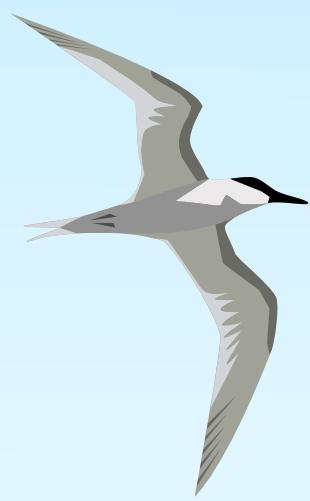


FLUID & ELASTICITY

17 - 19 JUNE 2024
ARCACHON



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ARCACHON

Welcome to Fluid & Elasticity 2024

On behalf of the organizing committee, it is our pleasure to welcome you in Arcachon for the fifth edition of the Fluid & Elasticity conference. We do hope that you will enjoy intense and stimulating discussions as well as an unforgettable stay in Arcachon.

Fluid & Elasticity 2024

17-19 June 2024, Arcachon, France

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Practical Information

Venue - The conference will take place at the second floor of the *Palais des Congrès d'Arcachon* (6 Boulevard Veyrier Montagnères - 33120 Arcachon, Tel.: +33 (0)5 56 22 47 00) on the beachfront, in the seaside resort of Arcachon. Participants will be accommodated in hotels located only a short walk away from the conference center.

How to get there - The city of Arcachon is serviced by a direct train line from Bordeaux (Bordeaux Saint-Jean train station) that runs every hour (one way ticket 12.20 €). Train tickets from Bordeaux to Arcachon can be purchased online. However, whether you land in Paris (Roissy-Charles de Gaulle international airport) or directly in Bordeaux (Bordeaux-Mérignac airport), you will have to get to Bordeaux Saint-Jean train station first.

From Paris to Bordeaux Saint-Jean train station (if you land at Roissy-Charles de Gaulle international airport) - There is a direct train line from Roissy-Charles de Gaulle international airport (TGV train station) to Bordeaux Saint-Jean train station. (duration 3h45, from 120 €). Train tickets can be purchased on the SNCF website (<https://www.sncf-connect.com/app/home/search>).

Bordeaux/Mérignac airport to Bordeaux Saint-Jean train station (if you land directly at Bordeaux-Mérignac airport) - There are three ways to reach the Bordeaux Saint-Jean train station from Bordeaux/Mérignac airport.

- **By tramway (55 mn):** the tram station Aéroport Mérignac (tram line A) is located in front of the arrivals area (Hall B). Tram tickets (1.70 €) can be purchased online (<https://boutique.infotbm.com>) or at the ticket vending machines available at the airport tram station. From the airport, the tram line A does not go directly to the train station; take tram line C to the Saint-Jean train station at the connecting tram station *Porte de Bourgogne* (details of the tram journey from Bordeaux Mérignac Airport to Bordeaux Saint-Jean train station available at <https://www.infotbm.com>).
- **By direct bus shuttle (30 mn):** a direct shuttle (bus stop located in front of the arrivals area, Hall B, Bordeaux/Mérignac airport) connects the airport to the train station (8 €) every 30 to 60 mn, depending on the date and time. Tickets can be purchased on-board or online (<https://www.bordeaux.aeroport.fr/acces-transports/navette-directe-aeroport-gare>) ; time schedule can be consulted by following the link <https://30direct.com/horaires/>.
- **By regular bus (1h10):** the bus station Aéroport Mérignac (bus line 39) is located 1 mn walk from the arrivals area (Hall B). Bus tickets (1.70 €) can be purchased online (<https://boutique.infotbm.com/products/1>), at the tram vending machines or in the bus. From the airport, the bus line 39 does not go directly to the train station; take bus line 11 to the Bordeaux Saint-Jean train station at the connecting bus station *Dassault* (details of the bus journey from Bordeaux/Mérignac Airport to Bordeaux Saint-Jean train station available at <https://www.infotbm.com>).

- **By taxi (30 mn):** from the airport, taxi services to the train station are available. Fares can fluctuate from 50 to 150 €, depending on the date and time.

■ **Hotels** - The participants will be accommodated in two hotels located very close to the Palais des Congrès (and very close to each other as well) :

- **Hôtel de la plage (Arcanse),** 10 Av. Nelly Deganne, 33120 Arcachon, Tel.: +33 (0)5 56 83 06 23, e-mail: infos@hotelarcachon.com.
- **Hôtel B d'Arcachon,** 4 rue du Professeur Jolyet, 33120 Arcachon, Tel.: +33 (0)5 56 83 99 91, e-mail: reservations@hotel-b-arcachon.com.

Participants will be notified of their hotel and room number by email one week before the conference. The room keys will be collected at the reception desk of the hotel upon arrival on Sunday afternoon/evening.

■ **Registration on site** - Registration will take place at the entrance hall of the Palais des Congrès (26 Blvd Veyrier Montagnères - 33120 ARCACHON) and will start on Monday 17 of June, 8:00 am (NB: there will be a standby service at the entrance of the Palais des Congrès between 4:30 pm to 7:00 pm on Sunday 16). A nominative badge, a paper version of the scientific programme and a USB key containing a full electronic version of the booklet (including abstracts), will be issued to the participants upon registration.

■ **Lunches** - Lunches will take place in two different restaurants on Monday and Tuesday. On Monday 17 (12:30), lunch will be served at:

Le Café de la Plage – Restaurant chez Pierre,
1 Boulevard Veyrier Montagnères,
33120 Arcachon
Tel.: +33 (0)6 85 53 54 64.

On Tuesday 18 (12:30), lunch will be served at:

Le Grang Café Victoria,
26 Boulevard Veyrier Montagnères,
33120 Arcachon
Tel.: +33 (0)6 85 53 54 64

Both restaurants are located close to the Palais des congrès (see Map 1, p.11). Participants will be free to enjoy the beach till 15:30 everyday.

■ **Evening reception** - The evening reception will take place on Tuesday 18 at 8:00 pm in the restaurant *Les Terrasses du Port*, 2 km from the Palais des Congrès (25 mn walk, see Map 2, p.12):

Les Terrasses du Port,
Quai Goslar, Pôle Nautisme (1st floor),
33120 Arcachon
Tel.: +33 (0)5 40 25 03 84

■ **Eat & drink** - There are many restaurants in Arcachon, most of them being located on the bay beach (*la Plage du Bassin*), just a stone throw from the hotels. You will find a wide choice of restaurant, ranging from pizzerias to sea food restaurants. Here are some good places you can try:

- Pizza Nofa Arcachon, 25 Boulevard du Général Leclerc, Tel.: +33 (0)6 99 20 00 33
- La Cabane du Breton (crêpes & galettes, vegan options), 4 Rue Maréchal de Lattre de Tassigny, Tel.: +33 (0)6 37 13 69 51.
- La Saison 3 (sea food), 21 Rue du Maréchal de Lattre de Tassigny, Tel.: +33 (0)5 56 83 24 05.
- Le Bistro'chon Arcachon (cuisine française), 29 Rue du Maréchal de Lattre de Tassigny, Tel.: +33 (0)5 56 83 08 44
- Ko-Sometsuke 2K (fusion asian food), 156 Boulevard de la Plage, Tel.: +33 (0)5 56 83 67 69.

■ Visiting the surroundings

Sailing to the Cap Ferret - It is worth spending an evening in the Cap-Ferret, a small town located at the end of a peninsula, on the other side of the bay. There, you will be able to visit the old town and enjoy oysters, a glass of white wine, or tapas on a terrace right by the sea. To go to the Cap Ferret, you will have to sail on a “pinasse”, a typical boat of the Arcachon bay. Tickets may be booked in advance (recommended) on the website of the “Union des bateliers Arcachonnais” (<https://bateliers-arcachon.com/welcome/>) or directly purchased on the Thiers pier (return ticket: 20 €)

Sailing to “L’Île aux Oiseaux” - L’Île aux Oiseaux (Birds’ Island) can be visited in a thousand different ways. The most common, however, is the guided tour by boat. Many service providers offer tickets to get to l’Île aux Oiseaux. Again, tickets can be purchased on the website of the “Union des bateliers Arcachonnais” or directly on the Thiers pier (single tour without stopover, 2 h, 24 €; single tour with a stopover at the Cap Ferret, 2 h, 31 €).

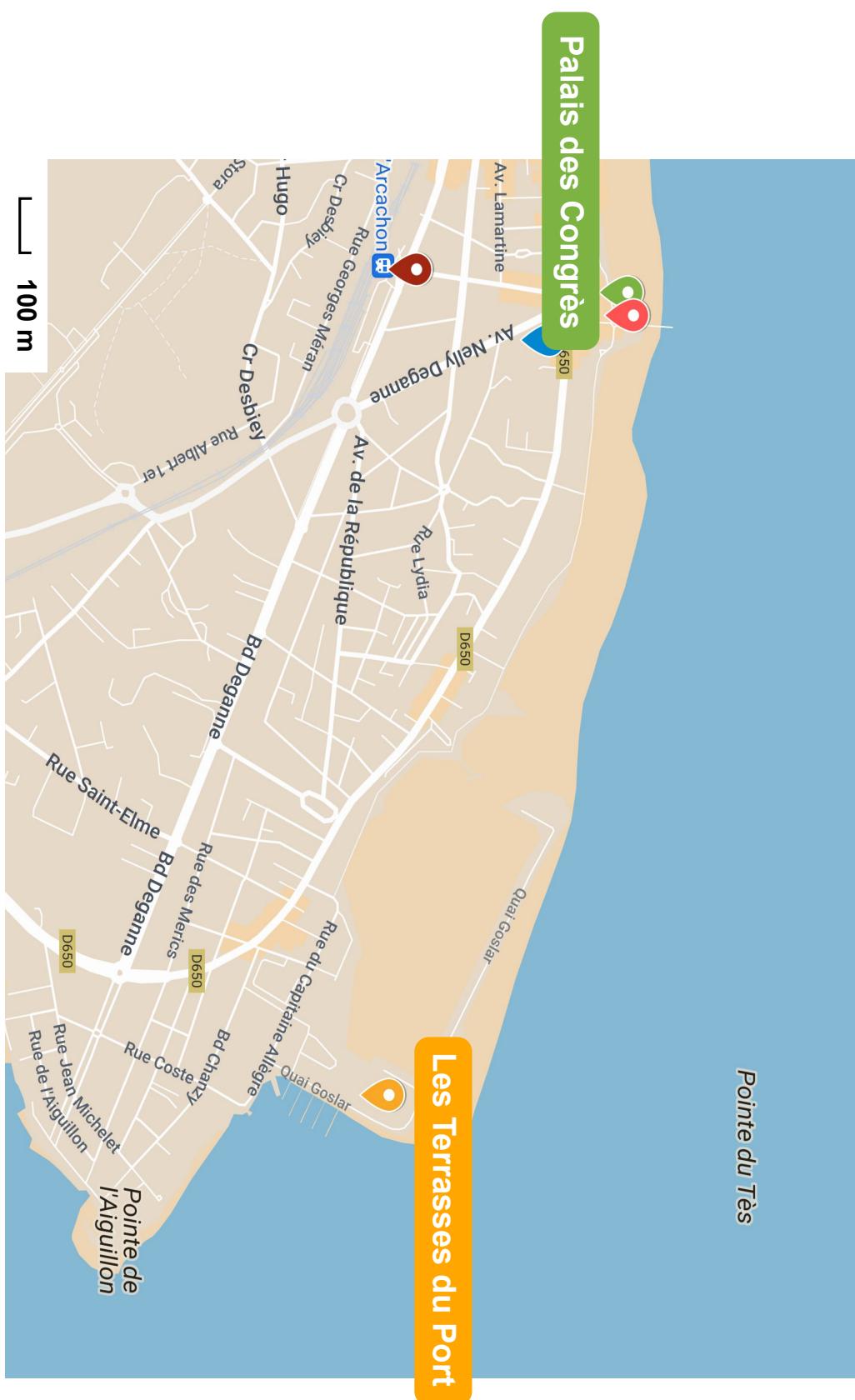
Going to the Oceanside and the Dune du Pilat - The Palais des Congrès and the hotels are located in front of the bay, but the other side of the town (a neighbourhood named Le Mouleau) faces the Cap-Ferret. If you push a bit further south, you will reach the highest sand dune in Europe - the Dune du Pilat - and eventually the Ocean beaches (plage de la Salie etc). You can get easily to both places by means of the local bus lines (ligne 3 and ligne 101, 1.70 €, bus schedules at <https://www.bassin-arcachon-info.com/dune-du-pilat-arcachon-baia1/>, tickets can be bought from the driver or at <https://www.bus-baia.fr/titres-et-tarifs.html>).

Maps



Map 1 - Main area. Access to the Palais des Congrès and to the hotels from the train station. Monday and Tuesday lunches will take place in two different restaurants : **Le Café de la Plage** (Monday) and **Le Grand Café Victoria** (Tuesday).

Map 2 - The Tuesday evening reception will take place at Les Terrasses du Port. The restaurant is located on the sea front, 2 km (25 mn walk) far from the Palais des Congrès (East dir.).



Scientific programme

NB - The last column of the programme table ('p. . .') refers to the electronic version of the booklet available on the USB Key.

Monday, June 17

8:00–9:00	Registration and opening	
9:00–9:45	<u>Invited speaker: Sophie Ramananarivo (Chair: C. Eloy)</u> <i>Harnessing kirigami technique for tunable deformation and forces in flows</i>	p.18
9:45–10:45	Session 1: Plants and flows (Chair: C. Eloy)	
9:45–10:00	Dominic Vella <i>Coupling turgor pressure and elastic deformation : two examples from plants</i>	p.19
10:00–10:15	Sungwhan Jung <i>Coherent vortices shed from an elastic leaf</i>	p.20
10:15–10:30	Frederick P. Gosselin <i>Soft coral vibrations, modelling and water-tunnel experiments</i>	p.21
10:30–10:45	Bastian Löhner <i>Investigation of the flow over a canopy consisting of highly flexible blades</i>	p.22
10:45–11:15	Coffee break	
11:15–12:30	Session 2: Swimming & flying at high Re (Chair: M. Polin)	
11:15–11:30	Ramiro Godoy-Diana <i>Waves in the wake of a surface swimming snake</i>	p.23
11:30–11:45	Éric Ibarra <i>Transport and deformation of flexible discs in homogeneous isotropic turbulence</i>	p.24
11:45–12:00	Thomas Barois <i>An aerodynamic trap : contactless manipulation of heavy objects by turbulent jets</i>	p.25
12:00–12:15	Médéric Argentina <i>Optimum control strategies for maximum thrust production in underwater undulatory swimming</i>	p.26
12:15–12:30	Lucas Gey <i>Fiber aggregation in flows</i>	p.27
12:30–13:30	Lunch	
13:30–15:30	Free Time	
15:30–16:15	<u>Invited speaker: Marco Polin (Chair: T. Bickel)</u> <i>Eukaryotic flagellar synchronisation from mechanics to hydrodynamics</i>	p.28
16:15–16:45	Short 3 mn talks (Chair: T. Bickel)	
	Luc Zorrilla <i>Inferring viscoelastic properties of eukaryotic flagella or</i>	p.29

<i>solving an inverse problem</i>	
Anaëlle Givaudan	p.30
<i>Roof formation in a bio-active fluid</i>	
Julien Bouvard	p.31
<i>Controlling the transport of passive beads in a suspension of phototactic microalgae</i>	
Alexander Chamolly	p.32
<i>Viscoelastic Rheology of Early Avian Embryos</i>	
Étienne Loiseau	p.33
<i>Understanding mucus transport in airways by using a reconstituted human bronchial epithelium</i>	
Simon Hadjaje	p.34
<i>How insects expand their wings</i>	
Mathieu Rivière	p.35
<i>Fast movements of Mimosa pudica: an osmotic muscle?</i>	
Ludovic Jami	p.36
<i>Embolism spreading in real & synthetic leaves</i>	
Lukas Hauer	p.37
<i>Membrane shapes, liquid-liquid interfaces, and elastocapillarity</i>	
Isabell Noichl	p.38
<i>Wall-bounded sedimentation of particles with elastohydrodynamic interaction at $Re_P \lesssim 0.1$</i>	

16:45–17:15 Coffee break and posters

Session 3: Elasticity-Capillarity coupling (Chair: M. Gomez)	
Ambre Bouillant	p.39
<i>Dew formation on soft substrate</i>	
Gwynn Elfring	p.40
<i>Capillarity nonuniform flexible channels</i>	
Jiayu Wang	p.41
<i>Elasto-capillary wrinkling in thin liquid-infused membranes</i>	
Aurélie Hourlier-Fargette	p.42
<i>Foams and soft intruders : exploiting elastocapillarity towards novel foam structures</i>	
Henri Lhuissier	p.43
<i>Jet Solidification</i>	
Vincent Bertin	p.44
<i>Sticking without contact : elastohydrodynamic adhesion</i>	

Tuesday, June 18

Invited speaker: Pierre-Thomas Brun (Chair: E. Lauga)	p.45
<i>Building with liquids: a lazy approach to fabrication</i>	
Session 4: Elastic filaments (Chair: E. Lauga)	
Raphaël Jeanneret	p.46
<i>Droplet and buckling instabilities in active fluid jets</i>	
Ehud Yariv	p.47
<i>Shape of a highly-compliant tethered filament in a uniform Hele-Shaw flows</i>	
Blaise Delmotte	p.48
<i>Dynamics of flexible fibers in structured environments</i>	
Marc Durand	p.49
<i>Deflection and oscillations of an anchored elastic fiber in a quasistatic foam flow</i>	

10:45–11:15	Coffee break	
11:15–12:30	Session 5: Colloidal systems (Chair: P. Meunier)	
11:15–11:30	Thomas Powers <i>Mechanics of colloidal membranes</i>	p.50
11:30–11:45	Emilie Verneuil <i>Particle-laden drops flowing through a pore</i>	p.51
11:45–12:00	Gabriel Amselem <i>Hydrogel beads flowing and clogging microchannels</i>	p.52
12:00–12:15	Diego Baresch <i>Active microrheology of soft materials using acoustical tweezers</i>	p.53
12:15–12:30	Andréa Feasson <i>Hydro-elasto-capillary interactions for programmable microfluidics</i>	p.54
12:30–13:30	Lunch	
13:30–16:00	Free time	
15:30–16:15	Invited speaker: Anne-Laure Biance (Chair: F. Nadal)	p.55
	<i>Droplet impact on deformable hydrophobic textures</i>	
16:15–16:45	Short 3 mn talks (Chair: F. Nadal)	
	Rodolfo Brandao Macena Lira <i>Sedimentation of elastic filaments</i>	p.56
	Karim Ayoubi <i>Settling of a Flexible Ribbon in a Viscous Fluid</i>	p.57
	Katie Wu <i>Dynamics of the transition to a coalesced equilibrium of elastic fibers withdrawn from a liquid bath</i>	p.58
	Manon L'Estimé <i>Elastocapillary drying of flexible fibres suspensions</i>	p.59
	Étienne Jambon-Puillet <i>Fluid flow in hairy channels</i>	p.60
	Alexander Gehrke <i>Unsteady forces and flows behind a poro-elastic membrane disk</i>	p.61
	Stéphane Poulain <i>Elastohydrodynamic of adhesion and translation of vibrating flexible foils near surfaces</i>	p.62
	Rishabh Nain <i>Tunable drag drop in origami</i>	p.63
	Lila Séguy <i>Deformation of hydrogels during freezing</i>	p.64
	Chandler Thomas <i>Fluid-body interactions in elastic anisotropic fluids</i>	p.65
16:45–17:15	Coffee break and posters	
17:15–18:45	Session 6: Swimming of microorganisms (Chair: S. Ramananarivo)	
17:15–17:30	Hélène de Maleprade <i>Light control of bioconvective dynamics</i>	p.66
17:30–17:45	Céline Cohen <i>Swimming of plant pathogens zoospores</i>	p.67
17:45–18:00	Michael Gomez <i>Twist dynamics of bacteria flagella</i>	p.68
18:00–18:15	Albane Thery <i>Bacterial upstream swimming is enhanced in non newtonian fluids</i>	p.69

18:15–18:30	Saverio Spagnolie <i>Self-buckling and self-writhing of semi-flexible microorganisms</i>	p.70
18:30–18:45	John Lister <i>The dynamics of elastic coupling in a two-link swimmer</i>	p.71

