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Proposition for internship 2019-2020

Short description of the projects proposed in Eric Clément's lab at the PMMH-ESPCI

Active matter

The paradigm of "active matter" has had over the past decade notable successes in describing self-organization in a surprisingly broad class of biological and bio-inspired systems: from flocks of starlings to robots, down to bacterial colonies, motile colloids and the cell cytoskeleton.

The projects currently developed at the PMMH, in the "active fluids group" are oriented towards applying these concepts to bacterial populations. In the group, we seek to address the question of transport in complex environments of dilute or dense populations of motile micro-organisms, using microfluidic channels mimicking biological network or physiological conducts as well are natural environments such as soils or fractured rocks. This is for example a central question in the context of medicine as it can control several physiological functions (e.g. spermatic transport in conducts or upstream contamination of urinary tracks etc..). It is also relevant to novel technologies concerned with drug delivery or crucial to ecological studies aiming at understanding the spreading of bio-contaminants in soils or the building of ecological niches.

Three possible subjects

In the lab we developed simple models for bacterial populations essentially based on wild-type strains of E.coli or using mutants obtained by kicking-off some function. The various techniques developed here to grow and manipulate these bacteria are safe and very simple, they do not need any a priori knowledge in biology. We also developed two novel tools and processes, in order to address these questions: i) a 3D tracking device suited to follow fluorescent bacteria (and their flagella) in complex flows. A 3D additive micro-printer to design and elaborate small scale (10-100 μm) complex objects with a sub-micron resolution.

We propose here two research directions that can developed as experimental projects.

Subject I- Bacteria swimming and organizing collectively in complex flows

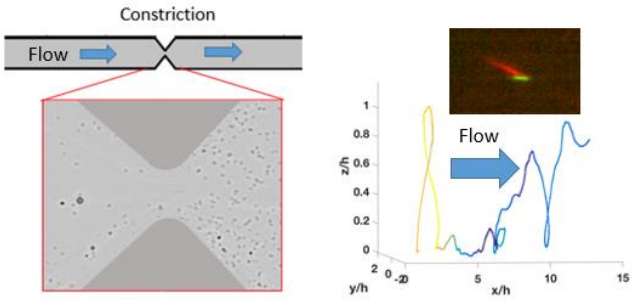

Fig1 (Left) Accumulation of E.coli bacteria past a microfluidic-channel constriction under flow. (Right) 3D tracking of an E.coli in a rectangular channel [Junot et al. 2018].

The first project seeks to understand how a populations of bacteria organizes and spreads in geometrically complex environments when driven by a flow. Using microfluidic techniques, we can control experimentally different channel geometries in order to understand the spreading of individual motile bacteria or a population. In the active fluids group we have already shown that flow complexity and interaction with surfaces can bring some very anomalous properties in terms of macroscopic transport and hydrodynamic dispersion processes.

More precisely the subject will be based on recent works of our group one on Lagrangian tracking techniques [Darnige 2017] and the other on a new surprising phenomenon baptized the “bacteria anti-hourglass effect” leading to a re-concentration of a bacteria population *after* passing through a constriction [Altshuler et al. Soft Matter 2013]. By tracking bacteria swimming in this geometry, we will reconstruct the trajectories in order to clarify the interplay between hydrodynamics and swimming, leading to the re-concentration effect. The second step will be to understand if the effect is likely to persist at higher bacteria concentrations and to which extend, the jamming process occurring naturally with suspensions of passive particles, can be modified in the case of autonomous simmers such as bacteria. A natural extension will be to study the transport process of bacteria suspensions in channels with multiple constrictions to see if a gradient in motility properties can be revealed. This may lead to some practical applications.

Subject II - The “Row-bot” project

The second project will explore the current possibilities to fabricate hybrid objects integrating artificial and biological components. In the lab, we manufacture additively, microscopic objects that can be combined with active bacteria. More precisely, we propose to study the momentum transfer induced by flagellated bacteria such as E.coli, anchored to micro-fabricated surfaces shaped as an array of hollow helices. We already established the trapping possibility of wild-type E.coli as a proof of concept. In a next step (i.e. the internship) the bacteria will be an E.coli smooth swimmer (no tumbling) for which the body and the flagella can be made of different colors. We will then directly visualize the flagella activating the fluid at the surface. Also, to probe the backflow due to the flagellar carpet, we will follow and analyze the trajectories of a microscopic latex bead deposited on the surface.

