Physique et
Mécanique des
Milieux
Hétérogènes
UMR 7636

PMMH
Sujets de stages - 2023

Master 2 internship proposal

Laboratoire de Physique et Mécanique des Milieux Hétérogènes

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Internship location: barre Cassan A, campus Jussieu, 7 Quai Saint Bernard, 75005 Paris

Bridging the Gap from Atomic to Discrete Lattice Models in disordered solids

Are you eager to explore the intriguing world of amorphous solids and dive into the fundamental physics behind plastic deformation? If so, we invite you to join our dynamic research team in an engaging and intellectually stimulating internship opportunity.

Overview: Our internship project addresses a longstanding question in materials science: How can we physically describe the plastic deformation of amorphous solids without relying on phenomenological assumptions? Our research group has developed an innovative method that allows us to measure systematically local yield stress down to the atomic scale. This breakthrough measurement opens the door to quantifying the intricate relationship between the material's structure and its plastic behaviour. Our goal is to extend this newfound knowledge to larger scales using discrete mesoscopic models, which treat plastic deformation as a discrete population of rearrangements in an elastic medium. These models draw parallels with the Ising model, where local plastic deformation corresponds to spins, and interactions between sites represent elastic propagation.

Project Objectives:

- Atomic-Scale Insights: The project's initial phase will focus on gaining atomic-scale insights into the plastic behaviour of amorphous solids. We will utilize our novel measurement method to uncover the local yield stresses and their correlation with structural features.
- Mesoscopic Modelling: Building upon the atomic-scale findings, we will implement discrete mesoscopic models to bridge the gap between atomic behaviour and macroscopic plasticity. These models have shown promise in replicating essential plasticity characteristics in various systems.

Feel free to reach out to us with any questions or expressions of interest. Informal contacts are welcome.

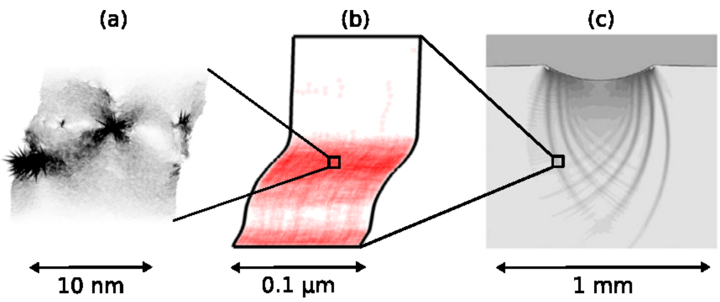

Figure: Multi-scale strategy [1]. Amorphous materials are studied at different scales: (a) atomic, (b) mesoscopic and (c) continuous. So far, the absence of a quantitative link between local structure and plasticity at the atomic scale has confined this approach to a qualitative description. Our new method has just addressed this scientific challenge, opening the way to an unprecedented understanding of the mechanical properties of glassy materials.

References

[1] D. Rodney, A. Tanguy and D. Vandembroucq, Modeling the mechanics of amorphous solids at different length scale and time scale, Model. Simul. Mater. Sci. Eng., 19 083001 (2011)
[2] S. Patinet, D. Vandembroucq and M.L. Falk, Connecting local yield stresses with plastic activity in a model amorphous solid, Phys. Rev. Lett. 117, 045501 (2016)

Expected skills: The applicant should have interest in physics and numerical modelling. Possibility of continuing with a thesis after the internship.

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

Contact: Etienne Reyssat, Antonin Eddi, Laurent Duchemin (laboratoire PMMH)
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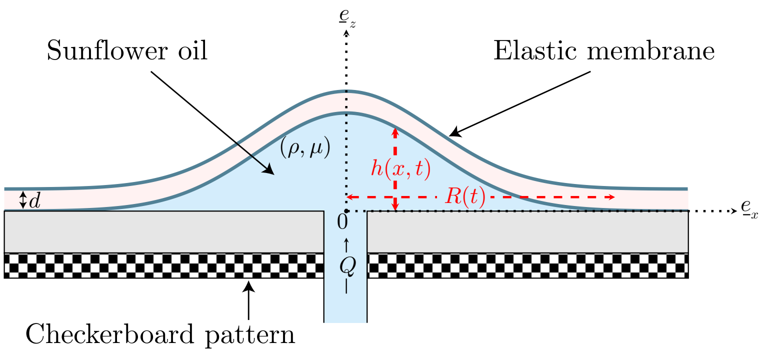
Internship location: Laboratoire PMMH

Laccoliths in the lab

Laccoliths are hills formed by intrusion of magma under deformable rock layers. Inspired by this geological system, we have studied the growth of liquid pockets under elastomeric membranes using a model system in the laboratory (see figure). The deformations fields are measured through the deformation of a checkerboard pattern placed below the experimental system.
Earlier work focused on the spreading and coalescence of such "elastic" drops, in a lubrication regime where the fluid layer remains very flat. We now wish to address new questions more closely related to the geologic inspiration system: i) What is the role of adhesion of the elastic layer to its support, and how does this affect the aspect ratio of the bump formed? ii) Can the covering membrane exhibit wrinkling when deformed?
We propose to explore experimentally and theoretically, at the laboratory scale, the formation and dynamics of these peculiar "drops".



A viscous liquid is injected under a deformable layer. The morphology of the resulting "bump", measured using the fast checkerboard demodulation technique, depends on the physical parameters of the liquid and solid membrane.

Expected skills: The project is mainly experimental, with minimal modeling of the observed phenomena. Image analysis will be performed. Numerical/Theoretical projects can complement the project.

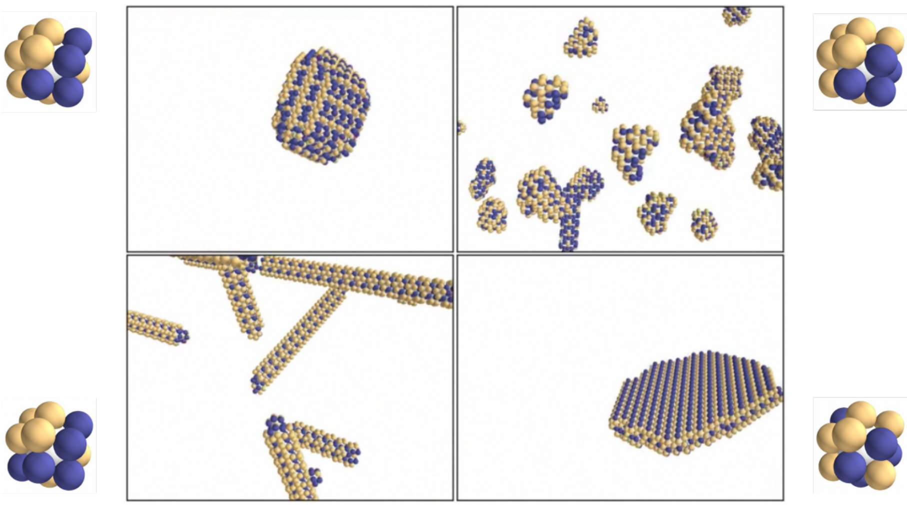
Frustrated self-assembly with multiple particle types

(theoretical internship, possibly leading to a thesis; funding available)

Self-organization is key to the function of living cells – but sometimes goes wrong! In Alzheimer's and many other diseases, normally soluble proteins thus clump up into pathological fiber-like aggregates. While biologists typically explain this on the grounds of detailed molecular interactions, we have started proving that such fibers are actually expected from very general physical principles. We thus show that **geometrical frustration builds up when mismatched objects self-assemble, and leads to non-trivial aggregate morphologies, including fibers**.

While we have shown that collections of identical particles form aggregates of various dimensionalities, realistic biological examples often involve multiple proteins. We will thus investigate how collections of several types of different particles typically interact and interfere. Our study will first consist in developing variants of the lattice-based numerical model presented in the illustration where multiple particle types are involved. We will then ask whether species with different types tend to phase separate, or conversely whether the mutiplicity of interactions they offer eases geometrical frustration and favors co-assembly. We will also wonder how this combinatorics affects the dimensionality of the aggregates, and whether we can identify generic features of the particles that distinguish between the two scenarios. We will then conduct off-lattice simulations to assess the robustness of these scenarios. Finally, we will attempt to construct a mean-field theory describing the co-assembly of a large variety of particles ($\geqslant 10$ or so) thus revealing the interplay between frustration and combinatorial freedom in self-assembly.

Beyond protein aggregation, this project opens investigations into a new class of "disordered" systems where the disorder is carried by each identical particle, as opposed to sprinkled throughout the system. This will help define the much-debated notion of frustration in dilute systems. This project will be conducted in collaboration with Pierre Ronceray (Turing Center for Living Systems, Marseille), who could co-direct a possible PhD project.