Wednesday, June 19

9:00–9:45	Invited speaker: Alain Goriely (Chair: S. Michelin) <i>The geometry and mechanics of chirality, hard and soft</i>	p.72
9:45–10:45	Session 7: Biological flows (Chair: S. Michelin)	
9:45–10:00	Ranabir Dey <i>Soft makes it hard to swim: Dynamics of self-propelled swimmers in soft micro-confinements</i>	p.73
10:00–10:15	Martin Brandebourger <i>Transport induced by nonlinear flow response in vessels with flexible leaflets</i>	p.74
10:15–10:30	Francesco Picella <i>Symmetry breaking through confinement in biological fluids</i>	p.75
10:30–10:45	Annie Viallat <i>Exploring the link between the spatial organisation of ciliated cells and the supported physiological function in Xenopus embryo</i>	p.76
10:45–11:15	Coffee break	
11:15–12:30	Session 8 : Fluid-structure instabilities (Chair: A. Goriely)	
11:15–11:30	Finn Box <i>Flow-induced choking of soft channels</i>	p.77
11:30–11:45	Patrice Meunier <i>Fluid-structure interaction of a cylinder in a stratified fluid</i>	p.78
11:45–12:00	Maryam Boukor <i>Instability Limitation of Drag Reduction by Elastic Reconfiguration</i>	p.79
12:00–12:15	Mazi Jalaal <i>Elasto-Visco-Plastocapillarity</i>	p.80
12:15–12:30	François Gallaire <i>Buoyant porous thin disks fall straighter than solid disks</i>	p.81
12:30	Closing speech	

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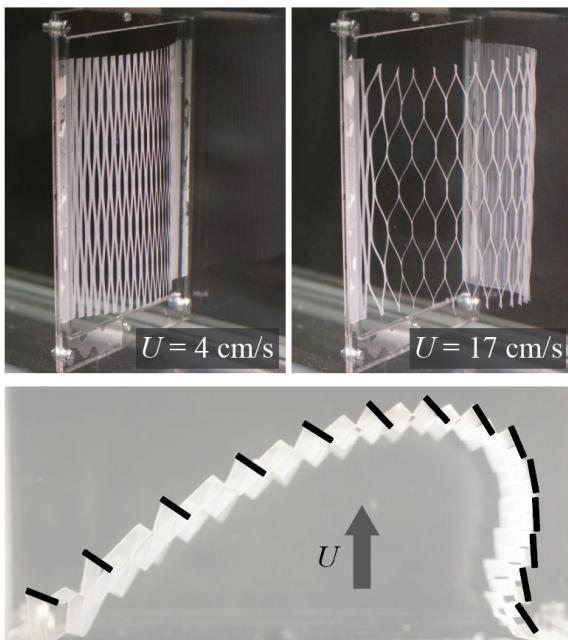
Abstracts

Harnessing kirigami technique for tunable deformation and forces in flows

S. Ramananarivo¹

¹ *LadHyX, CNRS, École Polytechnique de Paris, 91128, Palaiseau Cedex, France*

Engineering increasingly relies on flexible components for designing systems operating in a flow. Their flexibility enables them to passively adapt their shape to better withstand fluctuating fluid environments, enhance aerodynamic performance, or fulfill a function, such as that of a flexible valve, without requiring additional actuation mechanisms. However, the way the structure deforms is key to fulfilling its function, requiring control mechanisms. Here, we explore an approach to designing adaptive structures under flow, using surfaces with a network of cuts. This technique, called kirigami, provides a rich platform for designing reconfigurable systems, with kinematic and mechanical properties prescribed by the arrangement of cuts. We show that the interaction of the small-scale porous structure with the flow modulate local fluid forces, thus conditioning deformation at the macroscopic scale. We notably show that a sheet with a symmetric cutting pattern can produce asymmetric deformation and study the underlying fluid-structure couplings to further program shape morphing through the arrangement of cuts. We also demonstrate that kirigami sheets can exhibit deformation and drag with directional flow dependency.



Kirigami sheet under flow conditions.

Coupling turgor pressure and elastic deformation: two examples from plants

Dominic Vella¹, Arezki Boudaoud², Finn Box³, Thomas G. J. Chandler^{1,4},
Alain Goriely¹, Perla Maiolino⁵, Derek Moulton¹ and Chris Thorogood⁶

¹ Mathematical Institute, University of Oxford, Woodstock Rd, Oxford OX2 6GG, United Kingdom

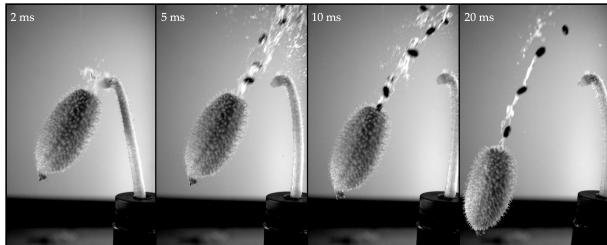
² LadHyX, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, 91128, Palaiseau Cedex, France

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Snapshots of the seed ejection in the squirting cucumber, *Ecballium elaterium*.

seem likely to be more relevant in plant cells. We develop models for monolayer plant cell sheets, inspired by shape changes in mosses as humidity changes. We show that geometrical, rather than mechanical asymmetries are most likely to be important for the observed shape change.

We also study how rapid turgor-driven motion occurs in the ‘squirting cucumber’, *Ecballium elaterium*, which disperses its seeds in a rapid jet (see figure). We develop a model coupling the change in fluid flow to elastic deformation of the cucumber fruit — this predicts changes in the ejection velocity as seed dispersal progresses, which we suggest has evolutionary advantages for seed dispersal.

Water pressure, or turgor, has long been known to be behind the rigidity of plant cells, as well as driving the motion of plants¹. However, the precise mechanical basis of the larger scale rigidity inferred by turgor remain somewhat puzzling: a pressurized vessel needs an up-down asymmetry for a rigidity to bending to emerge. While such asymmetry can emerge from wrinkling² other sources

¹J. Dumais & Y. Forterre, *Annu. Rev. Fluid Mech.* **44**, 453–478 (2012).

²L. Qiu, J. W. Hutchinson & A. Amir, *Phys. Rev. Lett.* **128**, 058101 (2022).

Coherent vortices shed from an elastic leaf

Zixuan Wu¹, Saikat Basu², Seungho Kim³, Mark Sorrells⁴, Francisco J. Beron-Vera⁵, & Sunghwan Jung⁶

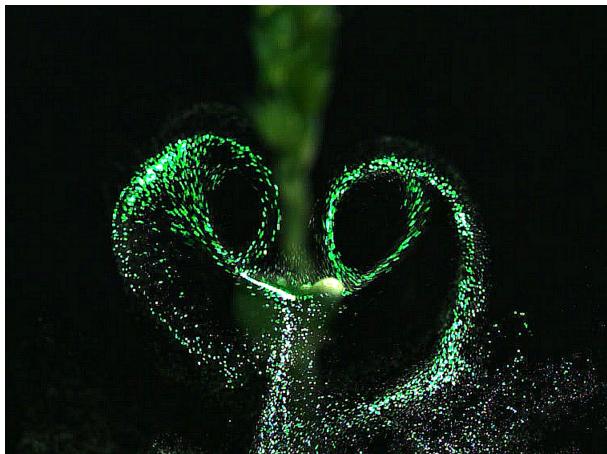
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² Department of Mechanical Engineering, South Dakota State University, SD 57007, USA.

³ School of Mechanical Engineering, Pusan National University, Busan 46241, South Korea.

⁴ School of Integrative Plant Science, Cornell University, NY 14853, USA.

⁵ Department of Atmospheric Sciences, University of Miami, FL 33124, USA.



Vortices shed from a vibrating plant leaf.

rately predicted the linear relationship between drop velocity, leaf properties, and edge vortex strength. Employing Lagrangian diagnostics, we revealed hyperbolic and elliptic coherent structures surrounding fluttering profiles, providing a dynamic framework for understanding local spore dispersion ¹

The dispersal of plant pathogens, including rust spores, accounts for over 20% of annual global yield losses. However, the mechanisms governing the release of pathogens from flexible plant surfaces into the canopy remain poorly understood. In this study, we explored intricate fluid-structure interactions between leaf elasticity and raindrop momentum, uncovering how flexible leaf structures create a super-diffusive flow stream. This flow stream features embedded coherent structures that significantly enhance the transport of pathogens. We developed a comprehensive theoretical model that accu-

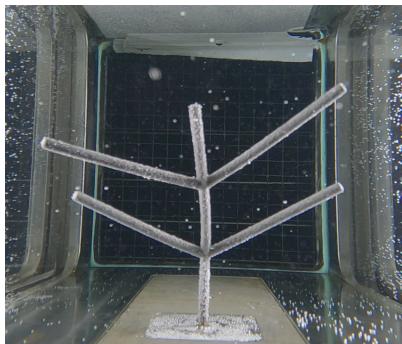
¹Wu, Z., Basu, S., Kim, S., Sorrells, M., Beron-Vera, F.J. and Jung, S., *Coherent spore dispersion via drop-leaf interaction*. Science Advances, **10**(5), p.eadj8092 (2024).

Soft coral vibrations, modelling and water-tunnel experiments

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F.P. Gosselin¹

¹ Département de génie mécanique, Polytechnique Montréal, Montréal, QC, Canada

² Facultad de Ingeniería, Universidad de la República, Montevideo, Uruguay



Synthetic idealised 3D printed soft coral in water tunnel.

Soft corals sway with the low-frequency swell of surface waves, and vibrate at a high frequency due to vortex-induced vibrations. It is hypothesized that these high-frequency vibrations allow the soft-coral colony to intercept more food particles and thus improve its feeding [1]. In this conference talk, we look at the effect of ramification on the dynamics of a structure undergoing vortex-induced vibration.

We present couple a co-rotational beam finite element formulation with a wake-oscillator model and an empirical drag formulation [2]. This workflow allows simulating the low frequency, large amplitude sway of the branched structure and its high frequency response to vortex-induced vibrations.

To validate these simulations, we perform water tunnel experiments on 3D-printed idealized coral colony structures. Simulations and experiments are performed for ramified structures with different numbers of branches, and for incrementing reduced velocity. Whereas a cantilevered beam exhibits well-defined and spaced-out lock-in ranges where the frequencies of vibration and of vortex shedding coalesce, a ramified structure with more and more branches exhibits a more and more continuous lock-in over increasing reduced velocity. A ramified structure with many branches possesses natural frequencies close to one another. There is thus always a natural frequency close to the frequency of vortex shedding.

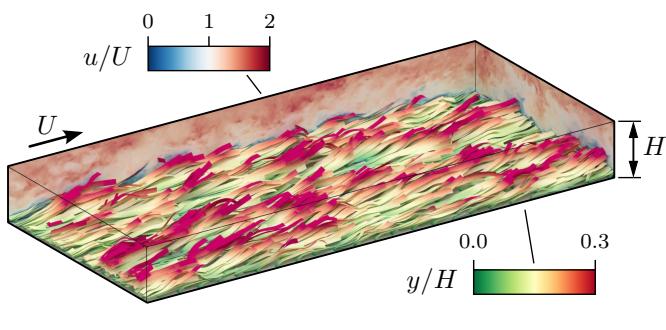
Flexibility allows the coral colony to lower the drag it faces under fluid flow. The vibrational response of the colony allows it to "sweep more water" and encounter more particles. Whereas a beam without branches can maximize this gain in the lock-in region of the second mode, a branched structure smooths out the capture gain over a larger reduced velocity range.

- [1] Boudina, M., Gosselin, F. P., Étienne, S. (2021). Vortex-induced vibrations: A soft coral feeding strategy? *Journal of Fluid Mechanics*, 916, A50.
- [2] Villié, A., Vanzulli, M. C., Zerpa, J. M. P., Vétel, J., Étienne, S., Gosselin, F. P. (2024). Modeling vortex-induced vibrations of branched structures by coupling a 3D-corotational frame finite element formulation with wake-oscillators. *Journal of Fluids and Structures*, 125, 104074.

Investigation of the flow over a canopy consisting of highly flexible blades

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¹ Institute of Fluid Mechanics, Technische Universität Dresden, Germany



Snapshot from a simulation.

In the present contribution, interactions between model vegetation canopies constituted of highly flexible, slender rods, and the surrounding turbulent channel flow are studied. The model vegetation elements are densely placed such that they form a body of low-momentum fluid, interacting with the surrounding flow. The investigation is carried out employing high-fidelity

Large Eddy Simulations, while the blades are modeled as geometrically exact Cosserat rods. Both are coupled via an Immersed Boundary approach¹.

The coupled problem is characterized by a large nominal Cauchy number $Ca \approx 25\,000$ and a bulk-velocity Reynolds number of $Re_H \approx 20\,064$. The roughness density λ , defined as the ratio of the mean frontal area of a structure divided by its share of the bed area, is $\lambda \approx 0.56$, well above the critical value of 0.1, which indicates a dense canopy².

Characteristics of flow and canopy motion are extracted by means of time averages, including Reynolds stresses. Quadrant analyses give access to sweep and ejection events which are linked to low- and high-speed velocity streaks. The canopy envelope is constructed by projecting the Lagrangian information associated with the canopy blades onto a horizontal plane. In this framework, frequency and wavenumber spectra of the canopy envelope are readily computable, and spatial correlations can be determined using the same tools as applied to the fluid data. The fluid-canopy interaction is studied through cross correlations between the two, and by collecting conditional fluid averages associated with certain patterns in the canopy hull.

¹S. Tschigale, J. Fröhlich, *An immersed boundary method for the fluid-structure interaction of slender flexible structures in viscous fluid*, Journal of Computational Physics, **423**, 109 801, 2020

²H. M. Nepf, *Flow and Transport in Regions with Aquatic Vegetation*, Annual Review of Fluid Mechanics, **44**, 123–142, 2012

Waves in the wake of a surface swimming snake

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³ Centre d'Études Biologiques de Chizé, CNRS, Villiers-en-Bois, France



Thamnophis snake swimming in a tank with a checkerboard pattern bottom used to measure the surface waves.

Research on animal surface swimming has mainly focused on small insects or on animals that use limb-surface interactions for propulsion, such as ducks or geckos (see Bush & Hu¹, for a review). For the case of snakes, apart from the pioneering observations of Hertel², no measurements appear to have been made. We report here the results from a surface swimming experiment performed with Natricinae snakes (see figure), where the surface waves produced by the swimming snakes have been quantified by measuring the water surface elevation perturbation. Measurements were performed using a synthetic

Schlieren imaging method³ that gives an instantaneous non-intrusive measurement of the height of the free surface η at every location in space. Using a filtering technique based on the dispersion relation of capillary-gravity waves on the measured wave field we show that, remarkably, a significant percentage of the waves that compose the wake pattern travel in a direction opposite to the swimming direction⁴. A contribution to the propulsive force of the animal from the waves is thus expected, so the surface wave wake of the snake is not solely a drag wake, despite its similarity with the Kelvin wake of a ship or a duck.

¹Bush and Hu, Walking on water: biolocomotion at the interface, *Annu. Rev. Fluid Mech.* **38**, 339 (2006).

²Hertel, *Structure, form, movement* (Reinhold Publishing, 1966) pp. 178–184.

³Wildeman, Real-time quantitative Schlieren imaging by fast Fourier demodulation of a checkered backdrop, *Exp. Fluids* **59**, 97 (2018).

⁴Stin *et al.* Not just drag from the surface wake of a swimming snake (In preparation).

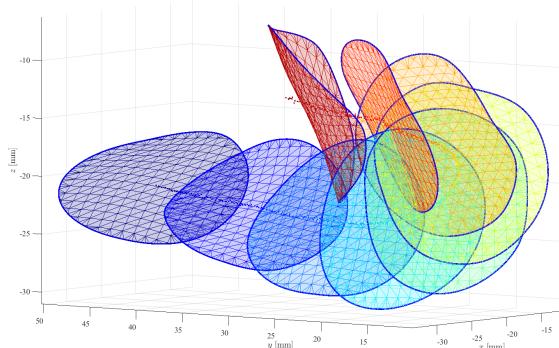
Transport and deformation of flexible discs in homogeneous isotropic turbulence

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Sample reconstructed trajectory

their thicknesses and bending moduli. The 3D shapes of the discs are reconstructed using high-speed recordings from 3 orthogonal views. This information allows for the position of the particles' center of mass to be tracked in time, as well as the evolution of their deformation.

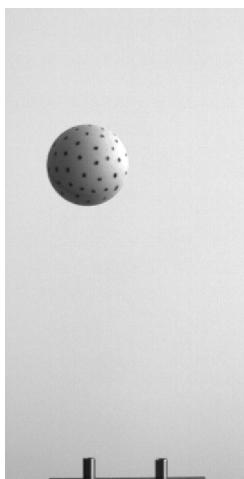
To better understand the dispersion and fragmentation of plastics in marine environments, lab experiments are performed by placing thin flexible silicone discs in homogeneous isotropic turbulence. Experiments are conducted in a cubic water tank, wherein a flow is created by the rotation of 8 impellers located at the vertices. The influence of deformation on the transport of the discs is explored with respect to the turbulent kinetic energy of the flow and the properties of the discs, specifically

An aerodynamic trap : contactless manipulation of heavy objects by turbulent jets

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Ping-pong ball in stable levitation in a two-jet configuration. The air flow comes from the two nozzle visible at the bottom of the image (ball diameter 4 cm).

A sphere can be maintained in stable levitation in air by a vertical turbulent jet. This can be easily demonstrated with a ping-pong ball and a hair dryer. For a range of injected flow rates, the ball finds a distance to the jet nozzle for which the air drag equals the ball weight. The stability of the ball in the horizontal plane is a consequence of the Coandă effect, which manifests by the ball being attracted to the high-velocity regions.

For the levitation in a single turbulent jet, it is already known that the vertical position of the ball is controlled by the injected flow rate. The objective of this work is the vertical and horizontal control of the position of a levitating ball using multiple turbulent jets. In this presentation, I will describe our results on the two-jet configuration. The position of the two jet nozzles is fixed and the control parameters are the flow rates of each individual jets. I will first characterize the trapping position of the ball for equal flow rates in both jets. Then, I will examine the asymmetric flow rates configuration and I will show how it can be used to control the location of the levitating ball. Finally, I will mention the levitation of chiral objects to illustrate the potential interests of aerodynamic traps for fluid-structure interaction problems.

- [1] S. Davoust, and L. Jacquin. The suspension of a sphere in a turbulent jet (2009).
- [2] T. Barois, P. D. Huck, C. Paleo, M. Bourgoin, and R. Volk (2019). Probing fluid torque with a hydrodynamical trap: Rotation of chiral particles levitating in a turbulent jet. Physics of Fluids.
- [3] T. Barois, G. Ricard, V. Champain, L. Gey, and H. Kellay (2020). The levitation of a sphere by two parallel turbulent jets. Physics of Fluids.

Optimum control strategies for maximum thrust production in underwater undulatory swimming

L. Fu¹, S. Israilov², J. Sánchez-Rodríguez³, C. Brouzet², G. Allibert⁴, C Raufaste^{2,5}, M. Argentina²

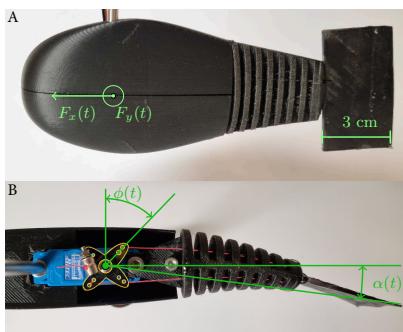
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³ Departamento de Física Fundamental, Universidad Nacional de Educación a Distancia, Madrid, 28040, Spain

⁴ Université Côte d'Azur, I3S, Sophia Antipolis France

⁵ Institut Universitaire de France (IUF), 75005 Paris, France



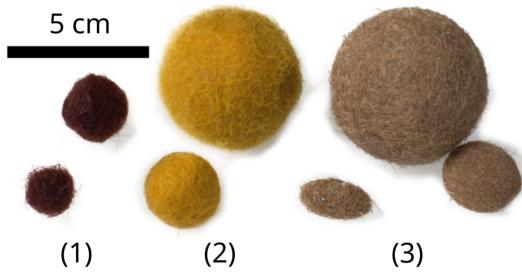
(A) Side view of the robotic fish.
(B) Top view without the top fairing.

Fish, cetaceans and many other aquatic vertebrates undulate their bodies to propel themselves through water. Numerous studies on natural, artificial or analogous swimmers are dedicated to revealing the links between the kinematics of body oscillation and the production of thrust for swimming. One open and difficult question concerns the best kinematics to maximize this force for given constraints and how a system tunes its internal parameters to reach this maximum. To address this challenge, we exploit a biomimetic robotic swimmer to determine the control signal that produces the highest thrust. Using machine learning techniques and intuitive models, we find that this optimal control consists of a square wave function, whose frequency is fixed by the interplay between the internal dynamics of the swimmer and the fluid-structure interaction with the surrounding fluid. We then propose a simple implementation for autonomous robotic swimmers that requires no prior knowledge of systems or equations. This application to aquatic locomotion is validated by 2D numerical simulations.