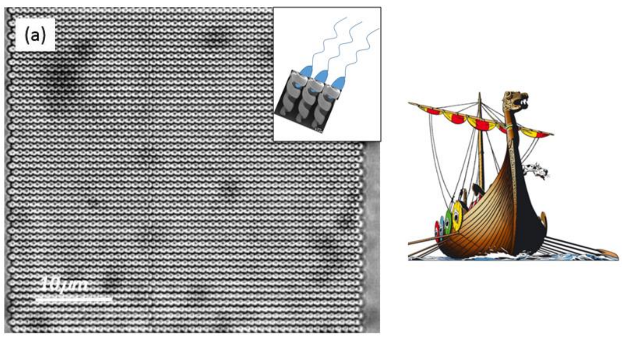

Fig2. The “Row-bot project”. Micro-fabricated surface in the form of an array of helices suited to trap flagellated bacteria at surfaces. The propulsive thrust of the flagella can be used for to activate macroscopic objects or be used as a microfluidic pump.

Once the surface is prepared, we can explore different properties such as the possibility to integrate this bio-activated carpet into larger objects such as to form a cargo ship (or more exactly a galley) or to use them as fluid pumps in microfluidic channels.

The last subject is on the hydrodynamics of fluid/structure interactions

Subject III : Building the 6th continent

Deformation of flexible elastic sheets under reversible shear

This project will explore the dynamics of a flexible 2D sheet suspended in a viscous fluid. Compared with the well-studied cases of rigid rods and flexible one-dimensional filaments, little is known about the fundamental behavior of two-dimensional very flexible elastic sheets mimicking plastic bags straying and agglomerating in the ocean. The immediate goal of this project is to analytically and/or experimentally investigate its behavior when driven by alternation of reversible shear. In particular, we will be interested by the conditions for which irreversible drift may occur, changing the foil size and flexibility. This study will form the first steps towards developing a statistical mechanics theory of passive flexible sheets and is expected to shed light on a variety of physical phenomena from the settlement of marine organisms at the bottom of the ocean to the formation of the “continent” of plastic bags on the ocean surface and its impact on marine faunas.

Internship M1 ICFP, March-July 2020

Subject : Coalescence of a droplet and a thin viscous film

Advisor : Laurent Duchemin

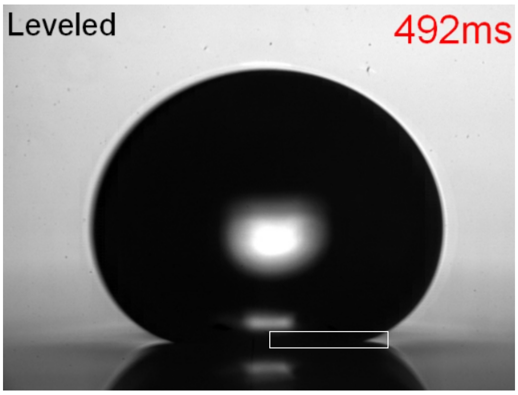

Figure 1.

We consider a liquid droplet landing gently on a thin liquid film, of the same viscous liquid. The question we want to address is: how long does it take for the two liquid surfaces to coalesce? We assume that the oscillations of the drop during the impact have had enough time to relax towards an equilibrium shape. This assumption is in perfect agreement with the experimental observation described a recent experimental article on this subject [1]. We are interested in the air film dynamics below the drop, of typical thickness h_0. This thin film eventually connects to the sessile drop surface at a distance L from the axis of symmetry such that $L \gg h_0$ (Cf. fig. 1).

The aim of this study is to understand the subtle dynamics of the air film and the liquid film underneath, leading to the finite-time coalescence. Using lubrication theory [2] and numerical 1D computations, we shall try to quantify this dynamics, by studying the effect of the boundary conditions at the two interfaces.

Bibliography

[1] Hau Yung Lo, Yuan Liu, and Lei Xu. Mechanism of contact between a droplet and an atomically smooth substrate. *Physical Review X*, 7(2):21036, 2017.