In our simulations, complex lattice particles with geometrically incompatible orientational preferences (in the corners: sites with identical colors attract) give rise to aggregates of different dimensionalities.

Expected skills:
A taste for statistical mechanics and numerical simulations connected to analytical aspects.
Mostly analytical projects also possible.

Location:
PMMH at ESPCI & Sorbonne U. and/or LPTMS at U. Paris-Saclay (Orsay)

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Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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Internship location: PMMH, campus Jussieu, Barre Cassan A, 7 Quai Saint Bernard, 75005 Paris

Levitation of fizzy droplets

A volatile liquid placed on a sufficiently hot solid levitates on its own vapor [1]. The absence of liquid-solid contact provides the so-called Leidenfrost droplets with intriguing properties such as the absence of adhesion, extreme mobility, and thermal insulation with its substrate. At ambient temperature, carbonated water droplets can also levitate on a superhydrophobic solid due to the continuous release of the CO_2 dissolved in the drop (Figure 1) [2]. The project will aim to experimentally visualize and measure the interface beneath a levitating drop using interfero-microscopy techniques. The experimental measurements will be confronted to numerical simulations and theoretical models to infer the dynamics of gas films insulating levitating droplet [3]. In particular, the expected results will contribute to a better understanding of the onset of droplet levitation, a question which remains to be understood in both Leidenfrost and carbonated droplets.

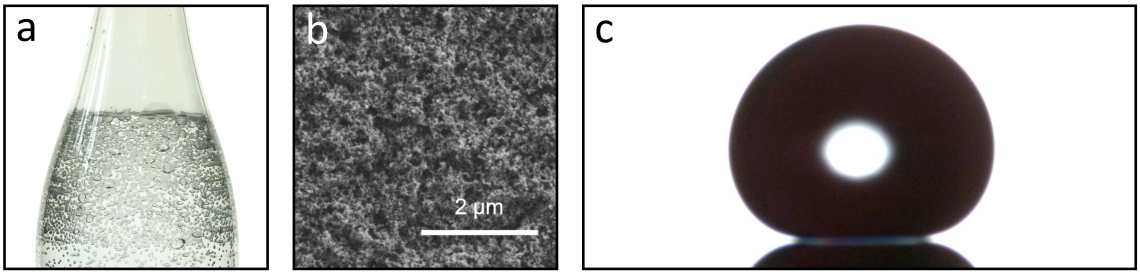

Figure 1: Levitation of fizzy water drops on a superhydrophobic solid. **a)** Image of the fizzy water obtained by pressurizing $CO_2(g)$ into deionized water. **b)** SEM image of a transparent superhydrophobic coating made by a random assembly of hydrophobic silica particles leading to a submicron-scale roughness. **c)** Photograph of a 30 μL carbonated water drop deposited on a silicon wafer made superhydrophobic. The thin ray of light between the drop and its reflection on the solid indicates the levitation of the drop on a micrometric-scale gas cushion.

References:
[1] D. Quéré, Leidenfrost dynamics, *Annual Review of Fluid Mechanics* 45 (2013).
[2] D. Panchanathan, **P. Bourrianne**, P. Nicollier, A. Chottratanapituk, K.K. Varanasi and G.H. McKinley, Levitation of fizzy drops. *Science Advances* 7 (2021).
[3] **L. Duchemin**, J.R. Lister and U. Lange, Static shapes of levitated viscous drops. *Journal of Fluid Mechanics* 533 (2005).

The applicant should have interests in fluid mechanics and soft matter.
The applicant will be encouraged to apply for a PhD.

Master 2 internship proposal

Laboratoire de Physique et Mécanique des Milieux Hétérogènes

Contact: Sylvain Patinet / @: sylvain.patinet@espci.fr / Phone: (+0033) 01 40 79 58 26 / Web: https://blog.espci.fr/spatinet/

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Uncover the Secrets of Granular Chain Packings: A Master's Research Internship

Are you passionate about the mysteries of material mechanics and eager to embark on a thrilling research journey? We invite you to join our cutting-edge research team in an exciting and intellectually stimulating internship opportunity.

Our internship project offers a unique opportunity to dive into the numerical exploration of athermal polymer analogs, specifically the packing of granular chains. By drawing parallels between polymers and granular chains, we aim to shed light on the impact of chain length and concentration within this intriguing macroscopic system.

Project Objectives:

- Static Mechanical Properties: In the first phase of the project, we will focus on deciphering the static mechanical properties of granular chain packings, with a particular emphasis on investigating the jamming transition?an essential aspect of granular materials.

- Dynamic Properties: The second phase aims to uncover the dynamic properties of granular chains. To achieve this, we will implement two distinct experimental protocols: vibrating the packing and subjecting it to various shear rates. These experiments will help us understand the variation in the effective viscosity of the system under different conditions.

Research Tools: We will conduct our simulations using a state-of-the-art particle dynamics code that we have recently developed and rigorously validated. One of the significant advantages of this numerical approach is its direct comparability with model experiments at the macroscale, offering a comprehensive perspective on granular chain packings.

Feel free to reach out to us with any questions or expressions of interest. Informal contacts are welcome.

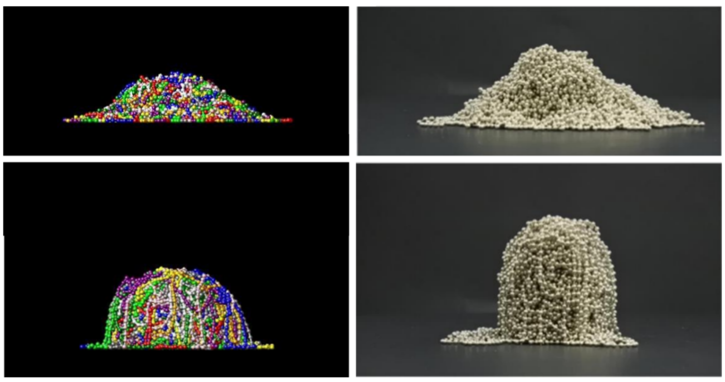

Figure: Static equilibrium reached after removing a cylindrical container for granular chains consisting of 5 (top) and 30 (bottom) grains. One observes a transition from flow to preservation of the original shape as the length of chains in the packing is increased. The numerical approach is fully consistent with the experiments. We now have to understand it!

References

[1] D. Dumont, M. Houze, P. Rambach, T. Salez, S. Patinet and P. Damman, Phys. Rev. Lett. 120, 088001 (2018)

Expected skills: The applicant should have interest in physics and numerical modelling. Possibility of continuing with a thesis after the internship.

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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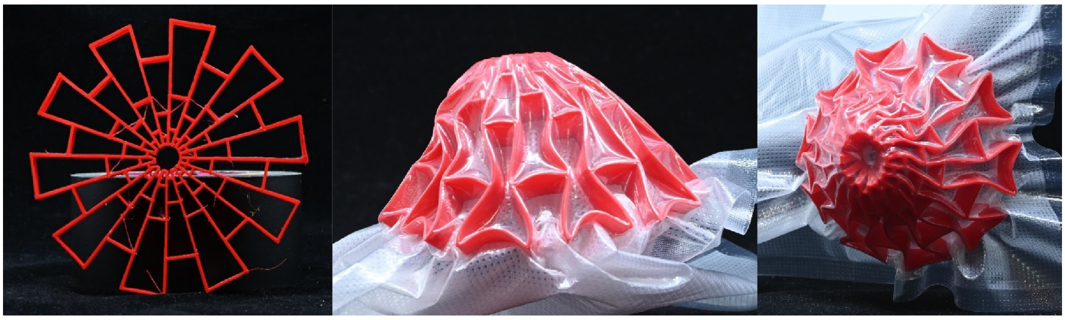
Internship location: Laboratoire PMMH

Physics and mechanics of deflatable reinforced structures

Two layers of inextensible fabric may be seamed together along lines to define a network of inflatable channels. When pressurized, the initially flat device deploys into a three dimensional shape controlled by the detailed design of the pneumatic network.

For some applications, such devices need reinforcement by an internal skeleton. We propose to explore the behavior of grid-like 3D printed structures trapped in an air-tight bag of fabric. As air is sucked out of the bag, the fabric penetrates the cells defined by the walls of the grid (see figure). The resulting forces tend to crush the cells, resulting in macroscopic dimensional variations and overall shape change. We propose to explore the physical parameters that rule these model deflatable reinforced systems. How should the material of the containing bag and of the skeleton be chosen to maximise the achievable deformations? How should one choose the geometry of the internal reinforcing structure to give rise to a target shape? What are the overall mechanical properties of the activated structures? Can one imagine large scale realisations? We will combine model experiments and minimal mathematical models to provide answers to these questions.