Fiber aggregation in flows

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*Fiber aggregates. (1) Aggregates of nylon fibers with diameter $d = 75$ m and length $L = 1$ cm
(2) $L = 0.8$ cm. (3) Sea balls found on Marseille seashore.*

Particle aggregation in turbulent flows plays a key role in many phenomena such as cloud formation¹ or enhancement of particle settling in water treatment², ... This has raised several fundamental questions to predict the collision and the growth rate of aggregates within turbulence³. The majority of the previous studies focused on small spherical particles. Motivated by the formation of fiber floc in the paper industry⁴ and the natural tendency of fibers to aggregate⁵, we aim to model the aggregation of fibers within turbulent flows.

In this talk, I will present our experimental work on the aggregation of nylon fibers in turbulent von Kármán flows.

I will discuss the impact of the different parameters on the formation of the aggregates, which can be seen on the figure, such as the turbulence intensity or the mechanical properties of the fibers and their concentration.

Moreover, the cohesion is due to friction between fibers and is then closely related to the spatial organization of fibers. Therefore we characterize the organization of the entangled network of the aggregate thanks to X-ray tomography allowing to track each individual fibers. Finally, as the formation of aggregates is expected to be a dynamical process with a balance between aggregation and fragmentation, we also study the fragmentation of balls by immersing a single aggregate within a turbulent flow to characterize its destruction.

¹Shaw, *Annual Review of Fluid Mechanics* **35**, 2003

²Li et al., *ACS Publications*, 2002

³Pumir et al., *Annual Review of Condensed Matter Physics* **7**, 2015

⁴Lundell et al., *Annual Review of Fluid Mechanics* **43**, 2011

⁵Verhille et al., *Proceedings of the National Academy of Sciences* **114**, 2017

Eukaryotic flagellar synchronisation from mechanics to hydrodynamics

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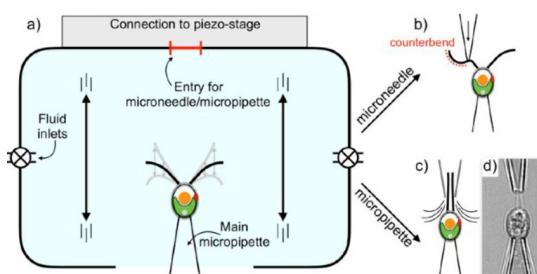
Cilia and flagella are active slender organelles highly conserved across the eukaryotic world and involved in a wide spectrum of different biological activities. When multiple flagella are close to each other, they often display striking degrees of coordination. This coordination arises from intra-flagellar coupling, but where is the coupling coming from ?

Taking ciliated green algae as a paradigmatic example, here I will discuss our current understanding of the importance of both hydrodynamics and direct mechanical coupling in flagellar synchronisation. I will then present the results of new experiments which allow us to selectively block hydrodynamic coupling between the flagella of a single cell and therefore probe directly the role of hydrodynamics in their synchronisation.

Inferring viscoelastic properties of eukaryotic flagella or solving an inverse problem

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¹ IMEDEA - 21 Carrer Miquel Marques, 07190 Esporles, Spain



Schematics of the intended experiment.

Flagella and cilia are ubiquitous organelles in eukaryotic organisms with a highly conserved structure. They perform a variety of functions such as motility and mechano-chemical sensing. To understand the link between structure and function, mechanical properties are an essential puzzle piece¹. In particular, the axoneme (the inner scaffold of flagella) plays a crucial role in the collective motion of flagellar beating. We know that flagella and cilia axonemes exhibit bending resistance in an elastic regime². But so far, most experiments probe static properties only while there could also be internal dissipations during beating³. Other types of elasticity and non-elastic regimes have also been found. We thus designed an experiment that aims to probe the response of eukaryotic flagella of *Chlamydomonas reinhardtii* to a periodic flow as shown in the figure. Amplitude and frequency of the flow, flagellar length - by suction and subsequent regrowth of flagella - and use of mutants are control parameters we aim at using to untangle the link between axoneme structure and viscoelastic properties. On one hand image analysis is used on experimental data to extract flagellar shape over time and flow field, while on the other hand a coarse-grained model is developed including internal viscosity and different kinds of elasticity. We will focus on how to infer viscoelastic parameters by combining experimental data and modelling using a Bayesian Inference method.

Flagella and cilia are ubiquitous organelles in eukaryotic organisms with a highly conserved structure. They perform a variety of functions such as motility and mechano-chemical sensing. To understand the link between structure and function, mechanical properties are an essential puzzle piece¹. In particular, the axoneme (the inner scaffold of flagella) plays a crucial role in the collective motion of flagellar beating. We know that flagella and cilia axonemes exhibit bending resistance in an elastic regime². But so far, most experiments probe static properties only while there could also be internal dissipations during beating³. Other types of elasticity and non-elastic regimes have also been found. We thus designed an experiment that aims to probe the response of eukaryotic flagella of *Chlamydomonas reinhardtii* to a periodic flow as shown in the figure. Amplitude and frequency of the flow, flagellar length - by suction and subsequent regrowth of flagella - and use of mutants are control parameters we aim at using to untangle the link between axoneme structure and viscoelastic properties. On one hand image analysis is used on experimental data to extract flagellar shape over time and flow field, while on the other hand a coarse-grained model is developed including internal viscosity and different kinds of elasticity. We will focus on how to infer viscoelastic parameters by combining experimental data and modelling using a Bayesian Inference method.

¹S. Prosser & L. Pelletier, Nature Reviews Molecular Cell Biology, 18(3):187-201, 2017

²A. Baba, J. Exp. Biol., 56(2):459-467, 1972

³D. Mondal, P. Sharma, Science Advances, 6:33:eabb0503, 2020

Roll formation in a bio-active fluid

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^a Institut Jean le Rond d'Alembert - UMR 7190, Sorbonne Université, 4 place Jussieu, 75005 Paris, France

The unicellular alga Chlamydomonas has two flagella whose beating enables it to swim in a breast stroke. Chlamydomonas is bottom heavy, which reorients its spontaneous swimming to the top. Moreover, like plants, algae get energy from photosynthesis and to assure this behavior, they swim towards light. This natural bioconvection favours the accumulation of a layer of denser cells at the free surface, with subsequently destabilises into sinking plumes ¹.

By studying the effect of light on plume patterns, we observed in addition to the plume migration, the emergence of a periodic structure along the illuminated wall. This behavior highlights the formation of a new hydrodynamic instability in a bio-active fluid. But, what drives this symmetry breaking? Where do these structures come from ? We assume that they follow the rise of a roll at the wall driven by phototactic swimming of the algae.

The experimental set-up is shown on the schematic (Fig. 1 (a)). We vary the light intensity, solution depth and Chlamydomonas concentration. Fig. 1 (b) and (c) show that the wavelength λ does not seem to depend on solution depth contrary to the roll width L . Based on classical hydrodynamic instabilities, we develop a model adapted to this active fluid.

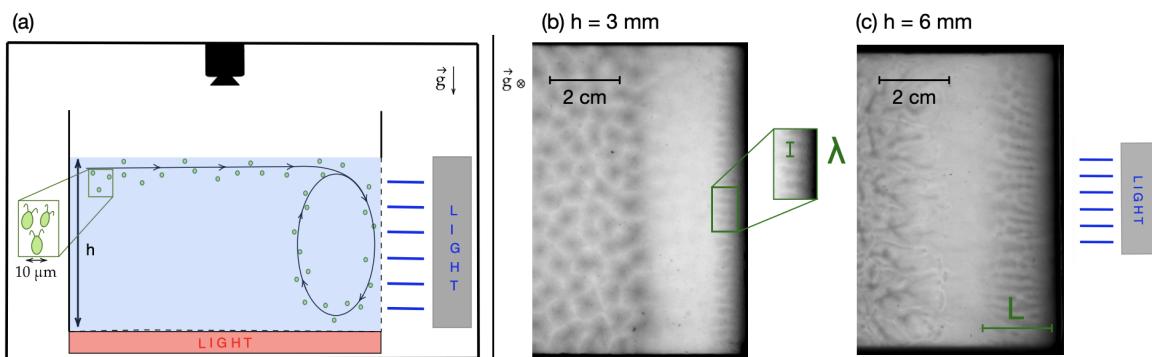


Fig.1: (a) Experimental set up is placed under a big dark box to ensure good control of light rays. A smaller box containing Chlamydomonas solution is illuminated by a blue lamp and a red lamp illuminates from below, as these micro-algae are not sensitive to red light. A camera records the top view. (b) Top view for a 3mm solution depth. (c) Top view for a 6mm solution depth. λ is the wavelength inside the roll and L is the roll width.

¹Martin A. Bees, *Advances in Bioconvection*, Annual Review of Fluid Mechanics, 449-476, 2020

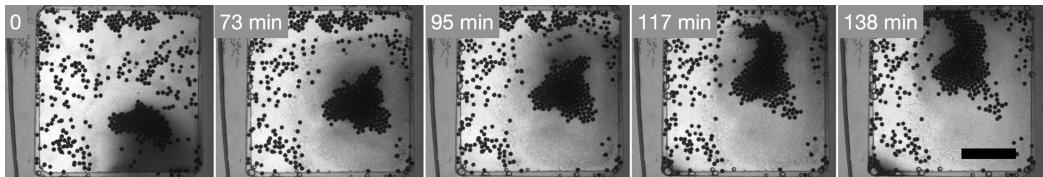
Controlling the transport of passive beads in a suspension of phototactic microalgae

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Raft of plastic beads assembled and transported directionally to the top of a centimetric well by swimming microalgae. Scale bar: 3 mm.

When passive beads are placed in a suspension of active particles, such as swimming microorganisms, they undergo a random motion with an effective diffusion coefficient orders of magnitude larger than that given by the traditional Stokes-Einstein relationship. Here we show how to rectify this random motion of passive beads into a directed one, by controlling the motion of the microorganisms in the suspension.

We enclose plastic beads (size 50 – 450 μm) and a suspension of the model microalga *Chlamydomonas reinhardtii* (size $\sim 10 \mu\text{m}$) in a centimetric well. The algae are phototactic and swim away from strong light stimuli. In the presence of a single source of light, *C. reinhardtii* accumulate at the boundary of the well away from the light and create photo-bioconvection rolls¹². These rolls displace beads denser than the surrounding medium away from the algae, while lighter beads are drawn towards the accumulated algae.

We then focus the algae in a region of a couple mm within the well, using two opposing light sources with two different light intensities. By gradually varying the two light intensities, the region of accumulated algae is progressively shifted towards one side of the well. The dense algal region attracts beads lighter than the fluid, creating a raft of beads that is transported directionally over $\sim 1 \text{ cm}$, see Figure.

¹Dervaux, J, Capellazzi Resta M, Brunet P, *Light-controlled flows in active fluids*, Nat. Phys. **13**, 306-313, 2017

²Arrieta, J, Polin M, Saleta-Piersanti, R, Tuval, I, *Light Control of Localized Photobioconvection*, PRL **123**, 158101, 2019

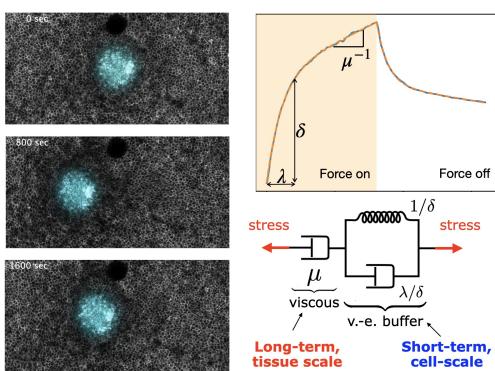
Viscoelastic Rheology of Early Avian Embryos

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* equal contribution



Inference of the viscoelastic model.

Early in their development, embryos pass a phase called gastrulation in which stem cells rearrange spatially and begin to differentiate into separate lineages. Recent work has demonstrated that in avians this process is controlled by a mechano-chemical instability, in which a contractile ring of forces generates a flow of the entire embryo¹². Crucially, this is enabled by the ability of the embryo to behave as a viscous fluid on the time scales of this process. However, many questions remain as to how this phenomenology emerges, and how to characterise it quantitatively.

Here we present a combined theoretical-experimental study of the rheological properties of the quail epiblast *in vivo*. We developed a novel micro-manipulator that allows for the controlled application of forces through an elastic cantilever, and recorded the resulting tissue deformation using high-resolution confocal microscopy. With a combination of particle-image velocimetry, finite element simulations, and analytical techniques we infer a viscoelastic model for the tissue behaviour, and obtain quantitative measurements of the mechanical properties such as the effective long-term viscosity. By changing environmental variables such as temperature and cell proliferation rate, we further gain an understanding of the origin and variation of these properties in terms of the biological constituents. Finally, we demonstrate more generally how a mathematical trick can be exploited to efficiently determine the best viscoelastic model fit in such experiments.

Our results provide a template for mechanical measurements on long time scales *in vivo*, and shed light on the physical conditions that need to be met by stem cells to successfully facilitate embryonic development.

¹Saadaoui, M., Rocancourt, D., Roussel, J., Corson, F., & Gros, J., *A tensile ring drives tissue flows to shape the gastrulating amniote embryo*. Science, **367(6476)**, 453-458, 2020

²Caldarelli, P., Chamolly, A., Alegria-Prévet, O., Gros, J., & Corson, F., *Self-organized tissue mechanics underlie embryonic regulation*, bioRxiv, 2021-10

Understanding mucus transport in airways by using a reconstituted human bronchial epithelium

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The airways are protected from inhaled pollutants and pathogens by a layer of mucus, a complex fluid that is transported along the bronchial walls before being cleared out and swallowed. The mucus is propelled via the continuous beating of active cilia exposed by the multiciliated cells. This process, called mucociliary clearance is impaired in chronic respiratory diseases, which affect millions of people worldwide. Yet, the relationship between ciliary density and the spatial scale of mucus transport, as well as the mechanisms that drive ciliary-beat orientations/coordination are much debated.

We reconstitute in-vitro, from human primary cells, a bronchial epithelium that faithfully reproduces the physiological intricacies of mucociliary clearance within our airways. We image and quantify the dynamics of formation and growth of swirl patterns of mucus flow during ciliogenesis. Our findings reveal that, for physiological cilia density, a macroscopic swirl of mucus develops associated with a circular coordination of ciliary-beat directions and a circular pattern of the planar cell polarity of the tissue ¹. We show that the mechanical feedback exerted by the mucus on top of cilia, triggers an active response of cilia. This results in a positive feedback loop, responsible for the coordinated transport of mucus across long distances at the surface of the bronchial epithelium. Based on these results, we developed a numerical hydrodynamic model that highlights two relevant physical parameters of the epithelium: the density of cilia and the viscosity of mucus ². This model allows us to establish a comprehensive phase diagram for mucus transport in bronchial epithelium. This paves the way to a predictive in-silico modelling of bronchial mucus transport in health and disease.

¹Loiseau, E., Gsell, S. et al. *Active mucus–cilia hydrodynamic coupling drives self-organization of human bronchial epithelium*, Nature Physics **16**(11), 1158-1164171, 2020

²Gsell, S., Loiseau, E., et al. *Hydrodynamic model of directional ciliary-beat organization in human airways*, Scientific Reports **10**(1), 8405, 2020

How insects expand their wings

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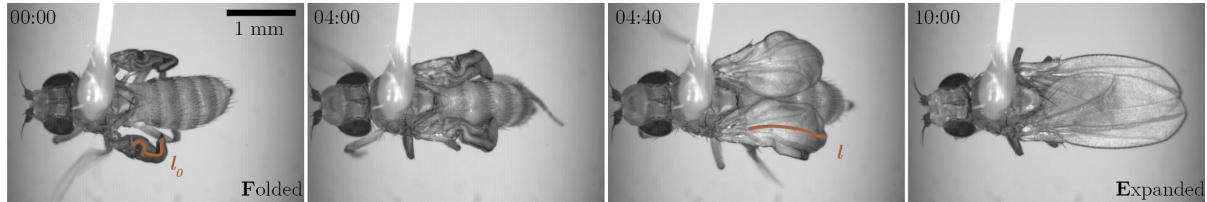


Fig.1: *Drosophila* wing expansion snapshots.

During its final transformation into its adult form, just after hatching from its pupal shell, an insect unfolds its wings within minutes. The wings expand rapidly from a compact, pleated structure to a rigid wing blade that allows the insect to fly. We study wing expansion in the fruit fly *Drosophila*. We characterize the unfolding kinematics through a multi-scale approach using a combination of optical and electronic microscopy together with micro-tomography. Expansion is regulated by increasing internal pressure and injecting a fluid (hemolymph) into a folded deployable structure under hormonal control. We quantify the insect internal pressure in vivo during wing expansion and investigate the mechanical properties of the tissue by performing tensile tests on folded wings and nano-indentation loading cycles. We show that the folded wing behaves as a viscoelastic material characterized by a shear modulus and a viscosity. Finally, we build a fundamental understanding of the kinematics and dynamics of wings expansion based on the wing structure and mechanical properties considering that the stress in the wing compensates for the increase in internal pressure during expansion. Our model also captures the dynamic of the wings expansion, regulated by internal tissue dissipation mechanisms.

Fast movements of *Mimosa pudica*: an osmotic muscle?

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Mimosa pudica leaf movement
(1 frame/s).

Plant movements span timescales ranging from tenths of seconds to several hours, and rely on a rich variety of physical mechanisms¹. The “touch-me-not” plant, *Mimosa pudica*, folds its leaves in a couple of seconds in response to mechanical or electrical stimuli. This movement is reversible, and leaves reset within a few tens of minutes.

Purely osmotic water transport across the pulvinus – a flexible, hinge-like bulge at the base of each leaf – constitutes the textbook explanation of the motion². This scenario

received only limited experimental evidence, however, and implies that pulvini operate near the physical limits of osmotic transport¹.

Here we experimentally characterize the kinematics of the movement and the mechanics of the pulvinus. We then build a simple osmotic motor model to capture the global dynamics and to estimate the microscopic quantities characterizing the motor. Finally, we elaborate an alternative mechanism for *Mimosa pudica*'s fast motions based on local water redistribution from cells to neighboring air cavities.

¹J. Dumais, Y. Forterre, “Vegetable dynamics”: the role of water in plant movements. Annual Review of Fluid Mechanics **44**, 453-478, 2012.

²D.A. Sleboda *et al.*, Multiscale structural anisotropy steers plant organ actuation. Current Biology **33**, 4, 639-646, 2023.

Embolism spreading in real & synthetic leaves

Ludovic Jami¹, François Xavier Gauci¹, Virgile Thièvenaz², Ludovic Keiser¹, Celine Cohen¹, Hervé Cauchard², Eric Badel², Jose-Manuel Torres-Ruiz², Benjamin Dollet³, Philippe Marmottant³, Xavier Noblin¹

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Embolism is the phenomenon of nucleation and expansion of bubbles in the venation network of the ascending sap. It is a major threat for plant life and it is of growing concern as global warming goes on. The ascent of sap relies on the building of a negative pressure (tension) in the venation network. But the ascending water is therefore unstable to the formation of vapor nucleation bubbles. Moreover any embolism bubble present should expand due to the depression inside the venation network. This propagation of embolism bubbles generates discontinuity in the wetting of the network which hamper plant water supply, leading eventually to its death if hydric stress is maintained.

The decomposition of plants venation bundles in vessel elements (interconnected channels) and the hierarchical organization of the bundles limits the expansion speed of the embolism. Due to this particular organization of plant venation network, embolism propagation tends to follow complex "stop and go" dynamics at different time and space scales. In particular this is revealed by the filming of the propagation of embolisms, including with high speed imaging.

We follow a bottom-up approach of the problem by micro-fabricating biomimetic venation systems with water permeable materials, and submit them to hydric stresses. We will present the observation of intermittent air invasion in 2D networks of interconnected channels made of PDMS. PDMS is permeable to water vapor and therefore small depressions build up in the drying channels which generate large deformations. We will also present nucleation of embolism bubbles and their ultra-fast expansion in a stiff hydrogel that can sustain high negative pressures. These examples enables to decipher the key physical ingredient that determines the nonlinear dynamics of embolism propagation accross scales.