[2] Stergios G Yiantsios and Robert H Davis. On the buoyancy-driven motion of a drop towards a rigid surface or a deformable interface. *Journal of Fluid Mechanics*, 217:547–573, 1990.

Computing with waves

Encadrants : A. EDDI (laboratoire PMMH, ESPCI) et E. FORT (Institut Langevin, ESPCI).

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Combinatorial optimization is an important problem for various applications such as drug discovery, resource optimization in wireless networks, and machine learning. Many such problems are considered difficult to solve efficiently with modern digital computers. They are said to be NP-hard or NP-complete problems. Several heuristic algorithms have been proposed in the field of computer science to find the solutions to those problems. It is known that combinatorial optimization problems can be mapped onto ground-state-search problems of the Ising model, composed of interacting spins, with polynomial resources.

Several approaches have thus been proposed to find solutions to Ising problems using networks of artificial spins based on various physical systems. Recently, interacting degenerated optical parametric oscillators have been coupled to produce a coherent Ising machine [1,2].

The goal of this project is to solve complex computational problems with water waves by implementing a coherent Ising machine using Faraday instability. Faraday instability is a parametric instability induced by the effective gravity modulation of a liquid bath: when excited vertically at a given frequency, the fluid surface becomes unstable with the appearance of standing waves at half the excitation frequency above an acceleration threshold γ_0. This threshold depends on the viscosity of the bath and thus can be tuned by controlling the temperature.

The project will build a coherent Ising machine based on this principle. The problem to solve will be implemented by creating a temperature map on the water bath using a scanning CO_2 laser. The temperature map defines the local parametric oscillators (“hot spots”) and their interactions (relative positions and connections).

To solve the problem, the bath is excited vertically with increasing amplitude (below the threshold at the ambient temperature). When the excitation is sufficient to reach the ground-state of implemented problem, a stationary standing wave pattern appears on the surface of the bath. This wave pattern gives the solution to the problem.

The project is mainly experimental coupling optics (CO_2 laser scanning, IR camera for temperature mapping and imaging surface deformation with Schlieren-like technique) and hydrodynamics (surface waves, Faraday instability).

[1] A. Marandi *et al., Nature Photonics* **8**, 937–942 (2014)
[2] P. L. McMahon *et al., Science* **354**, 614–617 (2016)

An anti-gravity swimming-pool ?

Encadrants : A. EDDI (laboratoire PMMH, ESPCI) et E. FORT (Institut Langevin, ESPCI).
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For this internship, we propose to design and build an inverted liquid bath that would defy gravity.

When a liquid film is suspended, it destabilizes under gravity. The interface is unstable with a typical wavelength. This phenomenon is known as the Rayleigh-Taylor instability. Two opposing mechanisms act on the liquid interface: gravity that pulls the liquid downwards and surface tension that prevents the liquid interface to increase its area. A stability analysis shows that wavelengths larger than a typical scale (about one centimeter for water) are unstable. As a consequence water doesn't flow when a container with a tiny bottom hole is filled with water. Beyond this critical size, the container empties out.

On the other hand, it's possible to dynamically stabilize unstable systems. For example, for a mass placed in an unstable potential which is sinusoidally modulated, there exist a parameter range where the mass finds a stable position. An experimental realization of such effect is the Kapitza pendulum where a vibrated pendulum exhibits a stable position with the mass on top [1].

Credits : Leandro Erlic

In this internship, we offer to apply this dynamical stabilization to a liquid interface. Applying a vertical vibration to an inverted liquid bath, it is possible to modulate the effective gravity acting on the liquid interface. Depending on the vibration conditions (frequency, amplitude, …), and the cavity shape, the range of stable wavelengths will be investigated and compared to theoretical values [2]. This internship is experimental and will try to define the parameters where such an anti-gravity swimming pool could exist.