A 3D printed cellular structure is placed inside an airtight bag. When applying vaccum, the bag is sucked into the cells, deforms them, leading to out-of-plane deformations of the structure as a whole.

Expected skills: The project is mainly experimental, with minimal modeling of the observed phenomena.

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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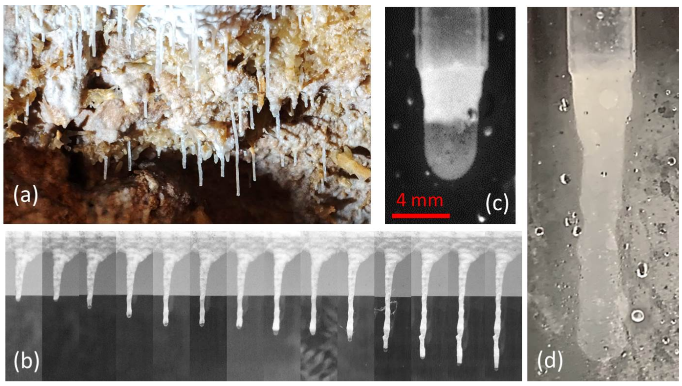
Location: Laboratoire PMMH

Lab-grown tubular stalactites

Among the various and beautiful shapes shown by calcite concretions in limestone caves, the soda-straw speleothems exhibit an astonishing regularity in diameter (Fig. (a)). Calcite precipitation occurs at the rim of the pendant drop, whose size ($\cong$ 5 mm) is fixed by gravity and capillary forces, thus templating the growing structure. A hanging tube grows downwards as successive drops detach and leave a ring of solid material. Tubular precipitation leads to significantly faster growth rates than for massive stalactites (1 cm/year as compared to 1 cm/century). Tubular stalactites can also grow in open air from concrete structures exposed to rainwater (Fig. (b)), with an even faster growth (1 cm/month).

The factors determining these growth rates are still far from being understood and difficult to be quantified in field conditions. The objective of the internship is to study an analogue system in the laboratory, under controlled conditions, in order to relate the spatio-temporal scales to the relevant physical parameters. We have recently worked with a solution of strontium hydroxyde ($Sr(OH)_2$) dripping in a chamber filled with CO_2, and obtained tubular $SrCO_3$ stalactites growing at a rate of 2 microns/min (Fig. (c) and (d)). Our aim is now to make this first study more quantitative, in particular by controlling the concentration of CO_2 in the chamber.



(a): Natural soda-straws in limestone cave (Grotte de la Madeleine, Ardèche). (b): Temporal evolution of a tubular stalactite growing from concrete structure in open air (campus Jussieu, Paris). (c) and (d): Artificial tubular stalactite in strontium carbonate ($SrCO_3$) grown in the PMMH laboratory.

Future directions featuring a PhD thesis on speleothem formation include analogue systems involving thermo-responsive precipitation (KNO_3) or solidification (PEG), various flow geometries templating different patterns (curtains ...) or sub-patterns (ripples, multi-layers ...), and comparisons with field measurements using 2D photogrammetry or 3D reconstruction.

Expected skills: This project is primarily experimental but will also include the modeling of the observed phenomena.

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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Flowing suspensions

Suspensions made of colloidal particles dispersed in a liquid are ubiquitous in a wide range of applications including cosmetics (toothpaste), foodstuff (coffee), construction materials (paints) or even in biological (blood), and geophysical fluids (muds). Those complex materials exhibit a variety of rheological behaviours limiting their ability to flow and deform under solicitation. In particular, at higher volume fraction, dense suspensions exhibit shear-thickening behaviour [1-3], i.e., a rapid and reversible increase of viscosity under shear (Figure 1a). By using a transparent suspension [3] (Figure 1b), we will describe and rationalize the flowing conditions of this ambiguous regime between solid and liquid states. The project will aim to quantify flows of shear-thickening suspensions using PIV techniques in various geometries. The expected results will contribute to solve practical questions such as industrial or geophysical complex flows, or even the puzzling run of a person over a bath filled with a shear-thickening fluid (Figure 1c).

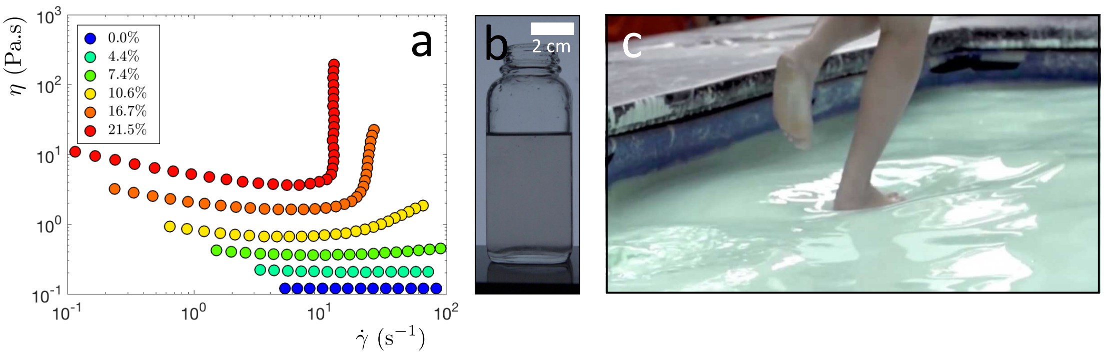

Figure 1: Shear-thickening suspensions. **a)** Flow curves $\eta(\dot{\gamma})$ of a suspension of fumed silica particles. At large volume fraction ϕ, the viscosity η increases (green to orange data) or even diverges (red) with the shear-rate $\dot{\gamma}$. **b)** Transparent shear-thickening suspension made of fumed silica [3]. **c)** While a walking person sinks into a liquid-like pool filled by a dense suspension, a faster solicitation transforms the shear-thickening fluid into a solid allowing a person to run on it.

References:
[1] J. J. Stickel and R. L. Powell, Fluid mechanics and rheology of dense suspensions, *Annual Review of Fluid Mechanics* 37 (2005).
[2] J. F. Morris, Shear thickening of concentrated suspensions: recent developments and relation to other phenomena. *Annual Review of Fluid Mechanics* 52 (2020).
[3] **P. Bourrianne**, V. Niggel, G. Polly, T. Divoux and G. H. McKinley, Tuning the shear thickening of suspensions through surface roughness and physico-chemical interactions. *Physical Review Research* 4(3) (2022).

The applicant should have interests in fluid mechanics and soft matter.
Possibility to apply for PhD position.

Experimental study on sailing aerodynamics performance

Gauthier Bertrand[1], *Marc Fermigier*[1], *Ramiro Godoy-Diana*[1] and *Benjamin Thiria*[1]

[1]Laboratoire Physique et Mécanique des Milieux Hétérogènes, ESPCI-PSL,
7 Quai Saint-Bernard, Campus Jussieu, 75005 Paris

Master internship proposal

The competitive practice of sailing and windsurfing is developing. This can be attributed to the desire to break speed records and to improve the performance of sailing boats. Thus, the development of new platforms with hydrofoils capable of generating lift is replacing the use of the so-called "classic" windsurf, which relies solely on buoyancy. These innovations include the new "iQFoil" class of windsurfing (windfoil) (Figure 1.a), which will be used in the next Olympic Games.

Figure 1: *Left (a): Aerodynamic measurements of an iQfoil's sail in a wind tunnel. Right (b): Chronophotography from top-left to bottom-right of a windsurfer during one oscillation period of a pumping phase.*

The hull is no longer in contact with the water and the resistance from the waves is eliminated, increasing speed. At the start of a race or in light winds, to get or keep the board in foiling mode, athletes use intermittent propulsion by pumping the sail, i.e. periodically changing the angle of incidence of the sail relative to the wind [1] (Figure 1.b). This pumping strategy was also widely used in the previous Olympic windsurfing class, the RS-X. Due to the flexibility of the rig (mast and sail), this is a complex fluid-structure interaction problem.

The internship will consist in studying the unsteady forces generated by an oscillating sail [2] and analysing the flying shape and then the deformation of a sail using photogrammetry. To characterise this, we will test 1/10 scale models in the laboratory's open aerodynamic tunnel with a wind wall.

This work includes part of the scaling analysis of the model to take into account the stiffness of a full scale sail. Moreover, some experiments in wind tunnels with full-scale sails or with French Olympic team might take place during the training, at the IAT Saint-Cyr l'Ecole (CNAM).

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Expected skills: The applicant has a taste for model experiments (manufacturing, electrical and python/matlab skills). Analysis will be performed essentially using scaling arguments.