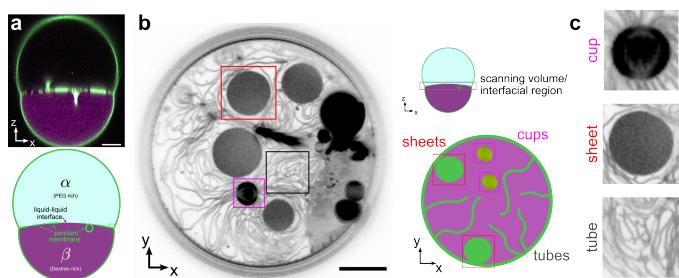
Membrane shapes, liquid-liquid interfaces, and elastocapillarity

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Formation of a liquid-liquid interface inside vesicles and the accumulation of interface-bound membrane. a) Vertical cross-section of the phase-separated vesicle. b) Horizontal section of the liquid-liquid interface. Excess membrane accumulates at the liquid-liquid interface. c) cup sheet and tube shapes. Scalebars are 10 μm .

morphologies on well-defined liquid-liquid interfaces. aqueous interior of a vesicle to form liquid-liquid interfaces, via osmotic quenches. We control the surface tension of the interface by the deepness of the quench. Excess membrane area from the vesicle accumulates on the interface and assumes different shapes (tubes, sheets, or cups), depending on the surface tension. The sizes of the shapes are in the μm range, enabling visualization with confocal microscopy. We complement our experimental observations with Monte Carlo simulations of a coarse-grained membrane model that reproduces the morphology transitions following experiments. Our results in vitro experiments will help to explain resembling in vivo observations during the morphogenesis of protein storage vacuoles in plants.

Liquid condensates and elastic membranes interact in cells, e.g., during the formation of organelles or the recycling of proteinous matter¹. The conditions that govern the morphology of the elastic membrane, and in particular membrane vesicle, are meanwhile well understood². However, the presence of a liquid-liquid interface gives rise to elastocapillary effects that influence the shape equilibrium and transition which are both poorly understood. Here, we bridge this knowledge gap by systematically investigating membrane

For this, we phase-separate the liquid,

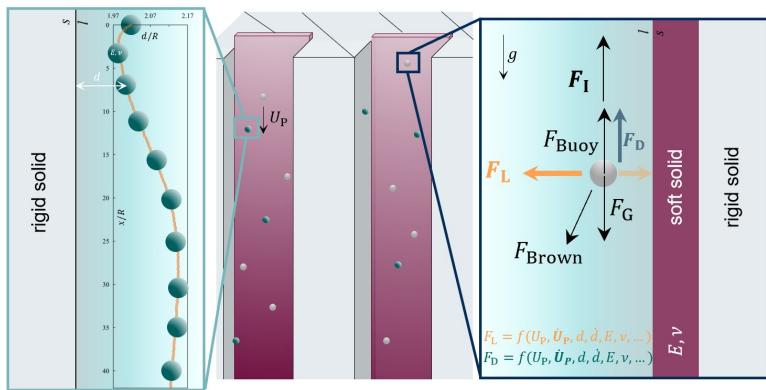
¹Agudo-Canalejo et al. *Nature* 591.7848 (2021): 142-146.

²Seifert and Lipowsky. *PRA* 44.2 (1991): 1182.

Wall-bounded sedimentation of particles with elastohydrodynamic interaction at $Re_{\text{scriptsize } P} \approx 0.1$

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Sedimenting spheres in rectangular channels (middle). Elastic sphere near a rigid wall (left). Rigid sphere near a soft layer (right).

Sedimentation of particles, such as microplastic spheres, along a deformable substrate (e.g. a biofilm) within rectangular microchannels is only one of the numerous examples for particle-laden flows with elastic interaction. It is a complex system in which the particle-fluid dynamics of a particle with small mass inertia ($Re_p \lesssim 0.1$) is coupled to the elastohydrodynamic interaction between the particle and the

bounding walls. The measurement of particle kinematics near solid, opaque or reflecting surfaces on the μm -scale is challenging. To investigate the underlying forces in these systems in detail, we performed model experiments of rigid and soft bodies on a macroscopic cm -scale by filling a large rectangular container with a Newtonian fluid with high kinematic viscosity. Previous experiments in the center of the container showed, that the particle dynamics of elastic spheres differs fundamentally from that of rigid spheres¹. Depending on the Young's elastic modulus, elastic spheres under symmetric wall influence accelerate at several stages during the sedimentation process. Here, we present results of recent studies with particles sedimenting from rest in the vicinity of a rigid and a deformable plane wall (asymmetric wall influence). The experiments showed surprising long-time unsteady motion of the particles including unknown kinematical phenomena, such as the *inertial wall attraction* phase towards rigid walls or undulating motions of spheres towards soft walls. We attribute the observed instabilities and nonlinearities to the interplay between particle-fluid inertial forces, e.g. memory effects, and elastohydrodynamic effects. The measurement data could serve as a first approach to model the forces in, e.g. biotechnological processes or, to model forces in aqueous solutions contaminated with soft microplastics.

¹I. Noichl and C. Schönecker, *Dynamics of elastic, nonheavy spheres sedimenting in a rectangular duct*, Soft Matter **18**, 2462 - 2472, 2022

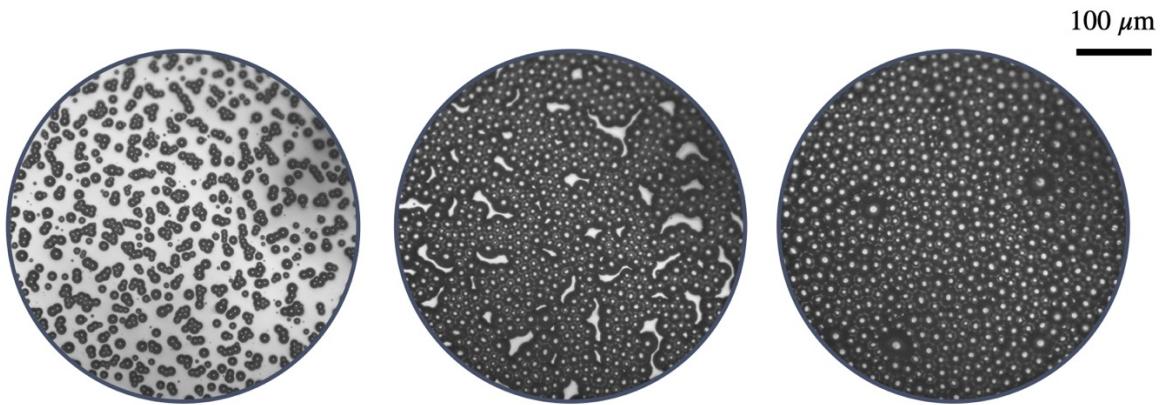
Dew formation on soft substrate

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³ Physics of Fluids, De Horst 2, 7522 NB Enschede, Netherlands



Top-viewed breath figures formed onto a soft PDMS gel after 5, 25 and 50 minutes (from left to right).

Vapor molecules can nucleate on cool substrates, provided the surrounding humidity is high enough. Dew formation has been investigated on both rigid (and rough!) solids as well as on liquids. However, how substrate elasticity affects the condensation process remains elusive. In this talk, I will present how water condenses on soft, elastic gels that are smooth at the nanometer scale. We prepare PDMS gels whose softness varies between that of a rigid substrate and an un-crosslinked polymeric liquid.

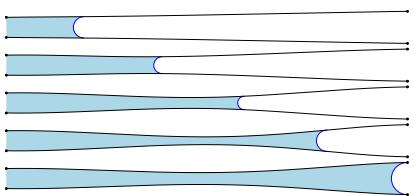
Although elasticity should be marginal at the nanometric scale at which drops form, we report that the nuclei density is highly sensitive to the substrate softness. In this talk, I will delve into the intricate dynamics of condensation and try to explain some of the intriguing characteristics we have observed. Among these are the influence of softness on nucleation; the sub-diffusive growth of droplets; and the absence of secondary nucleation events (unlike what is classically observed in heterogeneous nucleation). Later, when neighboring drops get closer, they attract each other due to interactions mediated by substrate deformations. Drops then gather into clusters that seem reluctant to coalesce. This ultimately results in the formation of a persistent, ordered, honeycomb-patterned liquid film.

Capillarity nonuniform flexible channels

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Capillary flow in a nonuniform channel.

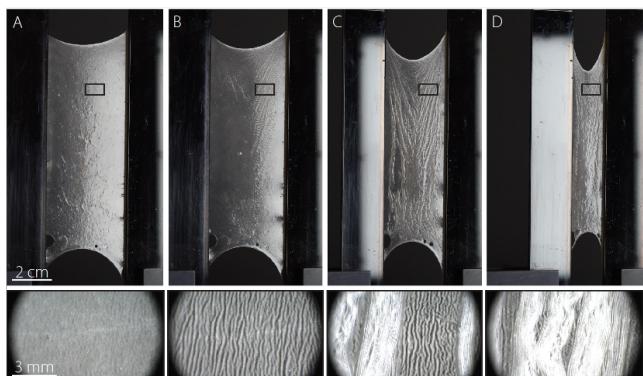
Surface tension in nature and engineering acts on elastic slender bodies of complex and nonuniform shapes. We study elastocapillarity in linearly diverging channels as a simplest geometrical nonuniformity and highlight advantages. We first show that diverging flexible channels prevent occlusion and, unlike rigid ones, speed up the capillary wicking compared to straight channels. We then examine the equilibria of a liquid bridge between nonparallel sheets. We find multiple

deformation profiles and identify a hysteresis effect, as well as an isola center. Unlike between rigid walls, the bridge remains in equilibrium away from the ends even if the liquid is totally wetting, and the channel stays open upon slow volume variation. Finally, we analyse the motion of a sliding drop between a pair of elastically hinged plates and the role of rest angles and initial conditions in delaying closure. We investigate by extension the collective clumping of side-by-side plates, an example of an unstable homogeneous medium where a disturbance amplifies while traveling in a constant speed and leaves behind a pattern of clusters.

Elasto-capillary wrinkling in thin liquid-infused membranes

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Wrinkling of the membrane under compression.

Elasto-capillary effects result from the interplay between surface tension and elastic deformation of slender structures. Recent studies have unveiled a variety of deformations induced by capillary forces, including softening the sharp geometry of a compliant substrate, bending and buckling of flexible fibers, and the folding, wrapping, wrinkling of thin sheets¹. Our investigation extends from experimental observations of a nano-fibrous liquid-infused tissue²

Under slight compression, it spontaneously develops wrinkles through elasto-capillary effects. With further contraction, specific regions experience substantial collapse, creating surface reservoirs that augment the membrane's deformability (c.f. figure). The notable deformability of this synthetic system closely mirrors that of cell membranes, rendering it intriguing for applications in stretchable electronics, smart textiles, and soft biomedical devices.

To elucidate the underlying mechanism, we employ theoretical and numerical modeling. The system is simplified to a thickness-neglected, inextensible membrane confined within a liquid layer of constant volume. The configuration of the membrane-liquid system under certain compression is formulated as an optimization problem, and the nonlinear problem is resolved using an open-source tool CasADI³.

The model reveals homogeneous wrinkles with slight compression. As compression exceeds a specific threshold, wrinkles localize at a distinct spot on the membrane. This transition provides insights into experimental observations, prompting further investigations into the behaviors of liquid-infused membranes.

¹J. Bico *et al.*, *Elastocapillarity : When Surface Tension Deforms Elastic Solids*, Annual Review of Fluid Mechanics **50.1**, p. 296-299 (2018)

²P. Grandjeorge *et al.*, *Capillarity-induced folds fuel extreme shape changes in thin wicked membranes*, Science **360.6386**, p. 629-659 (2018)

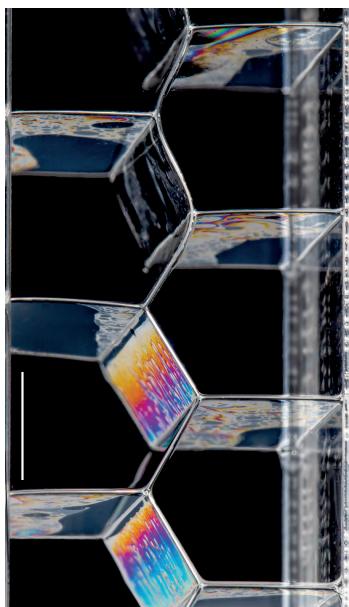
³J. Andersson *et al.*, *CasADI - A software framework for nonlinear optimization and optimal control*, Mathematical Programming Computation **11.1**, p. 1-36 (2019)

Foams and soft intruders: exploiting elastocapillarity towards novel foam structures

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Taking advantage of capillarity has proven to be an efficient way to assemble, orient, or spontaneously bend elastic slender structures, raising fundamental physics questions but also engineering perspectives in emerging fields such as micro-fabrication and soft robotics. However, the application of such an approach to complex cellular systems is limited so far. We will focus here on the question of tuning foam structures using systems involving capillarity and elasticity.



Elastic ribbon introduced
in a 2D column of bubbles.
Scale bar: 5mm

Foams consist of gas bubbles trapped in a continuous liquid or solid material, whose structure is strictly guided by capillarity. Despite recent progress in "liquid foam templating" ^{1, 2} to produce solid foams in a controlled and self-assembled way from liquid precursors, we still lack methods to explicitly tune the geometry and topology of foams. To reach a higher level of control of foam structures and of their resulting properties, we propose to investigate how integrating deformable objects in foams can modify their structure in the liquid state, before a solidification step occurs. Using a combination of model experiments and theoretical energy minimisation approaches, we first quantified the competition between elasticity and capillarity in a simplified liquid foam structure (deformation of a thin ribbon placed in a 2D bubble column ³; illustrated in the figure), before exploring the extension of this approach to 3D complex polymeric materials. In particular, we developed monodisperse 3D model foams able to solidify (hydrogel- and polyurethane-based), in which intruders incorporated at the liquid state can efficiently modify the foam architecture.

¹Stubenrauch, C., Menner, A., Bismarck, A., and Drenckhan, W., *Emulsion and Foam Templating - Promising Routes to Tailor-Made Porous Polymers*, Angew. Chem. Int. Ed. **57**, 10024-10032, 2018.

²Andrieux, S., Quell, A., Stubenrauch, C., and Drenckhan, W. *Liquid foam templating - A route to tailor-made polymer foams* Adv. in Colloid Interface Sci. **256**, 276, 2018.

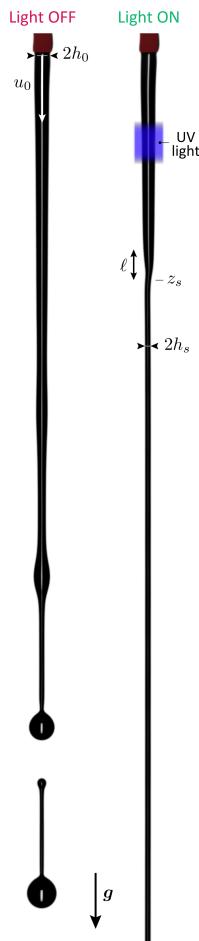
³Jouanlanne, M., Egelé, A., Favier, D., Drenckhan, W., Farago, J., and Hourlier-Fargette, A. *Elastocapillary deformation of thin elastic ribbons in 2D foam columns.*, Soft Matter, **18**(12), 2325-2331, 2022.

Jet Solidification

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Jet with light off and on.

The thinning and breakup of a thin liquid jet depend, subtly, on the liquid properties. This means that non-trivial and technologically relevant dynamics are expected when the liquid changes over time, i.e., evolves along the jet. We address this question by considering a gravity-stretched jet, which solidifies on demand into a solid thread.

We use a UV-photocurable resin with a short curing time, form a vertical capillary jet with a steady flow rate, control the jet length with a collecting water basin, and focus a strong UV light onto the jet.

Solidification is found to alter the jet, drastically. While without light (figure, left), the jet stretches only mildly and eventually breaks up, at sufficient light intensity (right), breakup is prevented and a thin continuous thread is formed. Within some distance from the lighting ($z < z_s - \ell$), the jet remains liquid and unchanged. Below ($z > z_s$), the thread is solid and thinner. In between, a short thinning front bridges both parts. Steadiness is reached after a transient regime lasting $\sim (L/g)^{1/2}$.

We harvest the close-to-unidimensional jet dynamics and short response length of the jet to obtain a fast characterization of the solidification kinetics. We will show how the steady solidification location z_s is governed by the light intensity, but also, and more surprisingly, by the jet dynamics. We will also explain how the thinning front can be understood, quantitatively, as a localized stretch by the solid thread weight.

Besides these steady considerations, important questions, such as unsteadiness, jet stability, the role of capillarity, or the challenge of in situ rheology, will be discussed.

Sticking without contact : elastohydrodynamic adhesion

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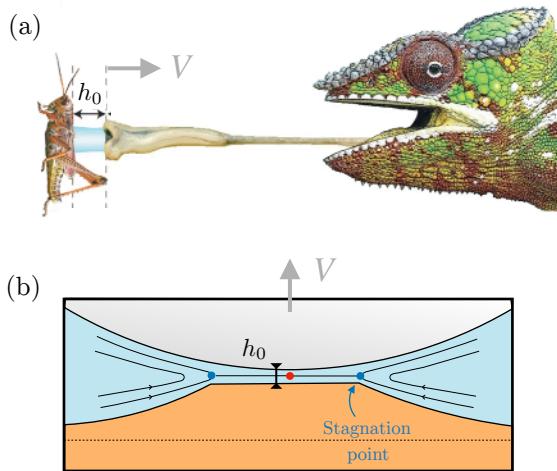


Fig.1: (a) Chameleon catching a prey (adapted from Ref. 1). (b) Model system of elastohydrodynamic adhesion.

bodies *stick without contact*, reminiscent of the JKR contact theory. Using self-similar solutions we analyse (i) the initial increase of elastic stresses and (ii) the dynamical snap-off once the contact radius is sufficiently small.

When pulling apart two solid surfaces immersed in viscous liquid, an adhesive force arises from a negative suction pressure. A variety of animals exploits this mechanism to catch prey like chameleons¹ or frogs (see Fig. 1(a)). Here we investigate viscous adhesion between soft bodies, using the model system sketched Fig. 1(b). We perform numerical simulations and theoretical analysis based on lubrication theory. The negative pressure inside the thin viscous film between the solids generates significant elastic deformations. The combine effects of lubrication flow and elastic deformations leads to an off-center stagnation point of the flow². Hence, the liquid film within the apparent contact radius is stable such that the two

¹Brau, F., Lanterbecq, D., Zghikh, L. N., Bels, V., & Damman, P, Dynamics of prey prehension by chameleons through viscous adhesion. *Nature Physics*, **12**(10), 931-935, 2016

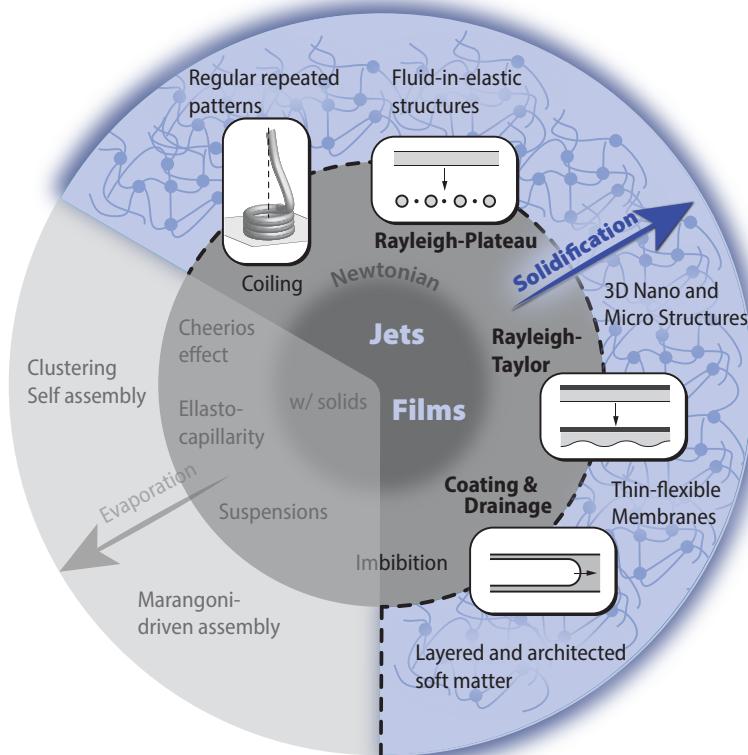
²Shao, X., Wang, Y., & Frechette, J. Out-of-contact peeling caused by elastohydrodynamic deformation during viscous adhesion. *The Journal of Chemical Physics*, **159**(13), 2023

Building with liquids: a lazy approach to fabrication

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In nature, organized arrays of elements arise spontaneously from the interactions between their component parts, e.g. reaction-diffusion problems, clustering colloidal particles and granular media, wrinkling surfaces, propagating cracks and flowing liquids. In the wake of biomimicry, I will discuss several strategies aiming to harness mechanical instabilities in flowing liquids, e.g., coiling, droplet formation, digitation, drainage, capillary suction, and use the regular shapes and universally self-organized patterns they naturally produce as templates for materials design. These flows are "frozen" as the liquids we use solidify into solids, e.g., through curing, cooling, or evaporation. The shapes and patterns they form are universal and transcend the traditional divisions between scientific fields or even between living and inert matter. I will show that these similarities result from the mathematical analogies in the rules that govern pattern formation. In turn, I will demonstrate how to combine these rules to augment our manufacturing capabilities, e.g., in soft robotics.

