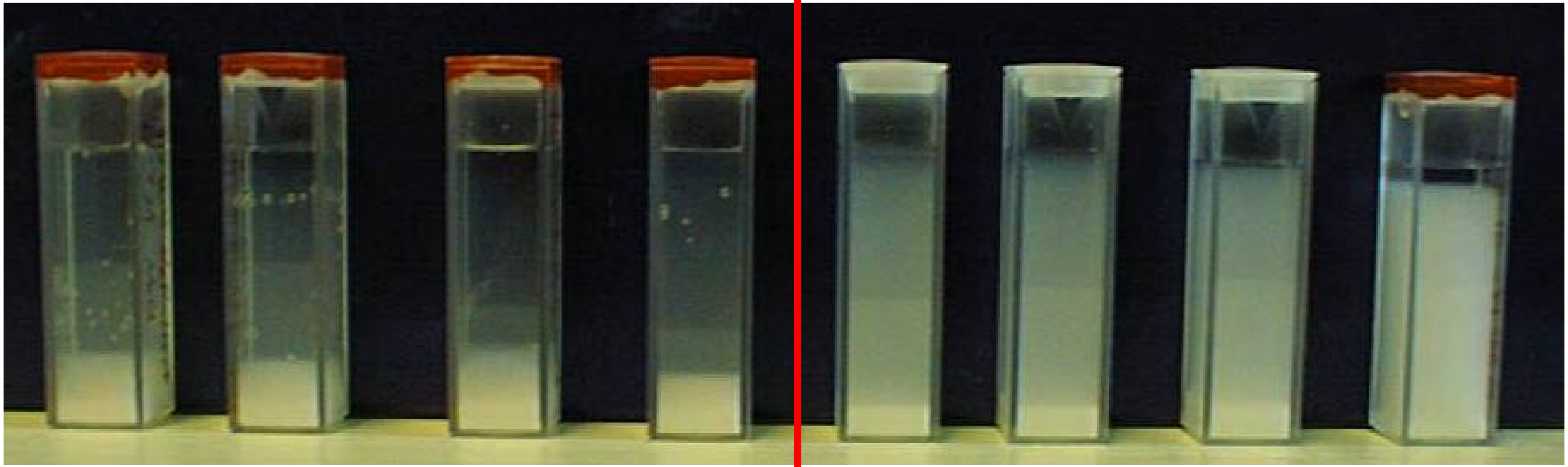
http://www.complexphysics.org/

http://folk.ntnu.no/fossumj/

0 days

Experiments by Nils Ivar Ringdal

Increasing salt:



"Repulsive nematic"
"Wigner glass"

"Attractive nematic"
"Gel"

Particles push each other out towards container walls,
→ nematic
at high enough concentration
→ "large" domains

Particles "catch each other" in DLVO local minima
→ small domains

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Observations of orientational ordering in aqueous suspensions of a nano-layered silicate. J.O. Fossum, E. Gudding, D. d.M.Fonseca, Y. Meheust, E. DiMasi, T. Gog and C. Venkataraman. **Energy The International Journal, Volume 3, 873 (2005)**