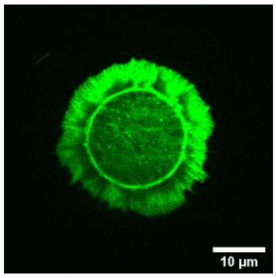
References:

[1] Anderson, J.M., Streitlien, K., Barrett, D.S., Triantafyllou, M.S., Oscillating foils of high propulsive efficiency, *J. Fluid Mech* 360, 41–72, 1998.

[2] Young J.D., Morris S.E., Schutt R.R., Williamson C.H.K., Effect of hybrid-heave motions on the propulsive performance of an oscillating airfoil, *J. Fluid Struct* 89, 203–218, 2019.

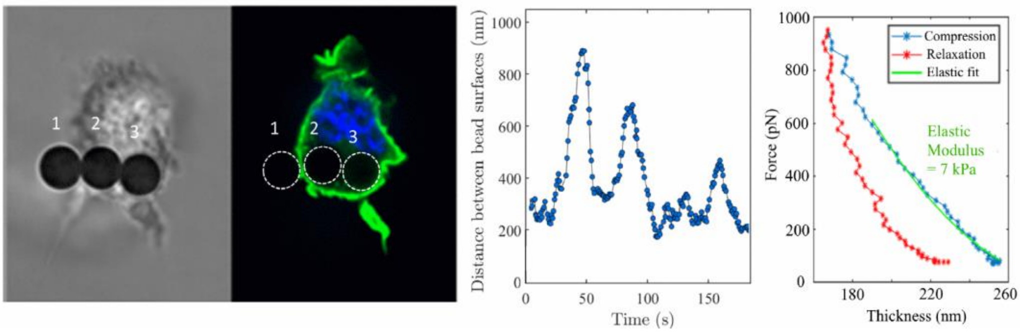
[3] Deparday J., Experimental studies of Fluid-Structure Interaction on Downwind sails. PhD thesis, Université de Bretagne Occidentale/IRENav, 2.3 51-64, 2016.

Mechanics and dynamics of the actin cell cortex



The actin cytoskeleton is a key player for mammalian cells mechanics and migration, as well as in the control of their shape. Of particular interest is the actin cortex (see image on the right), a dense thin layer of actin filaments and myosin motors associated to the plasma membrane. Animal cell's mechanics is believed to be largely prescribed by the properties of the cortex, but its precise contribution and the dependence on its rapid renewal and its active contraction is not fully understood.

We recently developed a new technique, the "cell pincher", to directly probe the mechanics and dynamics of cell cortex using two mutually attracted magnetic microbeads. Our results revealed for the first time that actin cortex thickness in live cells present myosin II-dependent fluctuations around an average value of a couple of hundred nanometers. These fluctuations are very large with amplitude comparable to the average cortex thickness (Laplaud et al Science Advances 2021). The same technique allows quantifying elastic and viscous properties by imposing transient forces on the cortex through the beads and measuring the resulting deformations.



Our setups combine the cell-pincher with control of the adhesion state on micro-patterns, quantitative spinning disk microscopy, and a nano-indenter to measure whole-cell mechanics. Cell biology expertise is assured by a close collaboration with the group of Matthieu Piel in Institut Curie.

This context makes possible to determine the evolution of the thickness, the active fluctuations and the viscoelastic properties of the cortex when the cell undergoes changes in its morphology to enable different functions. These functions includes migration, where the cell's front and back acquire different properties, during adhesion, when the part in contact with the substrate is different from its apex, or during cell cycle, where the cell rounds before mitosis. Additionally, measuring independently the viscoelastic properties of the cortex and of the whole cell will help determine how the first dictates the second.

We are looking for curious and enthusiastic candidates with a physical or biophysical background to join the team and tackle these ambitious questions. Prior experience with microscopy experiments, data analysis, cell culture and cell mechanics is a plus but is not required. The experiments will mostly take place in PMMH which is currently located in Campus Pierre et Marie Curie in central Paris.

Olivia du Roure et Julien Heuvingh - PMMH – ESPCI Paris, 7 quai St Bernard –case courrier 18 - 75005 Paris, France
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Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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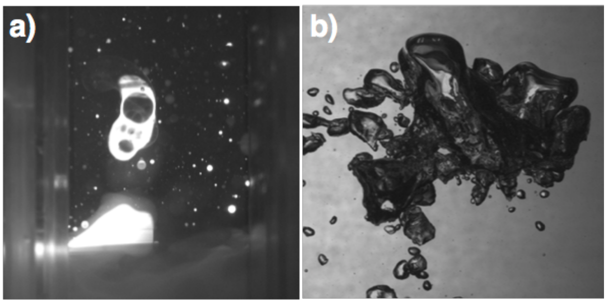
PhD opportunity : yes
Internship location: Laboratoire PMMH

Drop & bubble production in turbulent flows

Liquid and gas fragmentation by turbulent flows are of prime interest in numerous natural situations, such as gas transfer between the atmosphere and the ocean through wave breaking (in particular CO2 absorption by oceans), and industrial applications such as biphasic mixing processes (bubbling, mixers). However, associated fragmentation processes that lead to the production of small bubbles and drops are still poorly understood, even though the small satellites dominate mass and heat exchanges between the two phases.

During this internship, we will operate a model experiment, being built in the laboratory, that uses two liquids of different viscosity to study fragmentation processes in a closed tank stirred by rotating helices. The two liquids will be matched in refractive index so that we get a clear optical access within the tank, and high speed imaging can be conducted to reconstruct the interfacial dynamics in the volume, either in two or three dimensions of space. This set up will produce unique dataset on fragmentation dynamics in turbulent flows. We will aim at identifying the fragmentation processes at play from data analysis, and develop geometrical tools to describe the drop shapes, their statistics and their dynamics. The main control parameters will be the viscosity ratio of the two liquids, and the Weber number, which compares inertia and surface tension forces. Weber number will be tuned using the rotation rate of the helices. This work will be done in collaboration with Valentin Mouet, Phd Student at ENS performing experiments on turbulent two phase flows, and Aliénor Rivière, PhD student at PMMH performing direct numerical simulation of turbulent two phase flows.



Turbulent fragmentation processes *a) Liquid - liquid fragmentation, visualized using a couple of index matched liquids, a vertical laser sheet and fluorescent marker in one phase. b) Bubble fragmentation in turbulence, vizualized using backlight scattering.*

Expected skills: The project is primarily experimental, with some modelling (interfacial dynamics, turbulence statistics).

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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Internship location: ESPCI, between C3M (rue Vauquelin) & PMMH (Jussieu), 75005 Paris

Cracks propagation in colloidal gels

Many ubiquitous materials are prone to failure upon drying as seen in mud cracks or craquelures in ancient paintings (Figure 1a) [1-2]. The nucleation and propagation of cracks is a complex process at the crossroads between the physico-chemistry of solvent evaporation and transport through porous media, the structural evolution of out-of-equilibrium colloidal systems, and the associated formation, propagation and relaxation of internal mechanical stresses. The project will aim to observe and characterize experimentally the cracks formation and propagation within a model soft colloidal gel of controlled mechanical properties in a 2D cell. Using Small Angle Light Scattering (SALS) techniques, we will first measure the dynamical evolution of the colloidal structure of the gel upon failure to identify precursors of the fracture (Figure 1b) [3]. Furthermore, we will image the propagation of cracks within gels of various softness (Figure 1c). The expected results will contribute to a better understanding of cracks nucleation and propagation within soft materials.

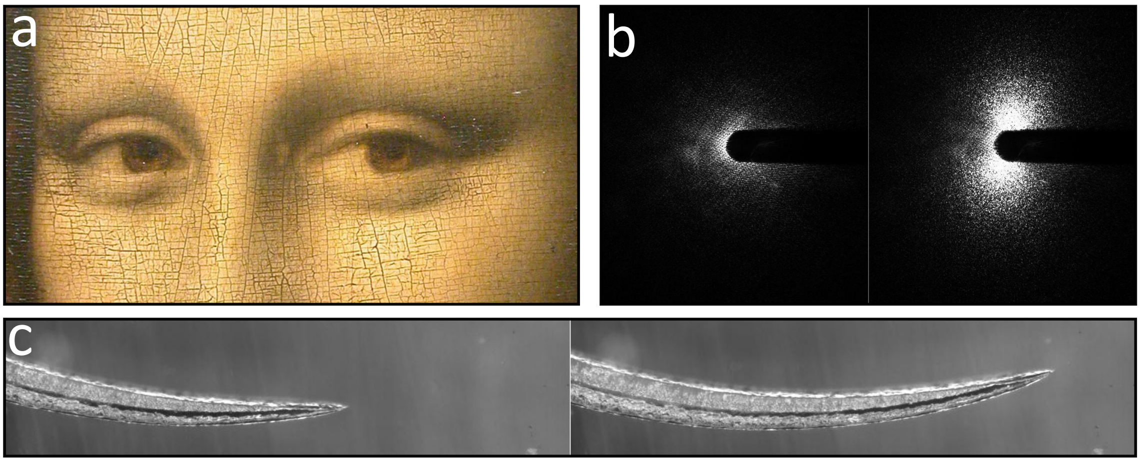

Figure 1: Cracks formation and propagation. **a)** Craquelures in ancient paintings add a layer of mystery on iconic gazes. **b)** Structural changes (from left to right) observed in colloidal gel upon drying prior to failure. **c)** Cracks propagation (from left to right) within a soft colloidal gel.