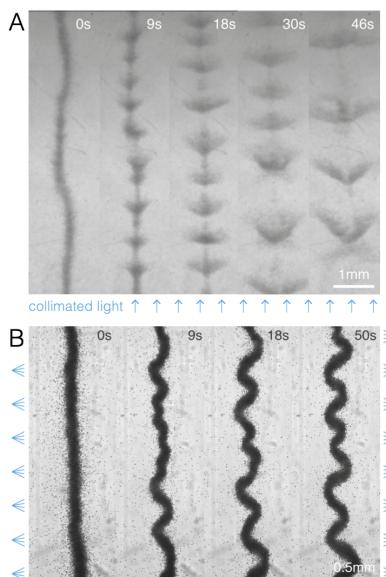


Droplet and buckling instabilities in active fluid jets

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² Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, United Kingdom



A. When cells all swim parallel to the jet direction (bottom to top) the hydrodynamic interactions between the particles destabilize the jet into clusters or "droplets" that get stretched perpendicularly after their formation, taking a characteristic "mustache" or V shape. B. When cells are now preferentially aligned perpendicularly to the jet direction, the same hydrodynamic interactions now lead to the destabilization into a zig-zag pattern.

of the system.

Collections of self-propelled particles moving within a viscous liquid interact via long-range hydrodynamic interactions that can lead to large scale phenomena, such as the so-called bacterial turbulence. In situations where the particles are confined within a jet and aligned along the jet direction, several instabilities driven by the hydrodynamic interactions between the agents have been theoretically predicted. For puller-like particles (like the micro-alga *C. reinhardtii*) an active fluid jet is predicted to destabilize into clusters in a phenomenology similar to the Rayleigh-Plateau instability of classical liquids, although from a different physical origin. For pusher-like particles (like the bacterium *E. coli*) the active jet is now predicted to buckle into a zig-zag pattern from the compressive stress imposed by the aligned force dipoles.

Here we report on the experimental realization of these two hydrodynamic instabilities in suspensions of the puller-like micro-swimmer *C. reinhardtii* by harnessing their phototactic response to confine the cells within a jet (see Figure). Because the flow developed by a puller is almost equivalent to the flow developed by a pusher oriented perpendicularly, the buckling instability can also be obtained in jets of puller particles when they preferentially align perpendicularly to the jet direction. We then demonstrate that the experimental instabilities are in good quantitative agreement with theoretical predictions and numerical simulations, e.g. by measuring the wavelength of the instabilities as a function of the jet width. Finally, we will show that other types of hydrodynamic phenomena can be observed in such suspensions of puller particles driven by light when changing the geometry

Shape of a highly-compliant tethered filament in a uniform Hele-Shaw flows

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Certain microfluidic applications involve the interplay between viscous flows in a Hele-Shaw cell and the deformation of a confined elastic fiber tethered to the sidewall of the cell. Considering the fiber as a Kirchhoff beam and employing the standard approximation where the depth averaged velocity is proportional to the in-plane pressure gradient, this coupled problem was modeled a decade ago¹ for the case of nearly-fitting fibers which are exposed to an otherwise uniform flow. The two key elements in that model is the identification of the pressure jump across the fiber as an “external” normal load on the fiber, and the generalization of the familiar impermeability condition to a leakage condition, relating the normal derivative of the pressure at the fiber centerline to the pressure jump across it.

By employing a dimensionless description where distances are normalized with the fiber length, the aforementioned model involves two parameters: the compliance parameter η , relating the curvature to the internal bending torque, and the leakage parameter β appearing in the generalized Neumann condition, which accounts for the narrow spacing between the fiber and the bounding walls. Our interest is in the limit of a “soft” fiber, $\eta \gg 1$, where it is anticipated that most of the fiber would align with the flow. The intuitive picture in this scenario is that of a boundary-layer near the tether point, where the fiber shape monotonically evolves toward the eventual aligned geometry.

While that picture is observed in the comparable “unconfined” problem,² it is incompatible with an integral leakage balance in the present problem. Rather, we find a multi-scale structure, where the shape variation takes place in three disparate asymptotic regions: a boundary layer of extent $\sim \eta^{-1/4}$, a thin-film region of width $\sim \eta^{-1/2}$, and the aligned part. An analysis of the thin-film region relates the uniform $\sim \eta^{-1/2}$ distance between the fiber and the sidewall in the aligned part to the net flux through the fiber in the boundary layer; that flux, proportional to β , is accordingly the quantity of interest. The boundary layer has a finite “blister”-like geometry, wherein the shape is governed by a universal problem. We solve that problem using the Helmholtz–Kirchhoff free-streamline theory in the complex plane, obtaining all the quantities of interest as pure numbers.

¹Wexler, J.S., Trinh, P.H., Berthet, H., Quennouz, N., du Roure, O., Huppert, H.E., Lindner, A., Stone, H.A., *Bending of elastic fibres in viscous flows: the influence of confinement*, J. Fluid Mech. **720**, 517–544, 2013

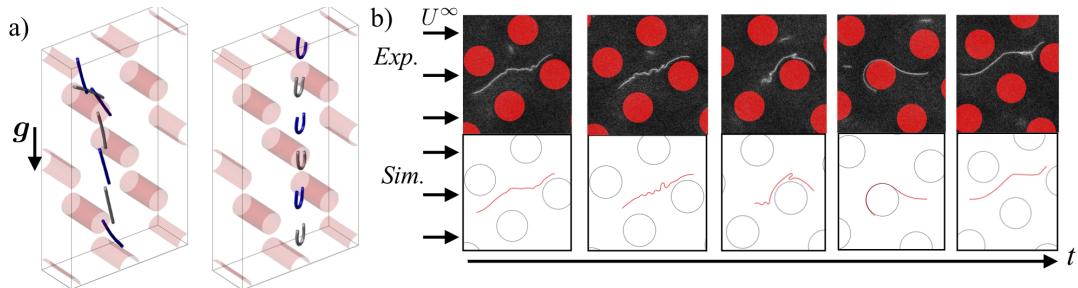
²Kurzthaler, C., Brandão, R., Schnitzer, O., Stone, H.A. *Shape of a tethered filament in various low-Reynolds-number flows*, Phys. Rev. Fluids **8**, 014101, 2023

Dynamics of flexible fibers in structured environments

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Sedimentation (a) and transport (b) of fibers in a pillar network.

In this talk we combine experiments, theory and numerical simulations to investigate the dynamics of flexible fibers in a viscous fluid embedded with obstacles of arbitrary shapes. We consider two different fields driving the fiber motion: gravity in a quiescent fluid and pressure-driven flows in microfluidic chips.

In the gravity-driven case, the obstacles can either trap or reorient sedimenting fibers upon contact. After reorientation, a fiber drifts sideways while relaxing back to its equilibrium shape. The resulting lateral displacement is large relative to the fiber length and strongly depends on its mechanical and geometrical properties. We show how these effects can be leveraged to propose a new strategy to sort particles based on their size and/or elasticity. This approach has the major advantage of being simple to implement and totally passive¹.

In a pressure-driven flow, richer dynamics emerges from fiber-obstacle interactions, where pole-vaulting is also observed ². However, since flexible fibers can barely migrate across streamlines, the shape and arrangement of obstacles must be carefully optimized to maximize lateral displacement. The resulting pillar networks can efficiently sort fibers by length and/or stiffness in microfluidic chips.

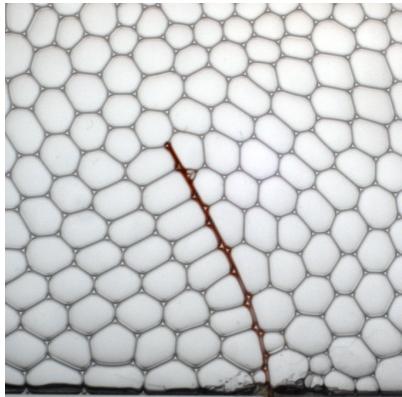
¹Makanga, U, et al., *Obstacle-induced lateral dispersion and nontrivial trapping of flexible fibers settling in a viscous fluid*, Phys. Rev. Fluids **8**(4), 044303, 2023

²Li, Z and Bielinski, C et al., *Rich dynamics of rigid fibers interacting with triangular obstacles in microchannel flows*, arXiv:2311.17635, 2024

Deflection and oscillations of an anchored elastic fiber in a quasistatic foam flow

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Elastic fiber deflected by the elastoplastic flow of a 2D foam (flowing from right to left).

We study the deflection and oscillations of a clamped elastic fiber embedded in 2D foam under quasistatic flow. At all times, the fiber conformation results from the elasto-capillary interactions with the foam. We independently measure the action of capillary and pressure forces on the fiber, and show that the fiber deformation is adequately described assuming a uniform continuous normal force acting on it. When bending energy exceeds a threshold value, the fiber relaxes to a less deflected shape, generating a cascade of plastic rearrangements within the foam, and the process repeats periodically. We analyze the statistical distributions of stored and released energy, and estimate the yield strain and shear modulus of the foam, as well as the number of elementary plastic events involved in a cascade¹.

¹Pellé A., Durand M., *Deflection and oscillations of an anchored elastic fiber embedded in a quasistatic two-dimensional foam flow*, arXiv:2302.11901

Mechanics of Colloidal Membranes

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¹ School of Engineering, Center for Fluid Mechanics, Department of Physics, and Brown Theoretical Physics Center, Brown University, Providence, RI 02912, USA.

Colloidal membranes are unique 2D assemblages consisting of a liquid-like layer monolayer of aligned rod-like viruses that are held together by osmotic pressure. Although they are a few hundred times thicker, colloidal monolayer membranes share many properties with lipid bilayers, such as in-plane fluidity and resistance to bending. However, they also display distinctive properties, such as a propensity to have exposed edges, as well as shapes with negative Gaussian curvature. Furthermore, colloidal membranes commonly have liquid crystalline properties because the rods twist near the edge of the membrane. I will discuss a few of the phenomena exhibited by colloidal membranes, and the theory we have developed to understand these phenomena. For example, doping colloidal membranes with short miscible rods transforms disk-shaped membranes into saddle-shaped surfaces with complex edge structures¹. The saddle-shaped membranes are well approximated by Enneper's minimal surfaces. Theoretical modeling demonstrates that their formation is driven by increasing the positive Gaussian modulus, which in turn, is controlled by the fraction of short rods. Fitting the shape of the membrane edge to our theoretical predictions allows us to determine effective moduli such as the Gaussian curvature stiffness and the chirality modulus, which arise because the rods break mirror symmetry. If time permits, I will also discuss theoretical predictions for the director configuration when the chirality is strong, in which case we predict cholesteric ordering and π -walls on catenoid-like membranes².

¹A. Khanra, L. L. Jia, N. P. Mitchell, A. Balchunas, R. A. Pelcovits, T. R. Powers, Z. Dogic, and P. Sharma, "Controlling the shape and topology of two-component colloidal membranes," *Proc. Natl. Acad. Soc. USA* **119** (2022) e2204453119.

²L. Ding, R. A. Pelcovits, and T. R. Powers, "Chiral fluid membranes with orientational order and multiple edges," *Soft Matter* **19** (2023) 8453.

Particule-laden drops flowing through a pore

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¹ Soft Matter Sciences and Engineering (SIMM), ESPCI Paris, PSL University, Sorbonne Université, CNRS, F-75005 Paris, France

² CNRS, Surface du Verre et Interfaces, Saint-Gobain, 93300 Aubervilliers, France

In water management, separating oil drops can be particularly challenging when solid particles adsorb and stabilize their interface. The efficiency of filtering such emulsions depends on the stability of their interface as they flow through the pores. At equilibrium, the behaviour of liquid interfaces laden with solids is well known. At low surface density, they exhibit the same interfacial tension as the bare interface. Above a threshold, repulsive interactions arise between particles and surface pressure builds up. At even larger When particles get in contact, the interface behaves as an elastic sheet that can buckle or wrinkle. By conducting experiments with a model system where a single drop is driven through a cylindrical pore by pressure, we identified different flow regimes and model them. As the drop enters the pore, it deforms and surface pressure accumulates at the rear. The flow regimes depend on the possible relaxation of this surface pressure, either by the lubricated flow of the raft from the rear to the front (Fig. 1 a,b), or by buckling and wrinkling (Fig. 1c), depending on the capillary number, pore diameter and particle size, which sets the bending stiffness of the raft. he particle raft is fully expelled from the drop interface when none of these two relaxation modes allow the surface pressure to relax (Fig. 1d).

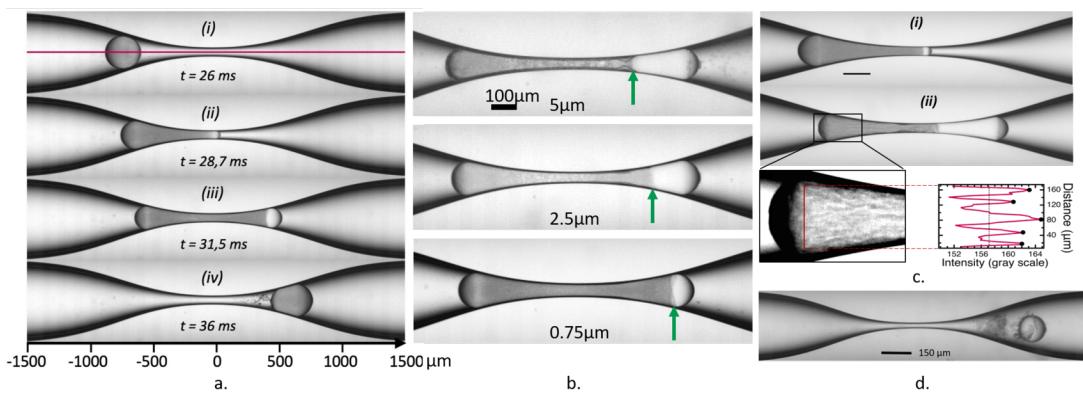
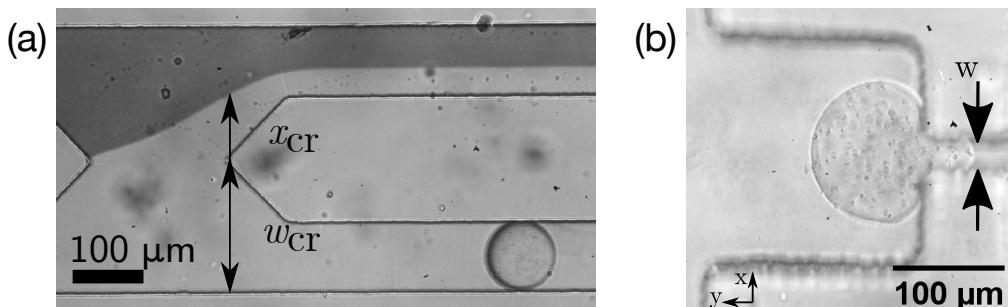


Fig. 1: Particle-laden oil drop through a cylindrical pore in water. Drop : 125 μm , pore: 25 μm . (a) Time-lapse at large velocity and small particles : (i,ii) raft accumulates at the rear; (iii,iv) raft recalled to the front. (b) For larger particles, raft accumulates more at the rear. (c) Timelapse at low velocity. Raft stops and wrinkles (insert). (d) After the pore, very large particles are fully expelled from the drop. [De Soete et al., Physical Review Fluids 7 104002, 2022.]

Hydrogel beads flowing and clogging microchannels

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(a) Measuring the hydrodynamic resistance of a confined gel bead in a microfluidic comparator. (b) Plugging a slit with a gel bead.

How hard should you push a soft particle for it to flow in a capillary, when the cross-section of the capillary is narrower than the diameter of the particle? And how much can you plug a rectangular slit with a soft, deformable, spherical particle? Here, we combine experiments, numerical simulations and theory to study two cases of fluid-structure interactions at low Reynolds number, occurring when a soft hydrogel bead is confined in a microchannel with a non-circular cross-section.

First, we consider a hydrogel bead flowing in a square microchannel, whose cross-section is smaller than the diameter of the bead (Fig. (a)). We find that the pressure needed to push the confined gel at a given velocity depends on the confinement ratio, the gel elasticity, and the viscosity of the surrounding fluid. All data fall onto a single master curve, where the control parameter is a dimensionless number comparing the gel elasticity with the applied shear stress.

Then, we look at what happens when the hydrogel bead is pushed towards a thin rectangular slit, and plugs the slit (Fig. (b)). The relationship between the pressure applied and the flow rate in the slit displays two regimes: a flow-dominated regime for small particle deformations, where flow rate increases with pressure, and an elastic-dominated regime in which solid deformations block the flow¹.

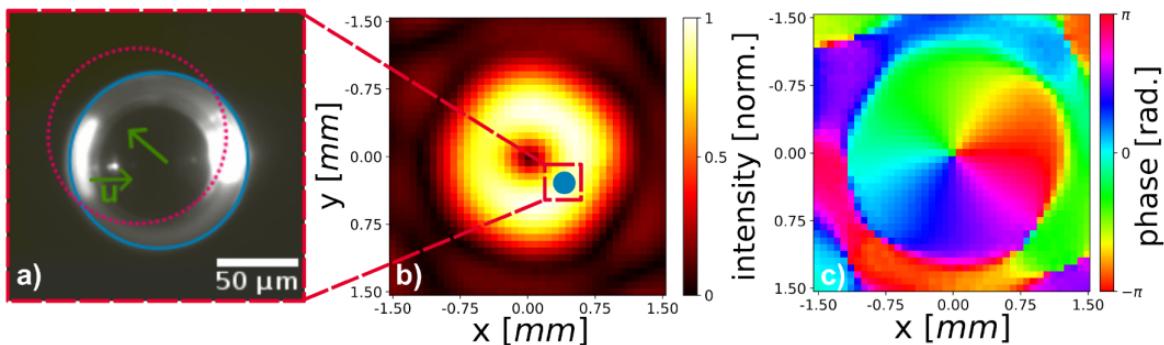
¹ Moore, C.P., Husson, J., Boudaoud, A., Amselem, G., Baroud, C.N., *Clogging of a Rectangular Slit by a Spherical Soft Particle*, Phys. Rev. Lett. **130**, 064001, 2023

Active microrheology of soft materials using acoustical tweezers

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Probing the local and internal viscoelastic properties of soft materials is important to characterize the mechanics of biological tissues. Therefore, this work focuses on the development of an active microrheological method using acoustical tweezers, a recently developed technique to exert contactless forces on microscopic objects. Here, a focused acoustic vortex beam pulls on a microbubble (100 μm in size) embedded in a soft hydrogel with the radiation force. The external force can be modelled using precise pressure measurements of the incident beam, and the net displacement of the microbubble centre can be detected using optical microscopy. Combined with a simple elastic model for the medium, the local elastic properties of the hydrogel can be deduced. In this work, yield-stress hydrogels with typical shear moduli ranging from a few tens to a few hundreds of pascals were used, and microbubble displacements in the 1 to 10 micrometer range were observed, consistent with forces in the micronewton range. Overall, this acoustic approach presents several advantages compared to conventional rheology methods based on optical or magnetic forces, as it can be considered minimally intrusive, local, and well-adapted to probe thick and opaque-to-light materials in bulk such as cellular aggregates and tissues.



a) Photograph of a bubble forced into motion by acoustic forces in a soft hydrogel. b)-c) Intensity and phase profile of the focused ultrasonic vortex beam.

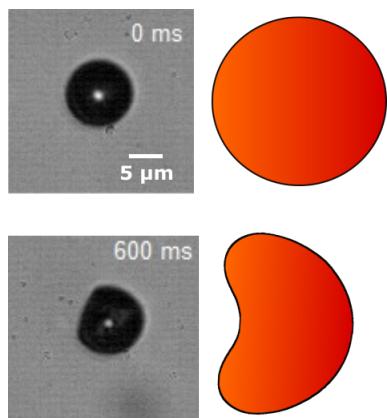
Optical investigation of the dynamics of ultrasound contrast agents during insonification in the kHz range

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Top: spherical UCA, Bottom: buckled UCA.

Artificial microswimmers could be a way of transporting cargo through the blood vasculature for targeted drug delivery. However, most of them to date are too slow to go upstream and are advected. Passive advection of micro or nanocarriers results in only 1% of them successfully reaching a target¹. It is thus necessary to develop faster microswimmers to gain efficiency and selectivity.

It has been demonstrated in previous studies² that an ultrasound contrast agent (UCA) can swim via a pressure-driven buckling instability activated at a frequency of order 1 Hz. Starting at ambient pressure with a spherical UCA, this instability will deform the UCA rapidly in a buckled state once a pressure threshold is reached. Then, if the pressure is released back to ambient pressure the UCA returns slowly to

its initial spherical state. For each of these pressure cycles, a net displacement of one-third of the UCA radius has been observed at 1 Hz. To increase the speed of the UCA, the frequency of the driving wave could be increased up to a point where the UCA will not have time to buckle properly. Simulations have shown that the kHz range would be optimal for the swimming speed of the UCA³. Thus, I am exploring experimentally the effect of an ultrasound wave at a frequency of around 20-40 kHz on the buckling of UCAs.