[1] Kapitza P. L. (1951). "Dynamic stability of a pendulum when its point of suspension vibrates". Soviet Phys. JETP. ***21****: 588–592.*

[2] V. Lapuerta, F. J. Mancebo, and J. M. Vega. Control of Rayleigh-Taylor instability by vertical vibration in large aspect ratio containers Phys. Rev. E, 64, 016318

INTERNSHIP PROPOSAL

Laboratory name: **PMMH (Physique et Mécanique des Milieux Hétérogènes), ESPCI**
CNRS identification code: UMR 7636 CNRS/ESPCI
Internship director'surname: Evelyne KOLB
Collaborations with M.B BOGEAT-TRIBOULOT (UMR SILVA, INRA Nancy), V. LEGUE (UMR PIAF, INRA Clermont), L. DUPUY (James Hutton Institute, Scotland)

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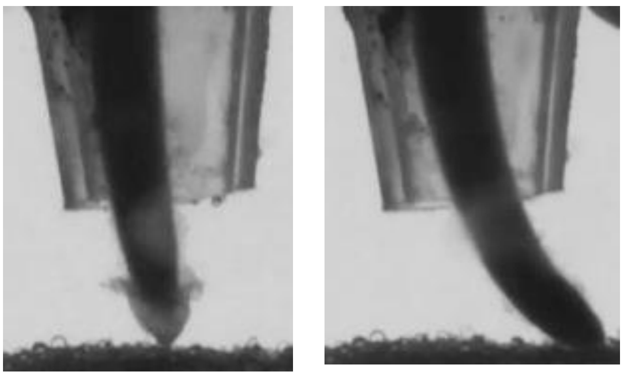
Plant roots interacting with a mechanical obstacle

The interaction between plant roots and soils is a wide issue involving many communities from agronomy, soil science, biophysics to civil engineering and geophysics. Under non-stressful biological and chemical conditions, the root growth trajectory highly depends on the mechanical strength of the soil and on the presence of obstacles at the root scale, as root apices must exert a growth pressure to overcome the resistance to deformation of the surrounding soil or reorient their growth to skirt around obstacles by mechanisms like buckling or active differential growth. The presence of zones of high mechanical resistance is one of the most common physical limitations to soil exploration by roots, which has direct impacts on yield crops. Increase in soil strength is known to reduce root elongation and alter root diameters as well as the average number of lateral roots that stem from primary axes.

During this internship we propose to study the growth features and forces developed by a root interacting with a single obstacle of known stiffness used as a force sensor. By time-lapse photography and image analysis, we will follow the temporal evolution of forces as well as longitudinal and radial growth rates for identifying the conditions for which the root experiences a reorientation of its growing axis (like in the figure) or stops growing. The pattern of growth will help in separating the mechanical response from the biological feedback in the root reorientation. We will implement the experiment for performing a kinematics analysis of the local deformation of the root by using techniques like particle image velocimetry (PIV) for following marks on the root surface.



Chick-pea root growing in hydroponics against a rough obstacle fixed to a force sensor (left: at contact; right: reorientation of the growth axis). The root's diameter is around 1 mm.

Kolb, Hartmann, Genet (2012) *Plant Soil* 360, 19-35
Kolb, Legué, Bogeat-Triboulot, 2017, *Phys. Biol.* **14** (2017) 065004

Microbial activity in curves spaces

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Active matter describes systems in which their elementary constituents consume energy to produce motion. The interaction between these elementary active objects usually leads to fascinating collective behaviors, which are widely observed in nature, from bird flocks to cellular cytoskeletons. How the behavior of the elementary active components determines the macroscopic behavior of the system is still uncertain. Microswimmers, such as bacteria, are model systems that allow us to address some of these fundamental questions.

In this internship, we will study the spatio-temporal patterns that emerge when bacteria are confined to curved interfaces. In particular, we will produce double emulsion droplets, where the active swimmers are confined to a thin spherical shell, that is, between the inner and outer interface of the double emulsion, see Fig.1. Due to the rod-like shape of bacteria (E-coli), they are expected to form an active nematic phase at high packing fraction. In the shell geometry, topological constraints are expected to induce complex organization in the system, and topological defects might play a key role.

This project will build on the knowledge of the intriguing defect structures in shells of passive liquid crystals, observed previously. In a first step, we will replace the liquid crystals with active bacteria to explore new possible metastable states and to study the non-equilibrium dynamics of the system in this highly confined geometry. Unlike in equilibrium systems, where defects are largely static structures, in active nematics, defects move spontaneously and can be described as self-propelled particles. Then we will confine a mixture of passive liquid crystals and bacteria into the thin shell to investigate the interactions between bacteria and the topological defects created by the passive liquid crystal. The combination of activity, topological constraints, and coupling between active and passive nematic materials is expected to produce a myriad of new dynamical states.