References:

[1] L. Pauchard and F. Giorgiutti-Dauphiné, Craquelures and pictorial matter. *Journal of Cultural Heritage* 46 (2020).
[2] **P. Bourrianne**, P. Lilin, G. Sintès, T. Nîrca, G.H. McKinley and I. Bischofberger. Crack morphologies in drying suspension drops. *Soft Matter* 17 (2021).
[3] **S. Aime**, L. Ramos and L. Cipelletti. Microscopic dynamics and failure precursors of a gel under mechanical load. *Proceedings of the National Academy of Sciences* 115 (2018).

The applicant should have interests in fluid mechanics and soft matter.
Possibility to apply for PhD position.

Master 2 internship proposal

Physique et Mecanique des Milieux Heterogenes

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Internship location: Barre Cassan A1, campus Jussieu, 7 Quai Saint Bernard, 75005 Paris

3D description of collective motion of *E. coli*

When swimming, bacteria produce a flow leading to hydrodynamic interactions between bacteria and the environment. At high densities of bacteria this hydrodynamic bacteria-bacteria interactions create a hydrodynamic instability that leads to active turbulence. In collective motion we observe correlations in the swimming orientation than can be 1000 times bigger than bacteria [1]. Using E.-coli bacteria we have observed that collective motion is suppressed by the presence of surfaces. This induces asymmetries that can lead to spatially heterogeneous collective motion in 3D. The intern will use advanced techniques such as confocal microscopy or 2 color channel microscopy via a beamsplittler to characterize this observation further. Analyzing the acquired images using tracking algorithms and PIV techniques we plan measuring simultaneously the liquid flow field and the bacteria velocity field and comparing the results with current active turbulence theories [2]. The internship project will take place in close collaboratoin with the PhD student Benjamin Perez.

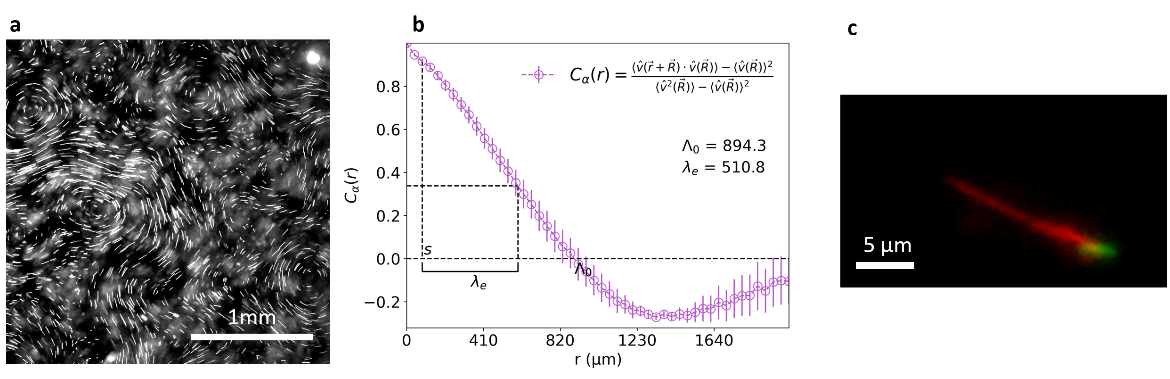

Figure : ***Collective motion of E. coli****. a) Image stack of* 0.5 *seconds to show the trajectories of bacteria that are undergoing collective motion. The scale bar corresponds to* 200 *μm b) Spatial correlation function of the swimming orientation of bacteria. The correlation function decays to 0 after* 380 *μm, meanwhile bacteria are only* 3 *μm long. c) Example of experiments using a beamsplitter to capture two different signals. In this case the flagella and the cell body. The intern will measure the movement of passive particles and bacteria using this technique.*

References

[1] Martinez, Vincent A., et al. "A combined rheometry and imaging study of viscosity reduction in bacterial suspensions." Proceedings of the National Academy of Sciences 117.5 (2020): 2326-2331.
[2] Theillard, Maxime, Roberto Alonso-Matilla, and David Saintillan. "Geometric control of active collective motion." Soft Matter 13.2 (2017): 363-375.

Expected skills: This experimental project does not require any a priori knowledge in microbiology.

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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Internship location: barre Cassan A, campus Jussieu, 7 Quai Saint Bernard, 75005 Paris

Micro-algae swimming under confinement

Eukaryotic micro-swimmers, such as micro-algae, often propel themselves using flagella that allow them to move in a breaststroke-like motion. In natural environments, e.g. in the soil or in an aquatic foam, their motion is however confined between boundaries, which consist in liquid-solid or liquid-air interfaces [1]. In this internship, we will explore the change in the swimming behaviour of the biflagellated microalgae *Chlamydomonas reinhardtii* from a 3D swimming to a motion in a confined controlled environment. The 3D swimming is usually described as an alternance of ballistic trajectories and random reorientations leading to a diffusive exploration of the space at long times. Using a Lagrangian 3D trajectory tracking technique that has been developed in the PMMH laboratory to track fluorescent objects such as colloids or bacteria over very long timescales [2, 3], we will investigate in detail the trajectory of microswimmers in confined environments, i.e. in a cuvette with a controlable thickness. By measuring observables such as the swimmer instantaneous velocity and long-time diffusion coefficient, we aim to evidence the characteristic length under which the swimmer is confined. We will also be able to analyse the swimming behaviour close to the surface and away from the surface. The original setup will allow to test different boundary conditions. This experimental internship will involve setting up protocols for observing the micro-organism's 3D trajectory, and following it in order to analyse its trajectories. The internship may be continued as a thesis. Although a great deal of emphasis will be placed on experiments, there will also be opportunities for rationalization of results and modelling.

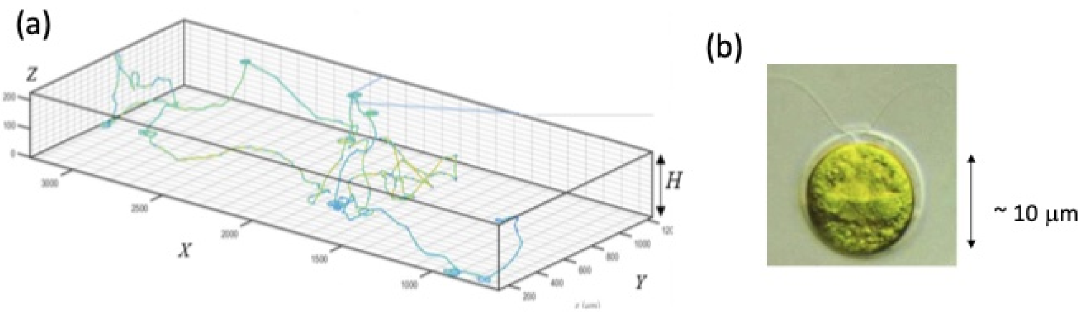

Figure : (a) 3D trajectory of a bacteria confined between two parallel plates, and measured using the PMMH 3D Lagrangian microscope. From [3]. (b) Unicellular eukaryotic bi-flagellated alga Chlamydomonas reinhardtii.

References

[1] Q. Roveillo, J. Dervaux, Y. Wang, F. Rouyer, D. Zanchi, L. Seuront and F. Elias, Trapping of swimming microalgae in foam, J. R. Soc. Interface, 117: 20200077 (2020).
[2] T. Darnige, N. Figueroa-Morales, P. Bohec, A. Lindner and E. Clément, Lagrangian 3D tracking of fluorescent microscopic objects in motion, Review of Scientific Instruments, 88, 055106 (2017).
[3] R. Baillou, M. Pedrosa Garcõa-Moreno, Q. Guigue, S. Meinier, T. Darnige, G. Junot, F. Peruani and E. Clément, Exploring space under confinement: a quantitative view on bacteria contamination, preprint.