¹ Anchordoquy T. J. et al., *Mechanisms and Barriers in Cancer Nanomedicine: Addressing Challenges, Looking for Solutions*, ACS Nano **11**, 12-18, 2017

² Chabouh G et al., *Buckling of lipidic ultrasound contrast agents under quasi-static load*, Philosophical Transactions of the Royal Society A **381(2244)**, 20220025, 2023

³ Chabouh G et al., *Coated microbubbles swim via shell buckling*, Communications Engineering **2(1)**, 63, 2023

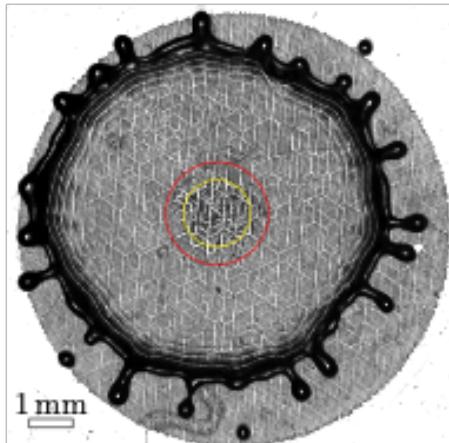
Droplet impact on deformable hydrophobic textures

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Top view of a droplet impact on a textured hydrophobic membrane (the circles correspond to the limits of the impalement zone)

When a droplet collides with a butterfly wing or a plant leaf, it may undergo fragmentation, bouncing, or adhesion. Both leaves and insect wings share the common features of being textured and flexible. In this study, we specifically investigate the phenomenon known as the impalement transition, wherein the liquid droplet penetrates the texture upon impact.

On a rigid substrate, droplet impalement occurs above a critical velocity threshold, which has been extensively documented and depends on the characteristic sizes of the texture. We examine here the influence of substrate deformability on this threshold velocity in two extreme scenarios.

Firstly, we analyze the impact of droplets on a liquid surface armored with hydrophobic particles. The liquid can exhibit Newtonian behavior or possess complex rheological properties, such as a yield stress. Our findings reveal a significant impact of particle size and liquid rheology on the impalement transition velocity.

Secondly, we explore the impact of droplets on textured elastic membranes. In this case, the impalement transition is influenced not only by the dynamic interaction between the droplet and the membrane but also by the deformation of the texture itself upon impact.

Sedimentation of Elastic Filaments

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Experiments show that a straight elastic filament bends as it sediments in a viscous fluid¹. These observations, however, seem to be at odds with the Resistive Force Theory, which predicts that a straight filament remains straight when settling either parallel or perpendicular to gravity. Given this discrepancy, previous models have instead employed the nonlocal Slender Body Theory, which accounts for hydrodynamic interactions between different parts of the filament². Although these nonlocal models have shown good agreement with experimental results, the inclusion of non-local effects complicates numerical and asymptotic analyses ; in particular, asymptotic solutions have only been obtained in the limit of weakly-flexible filaments. Bifurcation diagram for the amplitude normalised by the filament half-length.

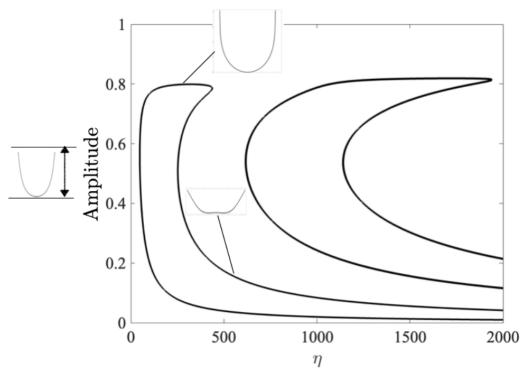


Fig. 2: Bifurcation diagram for the amplitude normalised by the filament half-length.

In this talk, we challenge the notion that non-locality is essential for explaining the observed shapes of sedimenting elastic filaments. In our analysis, we model hydrodynamic interactions following the Resistive Force Theory and focus on steady states. Our dimensionless model consists of a system of nonlinear ordinary differential equations involving a single compliance parameter, η . Irrespective of the value of η , we obtain two trivial solutions, representing horizontal and vertical filaments. However, when η exceeds a critical value, we observe a new branch of solutions that exhibit non-trivial shapes (see figure). Moreover, as η increases, additional solution branches emerge and disappear through a series of fold bifurcations. To gain further insight into these results, we consider the limit of flexible filaments (large η) and derive closed-form asymptotic formulae for the filament shape and settling speed. Furthermore, we show that the solution branches are related to the buckling modes of the filament. We discuss our results in light of previous experiments and simulations, demonstrating good qualitative and even quantitative agreement between them.

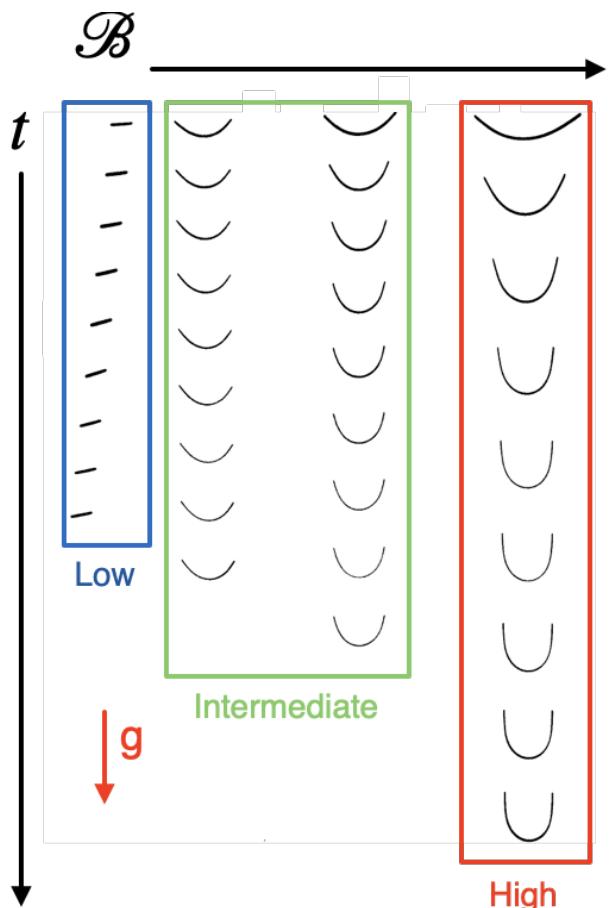
¹ Marchetti B. et al., Deformation of a flexible fiber settling in a quiescent viscous fluid, Phys. Rev. Fluids **3**, 104102, 2018

² Lagomarsino C. et al., Hydrodynamic Induced Deformation and Orientation of a Microscopic Elastic Filament, Phys. Rev. Lett 94, 148104, 2005 ; Li L. et al., The sedimentation of flexible filaments, J. Fluid Mech. **735**, 705-736, 2013

Settling of a Flexible Ribbon in a Viscous Fluid

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Ribbon sedimentation chronophotographies of increasing \mathcal{B} , ratio of gravitational torque over elastic torque.

The motion of a deformable elastic structure in a viscous fluid is of fundamental importance, from flagellar propulsion of micro-organisms, to wind-dispersed plant seeds and small flying insects. The interaction between internal elastic forces and hydrodynamic forces results in deformations of the object that govern its velocity.

Inspired by previous studies on the settling of elastic cylindrical fibers^{1, 2} or rigid slender ribbons³, we investigate experimentally the deformation and the settling velocity of elastic ribbons, at low Reynolds number.

We show that the deformation of the ribbons is governed by the competition between the torque applied by gravity to the ribbons and the typical elastic resisting torque, captured by a nondimensional number \mathcal{B} (see chronophotography on the left). Depending on the value of \mathcal{B} , i.e. the relative magnitude of these two effects, we observe three regimes of deformation, characterized by the length and the thickness of the ribbon, and independent of its width. These regimes can be classified as low and high deformation regimes, characterized by a drag proportional to the settling velocity, and an intermediate regime,

which exhibits a non-linear drag-velocity relationship.

¹Marchetti B., Raspa V., Lindner A., Du Roure O., Bergougnoux L., Guazzelli E., Duprat C. *Deformation of a flexible fiber settling in a quiescent viscous fluid*, Phys Rev Fluids, **3**, 104102, 2018

²Delmotte B., Climent E., Plouraboué F. *A general formulation of Bead Models applied to flexible fibers and active filaments at low Reynolds number*, Journal of Computational Physics, **286**, 14-37, 2015

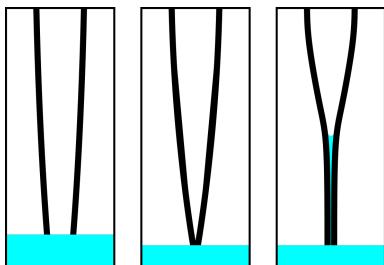
³Koens L., Lauga E. *Analytical solutions to slender-ribbon theory*, Phys Rev Fluids, **2**, 084101, 2017

Dynamics of the transition to a coalesced equilibrium of elastic fibers withdrawn from a liquid bath

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² LadHyX - École polytechnique, Rte de Saclay, 91120 Palaiseau, France



Two partially immersed elastic fibers. Images from left to right: attraction, contact, coalescence.

When slender elastic fibers separated by a small gap are withdrawn from a bath of a wetting liquid, attractive capillary forces due to the menisci cause them to draw nearer to each other and snap into contact once the capillary forces exceed what can be resisted by the stiffness of the fibers ¹. After the initial contact of the fibers at the level of the liquid bath, the system transitions towards a stable coalesced equilibrium state in which the two fibers are joined by a capillary bridge extending up to where the fibers diverge towards their respective points of support ².

This work investigates the dynamics of and mechanisms responsible for the transition to a coalesced equilibrium state after the initial contact, which are not well understood. In particular, we examine the capillary rise of liquid in the narrow gap between the fibers and their simultaneous self-assembly into a corner-like configuration. Experiments were conducted for withdrawal velocities ranging over nearly two orders of magnitude. In the quasi-static limit, experiments revealed regimes characterized by distinct rates at which fibers zip and join together. For increased withdrawal velocities, qualitatively different behavior of the fibers after contact suggest that there are other mechanisms responsible for the transition to a coalesced equilibrium state. Experimental results will be rationalized by considering the interactions between capillarity, elasticity, and viscous effects due to the necessary motion of liquid in thin films between the fibers in order to achieve the equilibrium configuration. This work contributes to the understanding of the coupling between imbibition into and deformation of elastic structures and to the general understanding of self-assembly of elastic objects due to capillarity.

¹Siefert, E., Hua, H., and Brau, F. Capillary coalescence of two partially immersed slender structures. Extreme Mechanics Letters **55**: 101823, 2022

²Py, C., Bastien, R., Bico, J., Roman, B., & Boudaoud, A. 3D aggregation of wet fibers. Europhysics letters, **77(4)**, 44005, 2007

Elastocapillary drying of flexible fibres suspensions

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¹ *LadHyX - École polytechnique, 91128 Palaiseau Cedex, France*

Nonwovens fibre-based materials such as paper are widely used for a variety of applications and could be largely developed as a sustainable alternative for fossil-based plastics¹. The first limitation of their widespread use is their response to moisture and more generally to liquids. Indeed, when wetted or dried, those materials exhibit irreversible deformations, structural changes and failure². The final mechanical properties of paper products highly depend on the initial fibre suspension and fabrication process. In particular, the removal of water from the suspension is a complex and crucial step which permanently affects the web structure and its subsequent interactions with liquids³. To gain a deeper understanding of the dewatering of fibrous networks, we investigate the drying of a model suspension composed of long and flexible hydrogel fibres.

Fig. 1 shows the successive top views of an experiment. At first, the fibres quickly sediment while water slowly evaporates. At one point, capillary forces start to act: adjacent fibres collapse into bundles that surrounds large pores filled with water. Upon further dewatering, air penetrates the network through the larger pores and the inter-fibre water starts to evaporate. Lastly, the fibres deswells as highlighted by their dimming and the whole network shrinks. We show how the drying dynamics and the network pattern are influenced by the drying conditions and the fibres characteristics: length, diameter and flexibility.

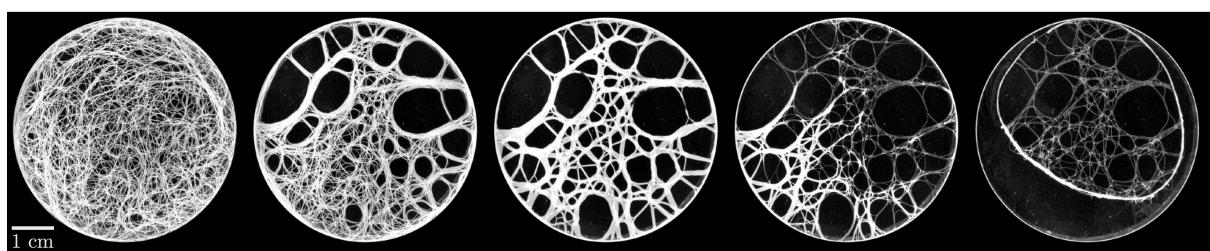


Fig.1: *Chronophotography of a drying suspension of hydrogel fibres of $90 \mu\text{m}$ in diameter, 3.5 cm in length and initial concentration $\phi = 0.06$, at 26°C and 12% RH. The experiment lasted 4 hours.*

¹Östlund, S., *Three-dimensional deformation and damage mechanisms in forming of advanced structures in paper*, Transactions of the 16th fundamental research symposium, 1–106, 2019

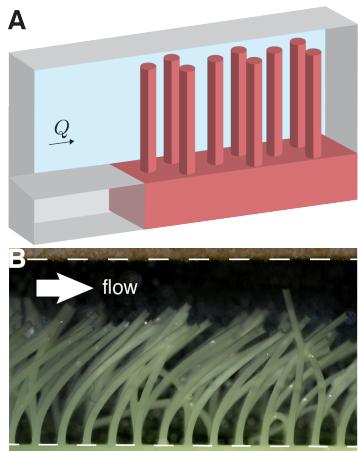
²Lee, M., Kim, S., Kim, H.Y., Mahadevan, L., *Bending and buckling of wet paper*, Physics of Fluids, **28**, 2016

³Keller, D.S., *Paper drying in the manufacturing process*, Paper and Water: A Guide for Conservators, 2013

Fluid flow in hairy channels

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¹ *LadHyX, CNRS, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*



A. Schematic of the experiment. **B.** Side view image of the experiment.

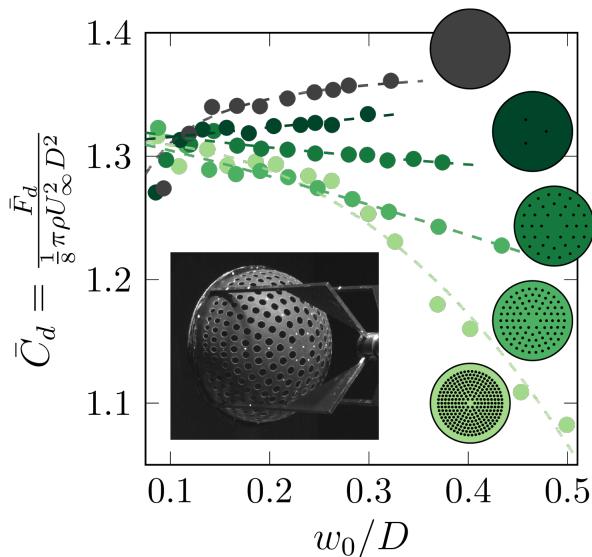
From fur to grass fields, large aggregates of one-dimensional deformable structures, i.e. elastic beams, in contact with fluids are ubiquitous in our daily lives. These slender structures, which can bend in response to the flow, are also omnipresent at the microscale inside and on the surface of living organisms under the name of filaments, flagella, hairs or cilia.

In this talk, I will explore how viscous liquids flow in a channel covered in thin elastic hairs. Using millifluidic experiments and theory I will discuss how the hair deformation couples to the flow to generate non-linearities in the flow response. In particular, I will show that in this Poiseuille configuration, the flow inside the hairs cannot be neglected and need to be accounted for.

Unsteady forces and flows behind a poro-elastic membrane disk

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Drag coefficient versus membrane deformation for different porosities. Inset: Photo of deformed porous membranes.

and drag forces for varying levels of porosity. As the dynamic pressure increases, the membranes undergo deformation, adopting spherical cap shapes, which consequently leads to the expansion of the pores (photo). The mean drag coefficient, \bar{C}_D , increases with larger deformation for non-porous disks (figure) due to increased levels of turbulent kinetic energy in the wake, as previously found in ³. Increasing levels of porosity reverses this trend, leading up to 20% drag reduction relative to the non-porous disks. Similarly, the drag fluctuations, C'_D , decrease with increasing porosity. Time-resolved PIV measurements of the wake behind the disks reveal the interplay between poro-elasticity, the shedding of coherent flow structures and their link to the drag forces experienced by the membrane. Our findings show that poro-elasticity stabilizes the unsteady wake behind the membranes, akin to natural mechanisms observed in dandelion seeds¹. We conclude our study by presenting a coupled aero-elastic scaling of the membrane deformation and associated porosity that characterizes the observed unsteady wake and drag behaviour with the aeroelastic number ($Ae = 1/Ca = T/[0.5\rho U_\infty^2 D]$).

In nature, flexible and porous structures are ubiquitous, aiding plants like dandelions in dispersing seeds or reducing structural loads of leaves in strong winds¹. The compliant and lightweight structures deform under fluid loading, reducing frontal area and streamlining body forms. Akin to these natural examples, kirigami structures deform into different shapes that have an upper limit on the drag reduction depending on their stiffness and patterns employed². Recent experiments by Mathai et al. reveal how vortex-induced oscillations behind a compliant membrane disk contribute to increased drag³.

This study extends that work and reports on the effects of poro-elasticity on thin circular membrane disks due to fluid loading, measuring deformation, unsteady vortex flow fields,

¹Cummins, C., Seale, M., Macente, A., Certini, D., Mastropaoletto, E., Viola, I.M., and Nakayama, N., *A Separated Vortex Ring Underlies the Flight of the Dandelion*. Nature, **562**, no. 7727: 414-18, 2018.

²Marzin, T., de Langre, E., and Ramananarivo, S., *Shape Reconfiguration through Origami Folding Sets an Upper Limit on Drag*. Proceedings of the Royal Society A, **478**, no. 2267: 20220592, 2022.

³Mathai, V., Das, A., Naylor, D.L., and Breuer, K.S., *Shape-Morphing Dynamics of Soft Compliant Membranes for Drag and Turbulence Modulation*. Physical Review Letters, **131**, no. 11: 114003, 2023.

Elastohydrodynamic of adhesion and translation of vibrating flexible foils near surfaces

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Inspired by locomotion strategies and soft robotics, we investigate the response of an elastic sheet submitted to vibrations and placed near a surface. A recent study¹ provides an experimental realisation – an eccentric rotating mass motor attached to a thin wafer – and shows that a vibrating sheet a few centimetres long can act as a contactless suction cup: it can support up to several hundred grams of weight and glide along the wall in a controlled fashion. We aim to rationalise this observation.

The key to this behaviour stems from the airflow and pressure developing in the thin layer separating the sheet from the surface. In particular, the elasticity of the sheet ensures that a time-reversible forcing can produce a non-reversible kinematics, allowing a net motion even at vanishingly small Reynolds number². Additionally, the Reynolds number is, in practice, small but finite, and the compressibility of air may also play a role: this grants this system additional possibilities to circumvent Purcell's scallop theorem and generate locomotion.

Given these points, we derive a lubrication model coupling the bending deformations of the elastic sheet and the viscous-dominated flow in the fluid layer, including the first-order effects of fluid compressibility³ and of fluid inertia⁴. We present our current attempts at rationalising intuitively and quantitatively how elasticity, compressibility, and inertia can each couple with vibrations and a viscous flow to produce a net lift or suction force. We also focus on the interplay of these effects with gravity to discuss the maximum weight the system can support as well as the equilibrium height it selects. We do so using asymptotic theory and compare our results with numerical solutions of the governing equations. We conclude by discussing future directions towards applications in soft robotics on both theoretical and experimental fronts.