The precise content of the internship, performed between the Gulliver and PMMH labs and also in collaboration with Eric Clement, PMMH, and the PhD student Martyna Goral, will be discussed with the candidate to fit his/her interests and knowledge and to fit in the above mentioned topic.

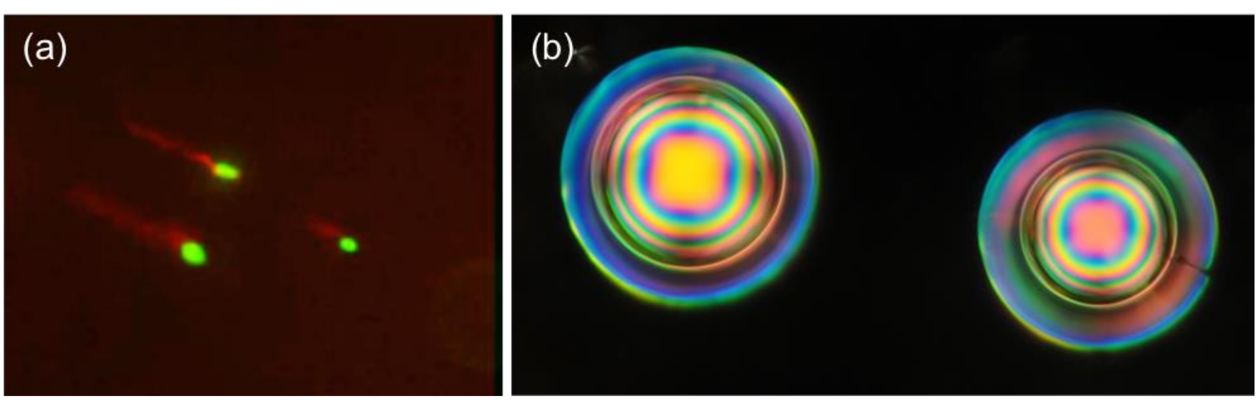

Figure 1. (a) Bacteria swimming in a liquid crystal. (b) Liquid crystal shells.

ICFP M1 internship proposal

Internship location
Laboratoire de Physique et mécanique des Milieu Hétérogènes (PMMH)
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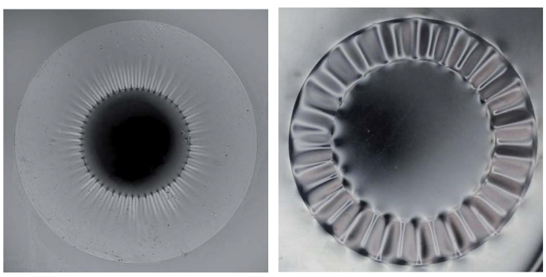
Stress reversal by a strong nonlinearity: an elastic sheet toy model

Experimental internship — soft matter

Living cells move thanks to nanometer-size molecular motors whose forces are transmitted up to the scale of the cell by a fiber network known as the cytoskeleton. On much larger length scales, individual cells generate forces that are similarly transmitted to the tissue level through the fibrous extracellular matrix. While the biology of these processes is rather well characterized, the simple problem of force transmission through these highly nonlinear elastic media is far from trivial, and leads to a **conversion of local extensile forces to contractile stresses**, with crucial biological implications.

To better understand this surprising physical behavior, we will set up a model force transmission experiment where the role of the nonlinear elastic medium will be played by a thin plastic sheet floating on water. By locally exerting extensile forces at the center of the sheet by inflating a balloon, we will **directly observe how the forces are rectified through the wrinkling of the sheet**. The goal is to help explain why the cytoskeleton is always contractile despite containing a significant number of extensile motors, and to inspire the design of counter-intuitive materials that contract when they should extend.

The student will have a taste for experimental physics. He/She will set up and run a model experiment, and participate in the theoretical analysis of the measurements.



Floating elastic sheets wrinkle under force, which induces a strongly nonlinear effective response akin to that of biological fibrous media.