Internship and/or PhD PROPOSAL

Laboratory name: **PMMH (Physique et Mécanique des Milieux Hétérogènes), ESPCI**
CNRS identification code: UMR 7636 CNRS/ESPCI
PhD director'surname: Evelyne KOLB
External collaborations with M.B BOGEAT-TRIBOULOT (UMR SILVA, INRAE Nancy), E. COUTURIER (MSC, Univ. Paris Cité), L. DUPUY (NEIKER Institute, Bilbao, Spain)
e-mail: evelyne.kolb@sorbonne-universite.fr Phone number: 00-33-1-40-79-58-04
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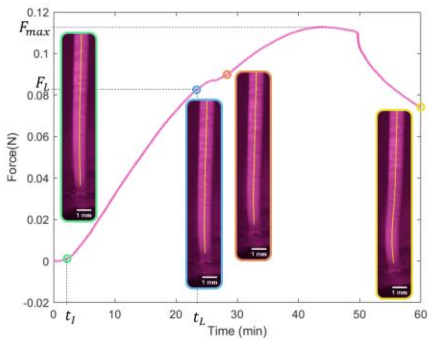
Biomechanical responses of plant root growth to mechanical stresses

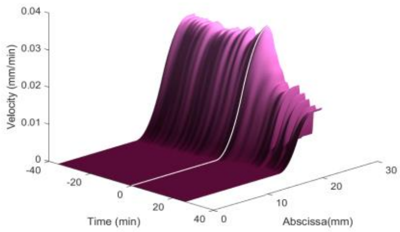
The interaction between plant roots and soils is a wide and interdisciplinary issue involving many communities from biophysics, agronomy, soil science to civil engineering and geophysics. The presence of zones of high mechanical resistance in the soil is one of the most common physical limitations to soil exploration by roots, which has direct impacts on yield crops. The root growth and trajectory highly depend on the presence of strong soil layers or obstacles at the root scale. The root apex must exert a growth pressure to overcome the resistance to deformation of the surrounding soil or reorient its growth to skirt around obstacles.

In the PMMH laboratory, we developped model experimental systems to study how the root changes its growth when encountering a single or a collection of obstacles mimicking the mechanical heterogeneities in a soil. In particular we investigated the growth response of a root (i) pushing against a single obstacle such as a force sensor or (ii) growing inside a 3D-printed array of stiff obstacles. For instance, by coupling force (Fig. i1) and kinematic measurements under infra-red lighting (Fig. i2), we probed the force-growth relationship of a primary root contacting a stiff resisting obstacle, that mimics the strongest soil impedance variation encountered by a growing root.

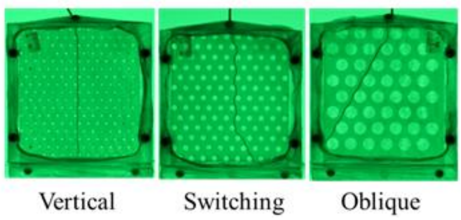
Different subjects are possible around the interaction of roots with mechanical obstacles.
One possible topic is 1) to investigate the response of the root to prescribed indentation steps to study its time-dependant mechanical properties and 2) to decouple the mechanical and biological responses by using a feedback loop on the applied force on the root. Another topic is 3) to use microfluidic systems to build arrays of granular substrates of soft hydrogel to vary the stiffness of obstacles encountered by roots and investigating the biomechanical parameters explaining the root trajectories in mechanically heterogeneous soils.



(i1) Evolution of the axial force exerted by a growing root pushing against a force sensor (acting as an obstacle) and visualization under infra-red lighting of the root texture.



(i2) Local growth velocity along the root length (obtained from a PIV-derived technique of the root texture) at different times, before and after contact (indicated by the white line).



(ii) Maize root growing in arrays of 3D-printed cylinders embedded inside an agarose gel. The root's diameter is around 1 mm.

Kolb, Hartmann, Genet *Plant Soil* (2012) 360, 19-35
Kolb, Legué, Bogeat-Triboulot, *Phys. Biol.* (2017) **14** 065004
Martins et al., *New Phytologist* (2020) 225: 2356–2367
Quiros et al., *Journal of the Royal Society Interface* (2022) **19** 0266

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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Internship location: barre Cassan A, campus Jussieu, 7 Quai Saint Bernard, 75005 Paris

Dispersion of bacteria in a real rock-structure porous medium

Diverse processes—e.g. bioremediation, biofertilization, and microbial drug delivery—rely on bacterial migration in disordered, three-dimensional (3D) porous media under flow[1]. The dispersion of motile bacteria in such a complex environment with the existence of the mixing effect of flow and geometrical constraints is still not well understood.
The aim of this project is to investigate and quantify the transport properties of E.coli (flagellate bacteria, run and tumble) in real rock-structure porous medium environments under various flow velocities. Swimming behaviour in quiescent flows could be a first step to study and compare with the following cases at different flow velocities. To investigate the motion of E.coli in 3D under various flow conditions, a Lagrangian tracking system developed in the laboratory by Darnige et al.[2] is a powerful tool for obtaining bacterial displacement in real-time. A simpler model experiment including straight channels of different heights could also precede this study for understanding the bacteria dispersion process.
During this internship, you will also learn microfluidic experimental skills: design the PDMS porous microfluidic device and set up a microfluidic system with a controlled flow field. Besides, the micron-PIV measurement can also be used to have a further understanding of the flow field inside the porous medium.
(This work is in collaboration with IFPEN (3D rock-structure geometry) and ICP, Stuttgart University (simulation).)

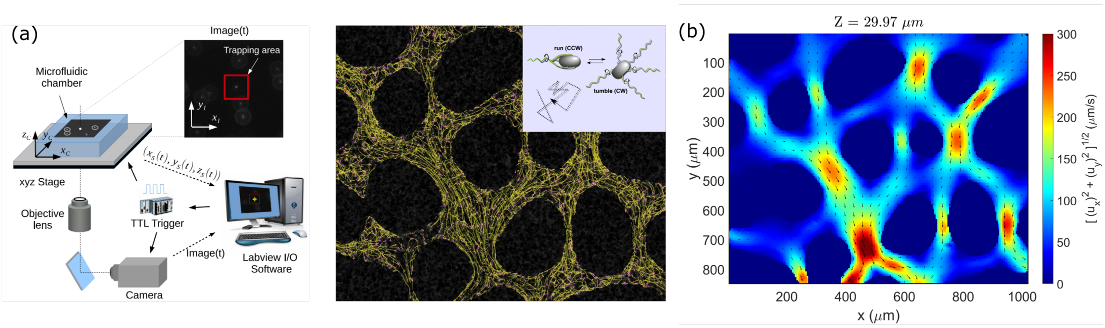

Figure: Experimental setup. (a) (Left) The 3D-Lagrangian tracking system[2]. (Right) The local trajectories of E.coli transporting inside the porous medium under flow. The subfigure describes the "run and tumble" bacteria. (b) The flow field of the porous medium from $\mu - PIV$ measurement.

References

[1] C. Adama, E. Clément, C. Douarche, M.V. D'angelo, and H. Auradou. Phys. Rev. Fluids. 4, 013102 (2019)
[2] T. Darnige, N. Figueroa-Morales, P. Bohec, A. Lindner, and E. Clément. Rev. Sci. Instrum. 88, 5 (2017)

Expected skills: The applicant should have an interest in physics (active matter); prior knowledge of the Matlab software/Python would be appreciated.

Control of Water Waves Using Time-Varying Metamaterials Experimental Study

***Magdalini Koukouraki*[1], *Philippe Petitjeans*[1], *Vincent Pagneux*[2], and *Agnès Maurel*[3]**

[1]*Laboratoire Physique et Mécanique des Milieux Hétérogènes (PMMH)*
[2]*Laboratoire d'Acoustique de l'Université du Mans (LAUM)*
[3]*Institut Langevin*

Time-varying metamaterials is a rapidly growing research field which provides the perfect playground for controlling wave propagation. We look to harness and control water waves by using some artificial structures, referred to as metamaterials, which are often small compared to the wavelength. These materials are carefully designed so that they can modify the propagation properties of the waves and enable us to explore various wave dynamics such as deflection, transmission, absorption or even cloaking of the wave in different situations.

For this internship we propose an experimental study of wave deflection. A submerged periodic plate array, depicted in Figure 1a), is used as a metamaterial inside a water tank in order to create an anisotropic medium seen by the propagating surface wave. In addition, the experimental setup is equipped with a mechanism allowing for the plates to be moved vertically through the fluid bottom, so that the topography is also varying in time. An abrupt switch from a constant depth to a structured topography is shown in Figure 1b). By changing the water depth everywhere in space at a given time using this type of metamaterial, the water wave velocity is modified in time. As a result, when the medium is switched from isotropic (homogeneous depth) to anisotropic (different effective depth in the x and y direction), one can deflect the wave. The goal of the internship is to experimentally observe the deflection of the wave and measure the reflection and transmission of the wave after its transition to the new medium. Optical measurement techniques will be used during the internship, including high resolution lasers, which measure the surface elevation at one point, and Fourier Transform Profilometry, a technique which provides the two-dimensional surface profile.