¹W.P. Weston-Dawkes, I. Adibnazari, Y.W. Hu, M. Everman, N. Gravish, M.T. Tolley, "Gas-Lubricated Vibration-Based Adhesion for Robotics", Advanced Intelligent Systems 3(7), 2100001, 2021

²C.H. Wiggins, R.E. Goldstein, "Flexible and propulsive dynamics of elastica at low Reynolds number", Physical Review Letters 80.17 (1998): 3879

³G.I. Taylor, P. G. Saffman, "Effects of compressibility at low Reynolds number", Journal of the Aeronautical Sciences 24.8 (1957): 553-562

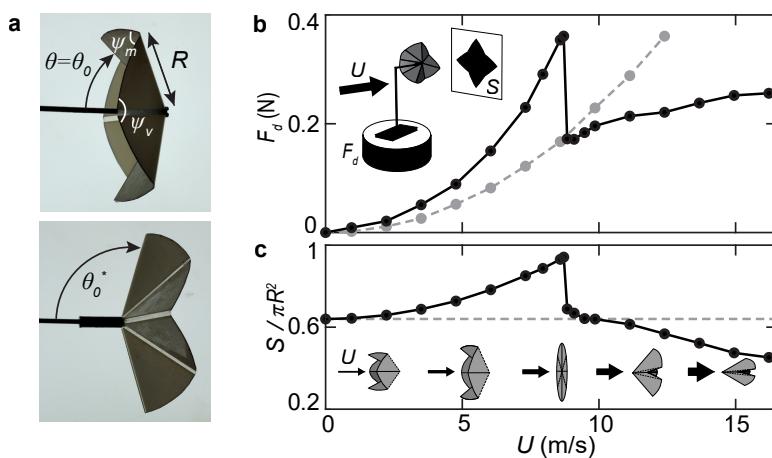
⁴N.O Rojas, M. Argentina, E. Cerdá, E. Tirapegui, "Inertial lubrication theory", Physical Review Letters, 104.18 (2010): 187801

Tunable drag drop in origami

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(a) Two stable states of the Waterbomb unit. Evolution of the Drag force F_d (b) and normalized frontal area $S/\pi R^2$ (c) of the unit with increasing flow speed U .

Prescribing specific folds enables one to get a desired kinematic pathway and mechanical properties in particular multistability².

Our study utilized a bistable origami unit, which shows a discontinuous evolution of drag with increasing flow speed. Airflow is used to passively actuate the origami unit which at a given critical flow rate snaps to a compact shape which causes a sudden drop in drag forces. We show that by changing the geometrical and mechanical properties of the unit the critical flow rate, maximum drag force, and drag jump can be fine-tuned. Experiments were corroborated by a theoretical aero-elastic model. The model was further used for the inverse design code. Which provides us with the geometrical and mechanical fabrication parameters required for the desired features of the drag curve. For example, we were able to achieve curves with the same maximum drag and critical flow rate but different drag jumps.

This study provides an Origami design strategy to make an efficient passive deployable structure with the ability to control drag in a fluid environment. The work can be applicable to make a pressure relief valve with a tunable pressure threshold.

The drag force typically rises with flow speed, except in cases like drag crisis or abrupt shape changes, such as wind-induced tree pruning¹. While pruning reduces drag sharply and maintains structure integrity, it's irreversible. An attractive alternative for abrupt shape change can be snap-through events in flexible structures. Origami provides a promising framework for crafting such shape-morphing structures. Prescribing specific folds enables one to get a desired kinematic pathway and mechanical properties in particular multistability².

¹Lopez, D. et al *Drag reduction, from bending to pruning*, EPL **108**, 48002, 2014.

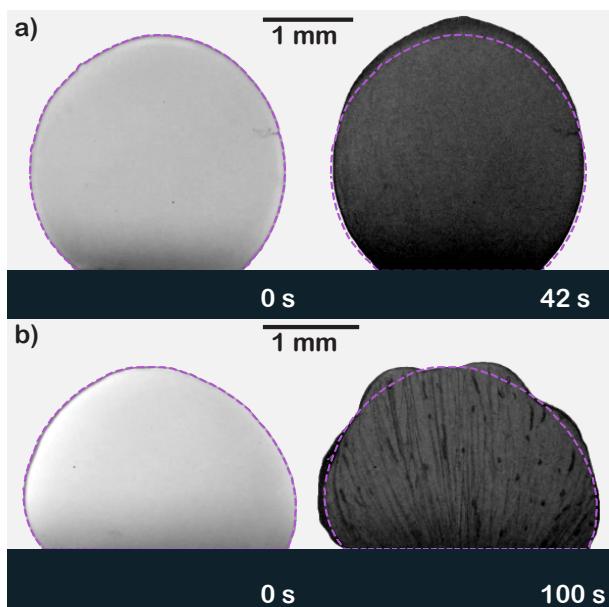
²Li S. et al *Architected Origami Materials: How Folding Creates Sophisticated Mechanical Properties*, Advanced Materials, 1805282, 2018.

Deformation of hydrogels during freezing

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² Université Paris Cité, CNRS, UMR 7057, Laboratoire "Matière et Systèmes Complexes" (MSC), 75205 Paris, France



a) 2% liquid (left) and frozen (right) agar drop at -38°C . b) 0.5% liquid (left) and frozen (right) agar drop at -11°C . Purple line is the initial shape.

two types of deformation results from a competition between the freezing velocity and that of the solvent moving through the hydrogel's porous matrix.

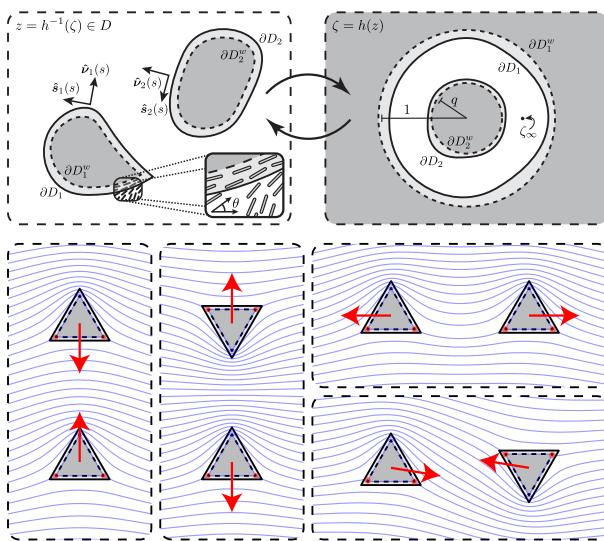
Hydrogel is a polymer matrix able of retaining a significant amount of water. During the directional freezing of water, it is well known that the ice formed leads to a larger volume as it is lighter than water. However, when varying the proportion of hydrogel or the temperature of the substrate, different types of shape changes occur. On Figure a, we observe mainly the elongation of the drop in the direction of the temperature gradient. We can describe quantitatively this deformation with simple hypotheses, inspired by previous work on water drop deformations under freezing¹. This can apply to any geometrical shape as hydrogel can be easily molded. In the case of slow freezing or hydrogels with reduced proportion of polymer, water is expelled from the gel onto its surface during the freezing process (Figure b, right) due to the poroelasticity of the material. In this talk, we will explain how the transition between these

¹D.M. Anderson et al, *The case for a dynamic contact angle in containerless solidification*, Journal of Crystal Growth **163**, 329-338, 1996

Fluid–body interactions in elastic anisotropic fluids

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Two bodies immersed in an nematic liquid crystal.

many biological settings.

In this talk, we will use complex variables to analytically solve for the interaction between bodies immersed in liquid crystalline environments. This approach allows for the solution of a wide range of problems, opening the door to studying the role of body geometry, liquid crystal anchoring conditions, and topological defects. Shape-dependent forces between bodies, local surface tractions, active stresses, and body deformation will also be discussed.¹²

Fluid anisotropy, or direction-dependent response to deformation, can be observed in biofluids like mucus or, at a larger scale, self-aligning swarms of bacteria. A model fluid used to investigate such environments is a nematic liquid crystal. Large colloidal particles undergo shape-dependent interactions when immersed in these complex environments, whilst deformable bodies (like red blood cells) tend to be stretched, offering a passive means of measuring cell material properties. Adding to the complexity are microorganisms that propel themselves through these environments, which give rise to active stresses, and topological defects, which focus elastic stresses and are important sites in many biological settings.

¹Chandler T.G.J & Saverio S.E., 2023, A nematic liquid crystal with an immersed body: equilibrium, stress, and paradox *J. Fluid Mech.* **967**, A19.

²Chandler T.G.J & Saverio S.E., 2023, Exact and approximate solutions for elastic interactions in a nematic liquid crystal. *Submitted. arXiv:2311.17708.*

Light control of bioconvective dynamics

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The unicellular green algae *Chlamydomonas* is bottom heavy: it spontaneously reorients its swimming to the top. This natural bioconvection favours the accumulation of a layer of denser cells at the free surface, which subsequently destabilises into sinking plumes. A regular pattern then develops over the whole petri dish (Fig. a, b), where darker spots indicate a higher algal concentration¹.

Chlamydomonas is also a phototactic microalgae, and we explored the effect of light on the plume pattern. When light comes from above or below, the pattern disappears. But when light comes from the side of the petri dish, plumes do not disintegrate and rather migrate at a velocity which depends on the light intensity, but not on the solution depth (Fig. c, d). The migration velocity arises from a balance between phototactic speed and bioconvective flows. We therefore explore velocity variations of a single alga a fonction of its light environment. We also wonder about the shape of plumes during their migration, as their top may bend to the light: we develop an echo-Doppler technique to access three-dimensional flows at a $\sim 100 \mu\text{m}$ scale.

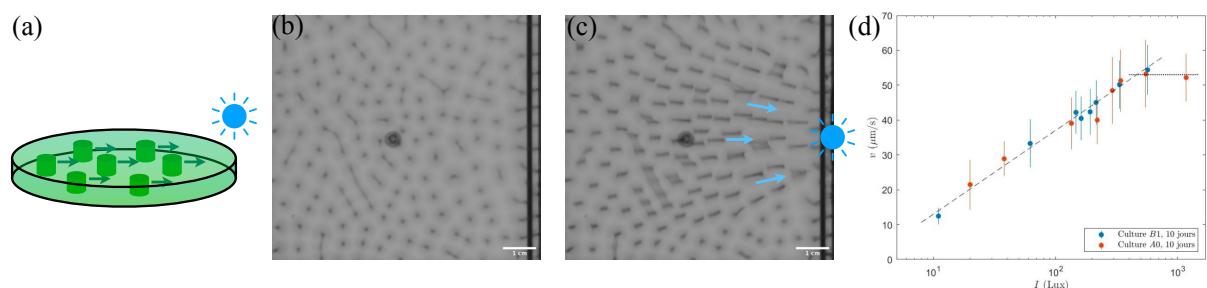


Figure: (a) Schematic of the experiment: plumes develop in a petri dish and skimming light is shown from the side. (b) Top view of the initial plum pattern. Scale bar is 1 cm. (c) Chronophotography over the first two minutes of lightening: plumes migrate to the light on the right. Blue arrows underline the direction of the motion. Scale bar is 1 cm. (d) Migration velocity v as a fonction of light intensity I in a semi-log scale. The dashed line shows a slope 1.

¹Martin A. Bees, *Advances in Bioconvection*, Annual Review of Fluid Mechanics, 449-476, 2020.

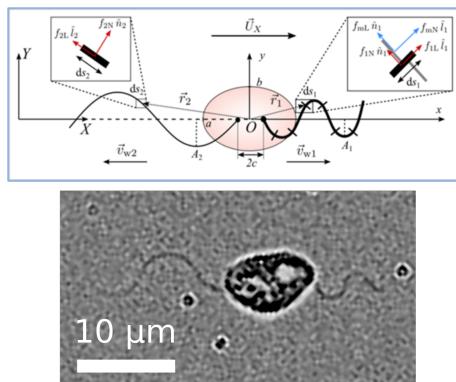
Swimming of plant pathogens zoospores

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Phytophthora zoospore.

Phytophthora species cause diseases in a large variety of plants and represent a serious agricultural threat, leading, every year, to multibillion dollar losses. Infection occurs when these biflagellated, unicellular, zoospores move across the soil at their characteristic high speed and reach the roots of a host plant. Characteristics of individual swimming of zoospores have not been fully investigated up to now. First, we present our study about the characteristics of two opposite beating flagella during translation and turning, and the roles of each flagellum on zoospore swimming. Here, combining experiments and modeling, we show

how these two flagella contribute to generate thrust when beating together, and identify the mastigonemes-attached anterior flagellum as the main source of thrust. Furthermore, we find that turning involves a complex active process, in which the posterior flagellum temporarily stops, while the anterior flagellum keeps on beating and changes its gait from sinusoidal waves to power and recovery strokes, similar to Chlamydomonas' breaststroke, to reorient its body to a new direction. Second, we present experiments of such microswimmers in more complex environment with walls, obstacles and confining structures. Third, we analyse the swimming behavior changes in a variable chemical environment.

Our study is a fundamental step towards a better understanding of the spreading of plant pathogens' motile forms, and shows that the motility pattern of these biflagellated zoospores represents a distinct eukaryotic version of the celebrated "run-and-tumble" motility class exhibited by peritrichous bacteria.

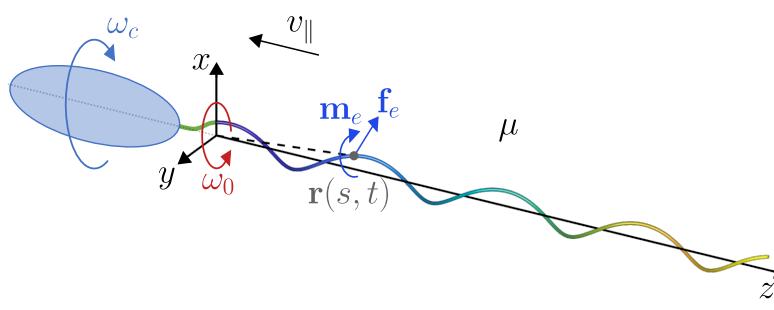
Twist dynamics of bacteria flagella

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Bacteria swim in viscous fluid by rotating slender elastic organelles (flagella) connected to rotary motors embedded in the cell wall. As each motor rotates, it winds up a short flexible ‘hook’ at the base of the flagellum, which transmits the torque produced by the motor to the helical flagellar filament during swimming. While the steady axial rotation of a helical filament in viscous fluid represents a classic problem in bacterial locomotion¹, the dynamic process by which a flagellum reaches a state of uniform rotation, following a change in motor speed, is much less understood. This process is too fast to be observed in real time, but high-speed imaging of the ‘flicking’ observed in single-flagellated bacteria — a type of instability in which the hook joint temporarily buckles to reorient the cell — has shown that the swimming speed recovers only after around ten milliseconds following motor reversal^{2,3}.



Here, we present an ‘effective column’ model for the flagellar filament, which replaces its helical geometry with a naturally-straight rod whose extensional and torsional deformations are coupled. The advantage of this model is that it may readily be combined with

resistive-force theory, to predict the time-dependent hydrodynamic loads and swimming speed resulting from a spatially-varying rotation rate. We then extend our model to incorporate twist-induced stiffening of the hook joint, which is known to occur during flicking³. We show that the hook stiffens on the timescale over which twist propagates along the length of the entire flagellum (hook and filament), and we calculate the time-dependent forces and moments exerted on the hook. Our analysis suggests that flicking relies on moments arising from ‘wobbling’ between the cell head and flagellum during swimming.

¹J. Lighthill. *Flagellar hydrodynamics*. *SIAM Rev.*, **18**(2): 161–230, 1976. doi: 10.1137/1018040

²L. Xie, T. Altindal, S. Chattopadhyay, and X.-L. Wu. *Bacterial flagellum as a propeller and as a rudder for efficient chemotaxis*. *Proc. Natl. Acad. Sci. U.S.A.*, **108**(6): 2246–2251, 2011. doi: 10.1073/pnas.1011953108

³K. Son, J. S. Guasto, and R. Stocker. *Bacteria can exploit a flagellar buckling instability to change direction*. *Nat. Phys.*, **9**(8): 494–498, 2013. doi: 10.1038/nphys2676

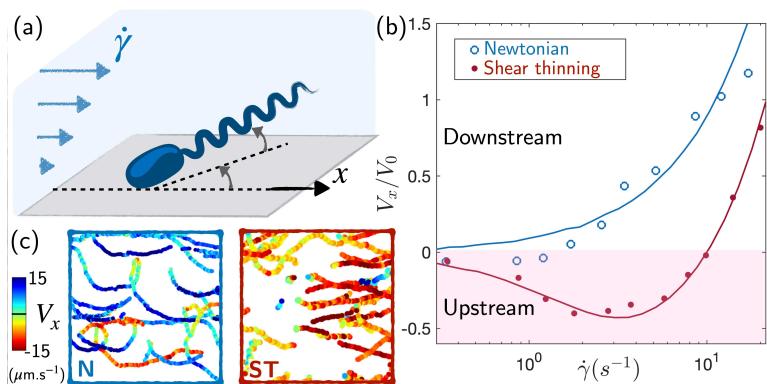
Bacterial upstream swimming is enhanced in non-Newtonian fluids.

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Our minimal model for the bacterium orientation (a) reproduces our experimental finding (b) that rheotaxis is enhanced in a shear-thinning fluid as swimmer trajectories are better aligned with the flow than in Newtonian fluids (c).

We demonstrate experimentally that near-wall rheotaxis is significantly enhanced in shear-thinning fluids, and can be sustained for a wide range of shear rates ². Using a minimal model and simulations, we show that the enhanced upstream swimming stems from the rectification of the trajectories of bacteria near walls in shear-thinning fluids. Because of the hydrodynamic interaction of the rotating head and counter-rotating flagella with the wall, bacteria in Newtonian fluids perform circular or loopy trajectories. This effect is reduced or suppressed in shear-thinning fluids where they instead swim in larger circles or straight lines. As a result, bacteria in shear-thinning fluids reorient upstream at lower flow rates, and are more aligned than in Newtonian fluids.

Our theoretical model accurately predicts the experimental observations in both Newtonian and shear-thinning fluids, and highlights the importance of fluid-mediated interactions with surfaces for bacterial contamination.

Bacteria often exhibit upstream swimming, in particular near walls. This process, called rheotaxis, can cause the contamination of biomedical devices and the infection in organs including the urethra or lungs. Surface rheotaxis has been studied extensively in Newtonian fluids,¹ but not the complex fluids that contain suspended particles or polymers, such as mucus or saliva, in which many microorganisms live.

¹Hill, J., Kalkanci, O., McMurry, J.L., and Koser, H. *Hydrodynamic surface interactions enable escherichia coli to seek efficient routes to swim upstream* Phys. Rev. Lett. (2007)

²Torres Maldonado B., Thery, Tao R., Brosseau Q., Mathijssen A. and Arratia, P. *Bacterial upstream swimming is enhanced in complex fluids*, (in preparation)

Self-buckling and self-writhing of semi-flexible microorganisms

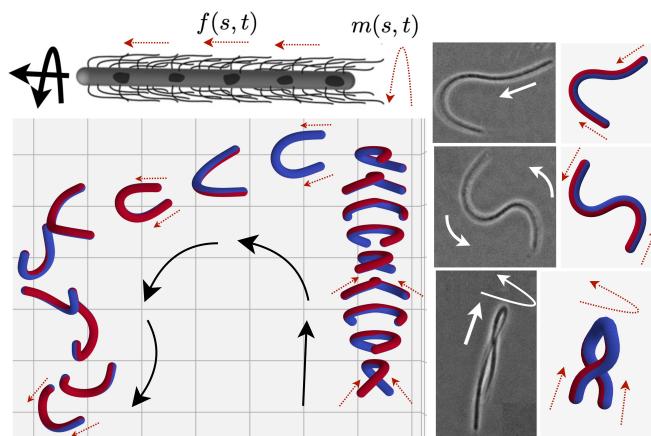
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The twisting and writhing of a cell body and associated mechanical stresses is an underappreciated constraint on microbial self-propulsion. Multi-flagellated bacteria can even buckle and writh under their own activity as they swim through a viscous fluid ¹. New equilibrium configurations and steady-state dynamics then emerge which depend on the organism's mechanical properties and on the oriented distribution of flagella along its surface. Modeling the cell body as a semi-flexible Kirchhoff rod and coupling the mechanics to a flagellar orientation field, we derive the Euler-Poincaré equations governing the dynamics of the system. Experimental observations of buckling and writhing in swimming *Proteus mirabilis* swarmer cells are reproduced by the model. Extending related work on the buckling of slender sedimenting filaments ²³, a sequence of bifurcations is identified as the body is made more compliant, due to both buckling and torsional instabilities. These studies highlight a practical requirement for the stiffness of bacteria below which self-buckling occurs and cell motility becomes ineffective.



The flagellar stress on a swarmer *P. mirabilis* cell is modeled as a dynamically evolving continuum, leading to predictions consistent with experimentally observed self-buckling and self-writhing dynamics.