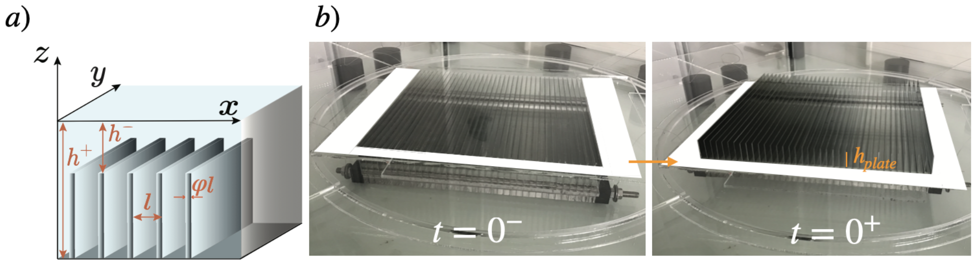

Figure 1: a)Representation of the plate array at the fluid depth. b)Fluid bottom inside the water tank before and after lifting the plate array.

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Sujet M2 ou stage fin d'étude ingénieur

Ondes sismiques et hydro-acoustiques émises par les glissements sous-marins à l'échelle du laboratoire pour la détection et l'évaluation des aléas associés

Contexte

Les glissements de terrain et potentiels tsunamis générés représentent un des risques naturels majeurs. Leur détection et leur simulation restent actuellement un problème ouvert et rendu extrêmement difficile par le peu de données de terrain sur la dynamique de ces écoulements, données pourtant nécessaires pour valider les modèles développés. Dans ce contexte, les ondes sismiques et hydro-acoustiques générées par les glissements de terrain sous-marins représentent un outil d'étude unique, transportant de précieuses informations sur les caractéristiques de l'écoulement (masse, vitesse, comportement mécanique, etc.) à des distances pouvant aller jusqu'à des centaines de km de la source [1,2]. Par contre, l'analyse de ces ondes est très difficile à réaliser car d'une part les mécanismes de génération sont complexes et d'autre part, elles sont fortement impactées par leur propagation.

Dans ce cadre, les expériences de laboratoire fournissent un opportunité sans équivalent pour étudier les processus de manière simplifiée, en séparant les effets comme la présence ou non d'eau, la topographie, les conditions initiales, etc. L'Institut Langevin, l'IPGP et l'EOST se sont associés, notamment dans le cadre de l'ERC SLIDEQUAKES, pour étudier la génération d'ondes élastiques lors d'écoulements granulaires secs (Figure 1). Les travaux réalisés sur des écoulements granulaires secs ont clairement mis en évidence des signatures spectrales, temporelles qui ont été validées par des approches numériques et interprétées à l'aide de modèles analytiques [3,4,5], faisant intervenir différents paramètres comme la température granulaire, la densité, le profil de vitesse, etc. Ces mesures de laboratoire ont été combinées à des simulations aux Eléments discrets permettant d'avoir accès à des variables internes non mesurables en laboratoire. Les résultats obtenus ont permis de clarifier l'origine physique des lois empiriques observées à l'échelle du terrain et de proposer de nouvelles façons d'interpréter les ondes sismiques en termes de caractéristiques de l'écoulement [3].

Nous proposons ici de changer de paradigme en étudiant **l'émission acoustique lors d'écoulements granulaires mais cette fois immergés.** Dès le début des années 2000, les travaux sur les avalanches granulaires [8] ont permis d'identifier trois régimes d'écoulement limites. Cependant, hormis une seule étude préliminaire réalisée en 2012 [9], l'émission acoustique associée à ces écoulements reste **un sujet très largement inexploré à l'interface entre la physique des granulaires et de l'acoustique physique**. Ces travaux sont d'autant plus importants qu'ils sont **des analogues des glissements de terrain sous-marins** pour lesquels il n'existe que très peu de données mais qui peuvent générer des tsunamis potentiellement dévastateurs [6].

Utiliser les ondes émises par ces glissements de terrain pour les détecter et contraindre leur comportement serait une **avancée exceptionnelle pour l'évaluation des risques associés**. L'exploitation des ondes hydro-acoustiques dans ce but est en effet quasi-inexistante bien que ces ondes se propagent très loin, portant notamment la signature de la vitesse du glissement de terrain [2].

Sujet de stage

Les phénomènes physiques impliqués aussi bien dans la dynamique de l'écoulement granulaire dans l'eau que dans la génération d'ondes élastiques et hydro-acoustiques sont complexes. C'est pourquoi le point de départ de cette thèse consistera en des expériences « modèles » à l'échelle du laboratoire de manière à pouvoir contrôler l'environnement et à pouvoir varier les conditions initiales

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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Internship location: Laboratoire PMMH, Jussieu campus
This internship can be followed by a thesis.

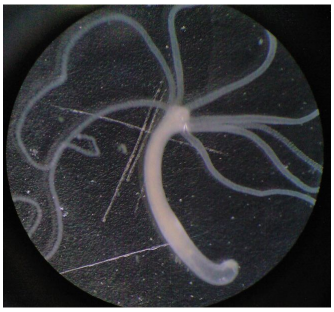
Pattern formation during Hydra regeneration

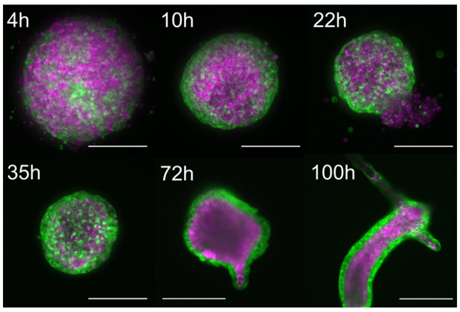
Chemical instabilities such as the Turing instability [1] have had a profound impact on our understanding and definition of self-organization. They are fascinating examples of how non-linear interactions of several components can lead to order at a higher level. Chemical instabilities have naturally been proposed to explain the morphogenesis of living organisms through a chemical patterning driven by the diffusion and reaction of morphogens [2].

Hydra vulgaris is a freshwater polyp famous for its regenerative capacities, as virtually any tissue piece amputated from an adult Hydra or even re-aggregated cells can regenerate into a viable organism and do so through a *de novo* axis definition.

Remarkably, spherically-shaped regenerating *Hydra* pieces undergo several osmotically-driven oscillations [3] before a Turing-like instability determines the position of the future head of the organism as the local maximum of a morphogen's concentration.

Based on known observational and biochemical data [3,4], the intern will formulate and analyse a reaction-diffusion model on an oscillating sphere, able to recapitulate the first symmetry-breaking of *Hydra* during the process of its regeneration.

a. 

b. 

***Hydra*: a.** Image of an adult organism (Courtesy Wikipedia). **b.** Timelapse images of *Hydra* regeneration from an aggregate of cells. At 35 h, the sample has a spherical shape whose symmetry is broken by 72 h. Scale: 200 μm up to 72h, 500 μm at 100 h. (Courtesy O. Cochet-Escartin).

References

[1] Turing, A. M., 1952. *Phil. Trans. R. Soc. B* **237**:37-72.
[2] Schweisguth, F., and F. Corson, 2019. *Developmental Cell* **49**:659-677
[3] Kücken, M., *et al.*, 2008. *Biophysical Journal* **95**:978-985.
[4] Vogg, M. C., *et al.*, 2019. *Nature Communications* **10** 312

Expected skills: The project requires both analytical and computational skills, at the interface between theoretical biophysics and pattern formation.

Master 2 internship proposal

Laboratoire de Physique et Mécanique des Milieux Hétérogènes

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Internship location: barre Cassan A, campus Jussieu, 7 Quai Saint Bernard, 75005 Paris

Wise and Efficient Sampling of Plasticity using Atomistic Simulations

Do you seek to push the boundaries of what is currently achievable in the field of materials science? If so, we invite you to join our dynamic research team for an immersive and intellectually rewarding internship experience.

Project Overview: Our internship project addresses two fundamental challenges in the modeling of material plasticity. Firstly, the limited accessible time scales, far shorter than those of experiments, and secondly, the intricate complexity of deformation processes. We propose an innovative approach to overcome these hurdles by implementing an automatic saddle point search method, guided by the elementary mechanisms of plasticity. This method systematically explores reaction paths at the atomic scale, enabling a comprehensive understanding of plastic deformation. Our focus will be on two distinct systems: Nucleation of Dislocations in Crystals and Plastic Rearrangements in Glasses.
By tackling these diverse simulation challenges in both crystalline and amorphous materials, this methodology promises to usher in a scientific breakthrough, profoundly impacting our ability to model the mechanical properties of real-world materials, which are inherently complex and heterogeneous.

Project Objectives:
1. Advanced Sampling Techniques: Develop and implement advanced sampling techniques based on automated saddle point searches, allowing us to capture critical atomic-scale plasticity events.
2. Dual-System Investigation: Conduct comprehensive simulations on both crystalline and amorphous materials to broaden our understanding of plasticity mechanisms.
3. Scientific Advancement: Contribute to a paradigm shift in the field of materials science by unlocking new insights into the mechanics of complex materials.

Feel free to reach out to us with any questions or expressions of interest. Informal contacts are welcome.

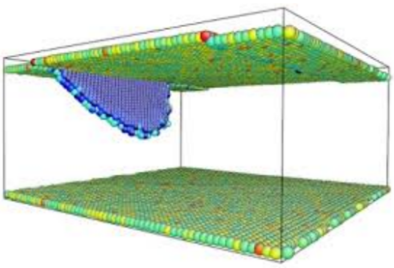

Figure: Elementary plastic events: (Left) Nucleation of a dislocation [2]. (Right) Plastic rearrangement in a glass [3]

References

[1] S. Patinet, D. Vandembroucq and M.L. Falk, Phys. Rev. Lett. 117, 045501 (2016)
[2] P. Hirel, J. Godet, S. Brochard, L. Pizzagalli and P. Beauchamp, PRB 78, 64109 (2008)
[3] A. Tanguy, F. Leonforte and J. L. Barrat, Eur. Phys. J. E, 20, 355 (2006)

Expected skills: The applicant should have interest in physics and numerical modelling. Possibility of continuing with a thesis after the internship.

Master 2 internship proposal

Physique et Mécanique des Milieux Hétérogènes

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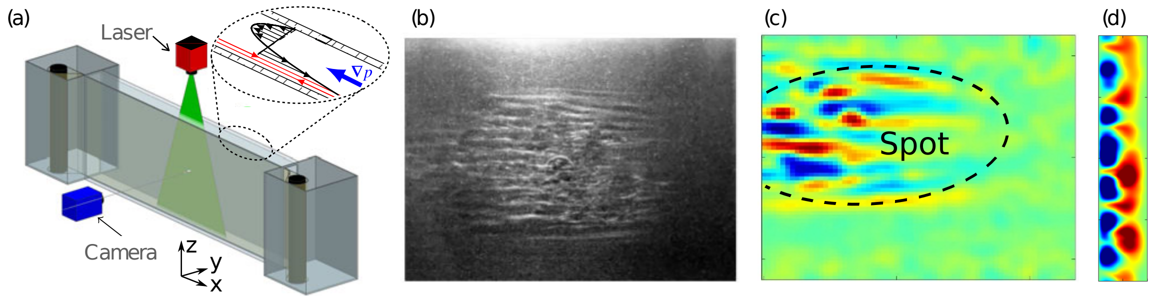
Internship location: Jussieu Campus, 7 Quai Saint Bernard, 75005 Paris, France.

Thesis possibility after internship: yes

Experiments on the transition to turbulence in Couette-Poiseuille flows

The transition to turbulence in wall-bounded shear flows is subcritical, which determines the existence of a transition regime where laminar and turbulent regions can coexist. In this regime, active turbulence is localized in turbulent spots (see figure) that can be considered as the elementary 'building blocks' of the turbulent flow. The velocity field of these spots is partly composed of random fluctuations, but it also contains coherent structures (called *rolls* and *streaks*), which are key to sustain the turbulence. The global objective of this project is to determine the interaction between the coherent structures.

We have recently setup a unique experiment to study these turbulent spots [1, 2], which consists of a Couette-Poiseuille channel connected to two reservoirs. The velocity field is measured using stereo-PIV. This existing setup will be the starting point of the internship. We have measured the structures in the plane parallel to the walls (xz), which does not allow to measure the rolls entirely. The goal of this internship is to investigate quantitatively the rolls and their interactions with the other structures in a plane normal to the walls (yz). These measurements are challenging because y is the small dimension, and have never been performed before. A recent result of numerical simulation is shown in panel (d). We aim at measuring experimentaly similar structures in presence of different noise levels.



(a) Couette-Poiseuille experiment at PMMH. (b) Flow visualisation, and (c) horizontal velocity field measured using PIV of a turbulent spot in a plane parallel to the moving wall (xz). The PIV field shows that the dark and bright streaks in the flow visualization are actually regions of faster (red) and slower (blue) horizontal velocity. (d) Numerical simulation showing a cross section of the stream-wise velocity field in the channel (yz-plane) [courtesy of S. Gomé].

References

[1] T. Liu , B. Semin, L. Klotz, R. Godoy-Diana, J. E. Wesfreid and T. Mullin (2021). Decay of streaks and rolls in plane Couette-Poiseuille flow, *J. Fluid Mech.*, **915**, A65.
[2] T. Liu , B. Semin, R. Godoy-Diana, J. E. Wesfreid. Lift-up and streak waviness drive the self-sustained process in wall-bounded transition to turbulence (submitted) `https://arxiv.org/abs/2308.16792`

Expected skills: knowledge in fluid mechanics, appetite for experimental work

Master 2 internship proposal

Physique et Mecanique des Milieux Heterogenes

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Internship location: Barre Cassan A1, campus Jussieu, 7 Quai Saint Bernard, 75005 Paris

3D description of collective motion of *E. coli*

When swimming, bacteria produce a flow leading to hydrodynamic interactions between bacteria and the environment. At high densities of bacteria this hydrodynamic bacteria-bacteria interactions create a hydrodynamic instability that leads to active turbulence. In collective motion we observe correlations in the swimming orientation than can be 1000 times bigger than bacteria [1]. Using E.-coli bacteria we have observed that collective motion is suppressed by the presence of surfaces. This induces asymmetries that can lead to spatially heterogeneous collective motion in 3D. The intern will use advanced techniques such as confocal microscopy or 2 color channel microscopy via a beamsplittler to characterize this observation further. Analyzing the acquired images using tracking algorithms and PIV techniques we plan measuring simultaneously the liquid flow field and the bacteria velocity field and comparing the results with current active turbulence theories [2]. The internship project will take place in close collaboratoin with the PhD student Benjamin Perez.

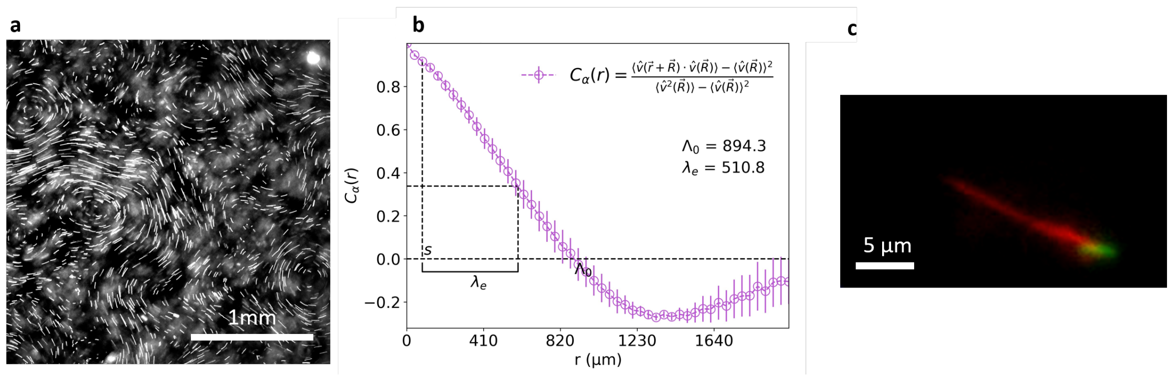

*Figure : **Collective motion of E. coli**. a) Image stack of 0.5 seconds to show the trajectories of bacteria that are undergoing collective motion. The scale bar corresponds to 200 μm b) Spatial correlation function of the swimming orientation of bacteria. The correlation function decays to 0 after 380 μm, meanwhile bacteria are only 3 μm long. c) Example of experiments using a beamsplitter to capture two different signals. In this case the flagella and the cell body. The intern will measure the movement of passive particles and bacteria using this technique.*

References

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[2] Theillard, Maxime, Roberto Alonso-Matilla, and David Saintillan. "Geometric control of active collective motion." Soft Matter 13.2 (2017): 363-375.

Expected skills: This experimental project does not require any a priori knowledge in microbiology.