¹Lough, W., Weibel, D.B. and Spagnolie, S. E. *Self-buckling and self-writhing of semi-flexible microorganisms*, Soft Matter **19**, 7349-7357, 2023.

²Li, L., Manikantan, H., Saintillan, D. and Spagnolie, S.E. *The sedimentation of flexible filaments*, J. Fluid Mech. **735**, 705-736, 2013.

³Manikantan, H., Li, L., Spagnolie, S.E. and Saintillan, D., *The instability of a sedimenting suspension of weakly flexible fibres*, J. Fluid Mech., **756**, 935-964, 2014.

The dynamics of elastic coupling in a two-link swimmer

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A swimming uniflagellar bacterium can be modelled as a rigid cell body attached to a rigid helical flagellum by a short flexible link called the ‘hook’. A molecular motor rotates the body end of the hook, and thence the flagellum, and drives the organism forward. A lot of effort has gone into detailed modelling of the body and flagellum for biologically realistic geometries and parameters, but less into modelling the bending of the hook or understanding its contribution to the dynamics.

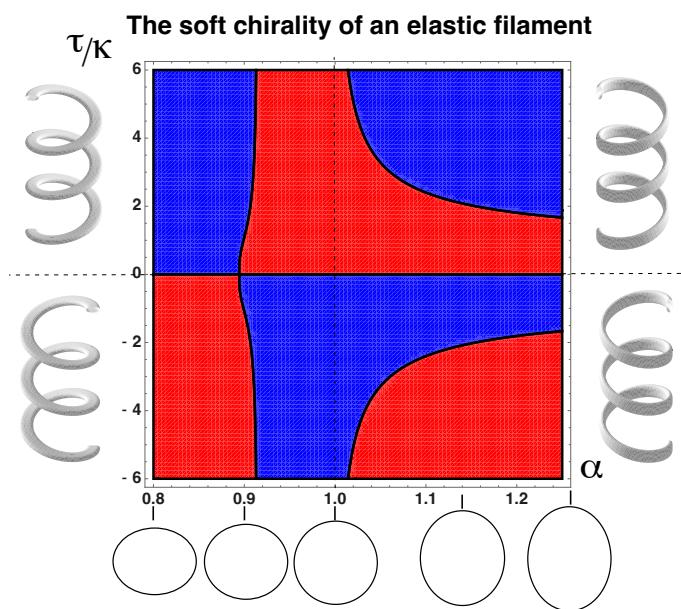
We present a complementary approach by analysing the dynamics of an idealised system of two rods connected by an elastic filament and driven by a follower force. With a Kirchoff-rod model of the filament, the whole forms a 5th-order dynamical system, with strong geometrical nonlinearity entering through the displacement–force relationship. We analyse the nature of the asymptotic reduction to a 1st-order system by a torsional-spring approximation, and consider when the bifurcation from straight swimming is stationary or oscillatory, and subcritical or supercritical.

The geometry and mechanics of chirality, hard and soft

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Many natural structures such as proteins, climbing vines, and seashells exhibit a well defined chirality, some are left-handed, some are right-handed, some are both. The ultimate origin of chirality is one of Nature's great mystery. However, geometry and mechanics play a fundamental role in assigning chirality and carrying this information from microscopic to macroscopic scales. A traditional way to define the hard chirality of a rigid body is to place it in a uniform flow and compute the torque acting on it. Assuming a linear response, the chirality of the body can be characterised in terms of the spectral properties of a symmetric tensor that connects the torque to the global field. However, if the object is soft, e.g. elastic, it will not only reorient but also deform in response to an external field. This deformation also possesses a chirality whose characterisation defines the problem of soft chirality. In this talk, I will use ideas from both fluid and solid mechanics to discuss the general problem of chirality, chirality measure, and chirality transfer, trace its history, and use examples from chemistry and biology to obtain general principles with some surprising twists.



Soft makes it hard to swim: Dynamics of self-propelled swimmers in soft micro-confinements

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The response of self-propelled microswimmers, e.g. pusher-type swimmers like flagellated bacteria, to alterations in the stiffness/softness of confining walls in their immediate vicinity, and their subsequent dynamics, remain ambiguous ^{1 2}. Here, we experimentally investigate the effects of reducing stiffness (increasing softness) of the walls of a micro-confinement on the swimming dynamics of self-propelled microswimmers, considering active droplets ³ in microchannels as a model system. We use a combination of double-channel fluorescence microscopy and micro-PIV analyses to reveal and characterize the microswimmer dynamics in the soft microchannels. In a microchannel with stiff walls, active droplets exhibit approximately unidirectional swimming along a wall with a steady velocity. However, in a soft microchannel of identical geometry, the droplet microswimmers exhibit unsteady swimming velocity with intermittent deceleration, stopping, and subsequent acceleration (Fig. 1). These intermittent stop events are followed by sharp reorientation in the subsequent swimming direction (Fig. 1). Interestingly, the microswimmer exhibits autonomous changes in its hydrodynamic signature over such stop events in the soft microchannel. We explain such swimming dynamics in a soft micro-confinement using concepts from squirmer hydrodynamics and soft lubrication.

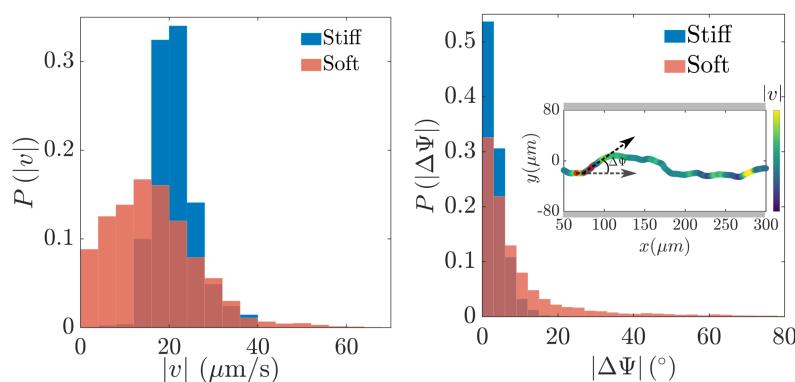


Fig. 1: Probability distributions for instantaneous swimming velocity magnitude (left) and local reorientation in swimming direction (right) for active droplets swimming in stiff and soft microchannels. Inset (in right) shows a swimming trajectory in a soft microchannel.

¹Song, F., Ren, D., *Stiffness of cross-linked poly(dimethylsiloxane) affects bacterial adhesion and antibiotic susceptibility of attached cells*, Langmuir **30**, 10354-10362, 2014

²Peng, Q. et al., *Three-dimensional bacterial motions near a surface investigated by digital holographic microscopy: Effect of surface stiffness*, Langmuir **35**, 12257-12263, 2019

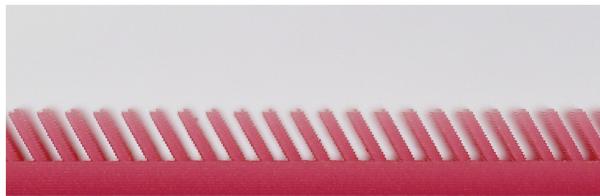
³Michelin, S., *Self-propulsion of chemically active droplets*, Ann. Rev. Fluid Mech. **55**, 77-101, 2023

Transport induced by nonlinear flow response in vessels with flexible leaflets

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Asymmetric leaflets in a channel.

Liquid flows in vascular networks are amongst the most effective ways to transport matter and information for life. Many of these vascular networks use asymmetric soft leaflets to generate fluid transport. These leaflets deform with the flow and promote unidirectional flows via nonlinear pressure-flow relationships.

One striking example is the lymphatic vascular network ¹ in which peristaltic contractions along vessels containing leaflets generate a remarkably efficient transport of interstitial fluid.

Here, we use asymmetric leaflets as local sources of nonlinearity and build bio-inspired channel networks in which unidirectional fluid transport emerges at low Reynolds numbers. We first study one channel and model the optimum leaflet geometry and leaflet density to maximize the fluid transport upon channel deformation. This channel is then duplicated to build a scalable porous material capable of efficiently pumping fluid upon contraction. In a second series of experiments, we explore the role of nonlinearity on peristaltic pumping. From these observations, we model how nonlinearity enables unidirectional fluid transport independently of the directionality of the peristaltic wave and identify unexpected regimes for which forward fluid transport is maximized for backward propagating peristalsis.

Our results highlight how nonlinear flow responses can be tuned to maximize fluid transport in vessels and vessel networks. This opens the way to a better understanding of the lymphatic vascular system and the diseases connected to its failure.

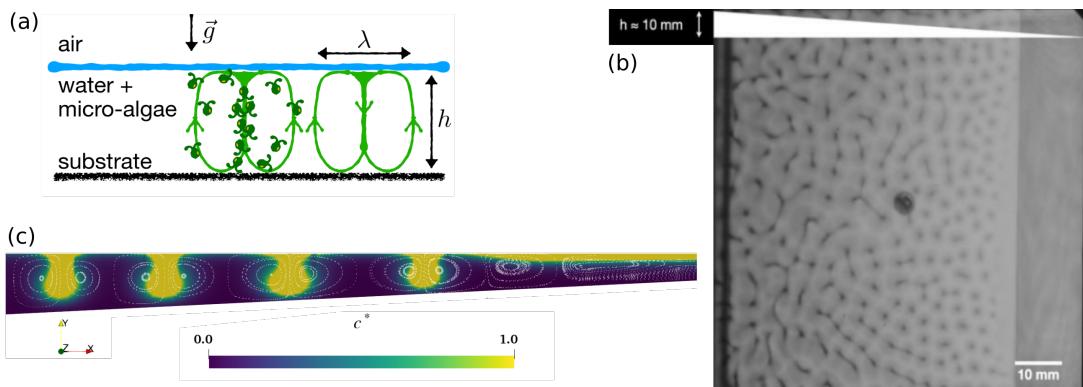
¹Moore, J.E. and C.D. Bertram *Annu. Rev. Fluid Mech.*, **50(1)** (2018.)

Symmetry breaking through confinement in biological fluids

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¹ *∂'Alembert - Sorbonne Université, Place Jussieu, 75005, Paris, France*

A dense solution of *Chlamydomonas Reinhardtii* (CR) spontaneously destabilises to form plumes (fig. a)¹. The center of the plumes appears black, indicating an area of high algal concentration. Surprisingly, currents generated in these convection cells are up to 10 times faster than the swimming speed of a single microalgae itself. The wavelength that naturally appears in this pattern is proportional to the depth of the solution, and the plumes are statistically steady. But, what happens when the thickness of the solution is not constant? We study how spatial confinement affects symmetry breaking of these active fluids, coupling experimental (fig. b) and numerical (fig. c) tools, both developed in our group. A continuum approach² is implemented within NekStab³, providing 3D measurements and global modes, key to identify the underlying physics. We show how this asymmetric confinement gives rise not only to a geometrical, but also to a temporal symmetry breaking of this out-of-equilibrium biological system.



(a) Sketch of CR plume, side view. (b) top view from an experiment, with the onset of plume patterns in a CR solution. Black dots characterise areas of high algal concentration. Depth decreases linearly from 10 (left) to 0 (right) mm. (c) Simulation of the same configuration, detail, side view. Both plume dimensionless concentration (c^*) and intensity (streamlines) varies with depth.

¹John O. Kessler. *Co-operative and concentrative phenomena of swimming micro-organisms*, Contemporary Physics, March 1985

²Pedley et al., *The growth of bioconvection patterns in a uniform suspension of gyrotactic micro-organisms.*, Journal of Fluid Mechanics, 1988

³Frantz, R. A. S. and Loiseau, J.-Ch. and Robinet, J.-Ch., *Krylov Methods for Large-Scale Dynamical Systems: Application in Fluid Dynamics*, Applied Mechanics Reviews, 2023

Exploring the link between the spatial organisation of ciliated cells and the supported physiological function in *Xenopus* embryo

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From swimming microorganisms to major organs, ciliated epithelia are ubiquitous in living systems. Active cilia fulfil myriads of biological functions including locomotion, feeding, washing and transport. The vast diversity of cilia in terms of morphology, dynamics and spatial arrangement at both cellular level and tissue scales, suggest that it exists a configuration optimised to a dedicated physiological function. One fascinating example is found on the skin of *Xenopus* embryo, where the ciliated cells are distributed on the nodes of a regular array. This specific spatial organisation has been hypothesised to be optimised to wash external pathogens from the surface of the embryo. This hypothesis is supported by the fact that the ciliated epithelium is only present during a few days, when the immune system of the embryo is not mature. Yet the link between the spatial organisation of ciliated cells and the physiological function it supports remains to be established.

We combine experimental active matter physics with computational fluid dynamics and cell biology techniques to test this hypothesis. We cultivate in-vitro ciliated epithelia of *Xenopus* embryo on which we can modify the spatial distribution of the ciliated cells. We quantify the spatial distribution and beat directions of ciliated cells and the resulting 3d flow field at the tissue scale. The measured physical parameters serve as a basis to calibrate and validate a numerical hydrodynamic model. Then, we use this model to compute the 3d flows generated across the entire embryo. By systematically varying, numerically, the density and spatial distribution of ciliated cells, we predict the probability of bacteria to reach the surface of the embryo.

We showed that the ciliated cells on the flanks of the embryo create a liquid shield that protects the embryo from external pathogens. Remarkably, this protective barrier is very robust against variations in both density of ciliated cells and spatial distribution. This suggests that the system does not optimise the function from an energetic point of view. Rather, the biological system appears to prioritise the optimization of physiological function robustness, ensuring functionality even within challenging environmental conditions.

Flow-induced choking of soft channels

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We present an experimental study of the flow-induced deformation of a soft channels. Initially, we consider a compliant Hele-Shaw cell, comprising a soft substrate and a rigid upper boundary separated by a thin gap, as shown in Fig. 1a. An axisymmetric displacement flow is formed by injecting viscous fluid, at a constant volumetric flux, into the center of a cell which is pre-filled with the same fluid. The injected fluid spreads from the central source towards the cell rim, which acts as a sink, displacing fluid that was initially resident in the cell. The non-uniform pressure distribution within the fluid deforms the soft solid which, being laterally confined, compresses near the cell centre and bulges near the cell rim, as shown in Fig. 1b.

This raises the possibility of flow-induced ‘choking’ of the cell, whereby the deforming solid makes contact with the upper boundary and seals the gap, preventing fluid from escaping the cell¹. By measuring the flow-induced deformation of a soft elastomer and modelling the fluid-structure interaction, we identify the critical flow rate above which the flow is interrupted.

Finally, we turn our attention to on-going work focused on flow through a soft channel of circular cross-section., and how channel geometry affects the threshold for choking. Our goal is to design a soft fluidic fuse that functions as a passive flow limiter and can be integrated into microfluidic devices for flow control.

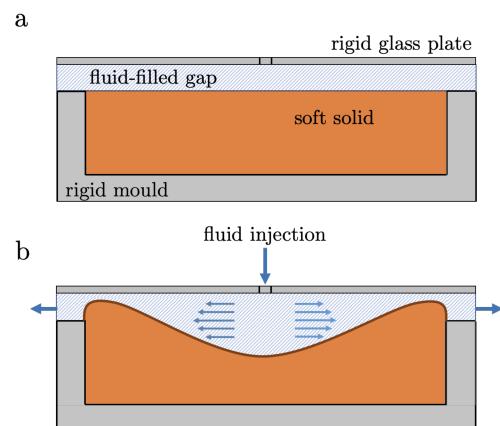


Fig. 1: a. Schematic diagram of a compliant Hele-Shaw cell. b. Injected fluid spreads outwards and deforms the soft solid.

¹Box, F. , Peng, G.G., Pihler-Puzović, D. and Juel, A. *Flow-induced choking of a compliant Hele-Shaw cell*, PNAS, **117** (48), 30228-30233, 2020

Fluid-structure interaction of a cylinder in a stratified fluid

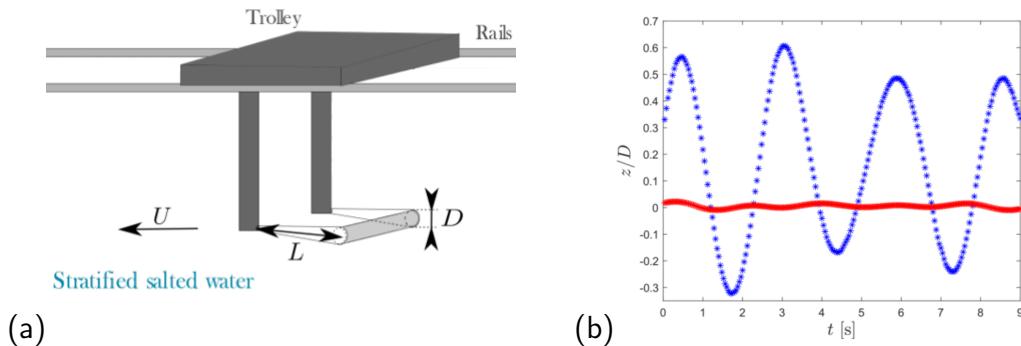
P. Meunier¹, S. Christin¹, S. Le Dizès¹

¹ IRPHE, Aix Marseille Univ, CNRS, Centrale Marseille, 13013 Marseille, France

Fluid-structure interactions have been widely studied in the past century, mainly under the angle of Vortex Induced Vibration (VIV) where the structure oscillates when the vortex shedding frequency induced by the flow is close to the structure's frequency¹. However, although most geophysical fluids are stratified, this kind of study has never been carried out in a non-homogeneous fluid.

The classical experiment of a spring-mounted cylinder is adapted to the case of a fluid linearly stratified in density using salt (see figure 1a). Cylinders of various diameters D (3, 4 and 6 cm) are towed horizontally using arms which are free to rotate, thus allowing vertical oscillations of the cylinder. The drag creates a restoring force which mimics the action of a spring in classical VIV experiments.

Figure 1(b) shows the vertical position of the cylinder as a function of time in both the stratified (blue symbols) and homogeneous (red symbols) cases. Clearly, the strong oscillations of the cylinder only exists for the stratified case. This can be explained by the restoring buoyancy force which modifies the resonance frequency of the VIV mode². Furthermore, a large amplitude galloping mode has been observed in contrast to a homogeneous cylinder wake where this type of vibration cannot occur. This study shows that stratification has a strong influence on the flow induced vibration phenomena occurring to a cylinder.



- (a) Experimental set-up for a cylinder towed horizontally and free to oscillate in the vertical direction.
- (b) Temporal evolution of the altitude of the cylinder in the homogeneous case (red) and in the stratified case (blue symbols).

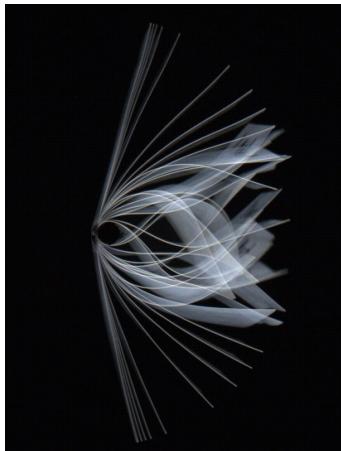
¹Williamson, C.H.K., Govardhan, R.. *Vortex-induced vibrations*, Annu. Rev. Fluid Mech. **36**, 413-455, 2004

²Christin, S., Meunier, P., Le Dizès, S. *Fluid-structure interactions of a circular cylinder in a stratified fluid*, J. Fluid Mech., **915**, A97, 2021

Instability Limitation of Drag Reduction by Elastic Reconfiguration

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Many natural structures such as plant leaves and bird feathers exhibit remarkable adaptive and compliant behaviors, deforming with large amplitude under aerodynamic/hydrodynamic loading. These behaviors give rise to various phenomena, including the swaying of trees due to the wind, the dynamics of branches and plants, and the fluttering of tree leaves. Such phenomena can have repercussions on society and the economy; for instance, broken trees can damage electrical installations, block roads, or harm houses ¹.

To better understand the fundamental mechanics at play in these challenges, simpler idealized structures offer the possibility to conduct clean and reproducible experiments. We consider an ideal plant leaf as a flexible, thin, rectangular plate clamped at the midpoint and positioned perpendicular to an airflow.

Dynamic behavior of reconfigured plate in wind tunnel.

Flexibility offers advantages at low to moderate flow speeds, enabling drag reduction through elastic reconfiguration. However, this same flexibility may lead to various flow-induced vibration phenomena at higher flow speeds.

An experimental wind tunnel campaign is conducted to identify the limitation to elastic reconfiguration that instability imposes, while also investigating the wake characteristics of the flexible plates using Particle Image Velocimetry (PIV), thus providing insights into the presence or absence of VIVs (vortex-induced vibrations) in the wake.

Here, we show by increasing the flow speed that the flexibility permits a considerable drag reduction by reconfiguration, compared to the rigid case. Our results reveal the existence of a critical flow velocity below which static reconfiguration with drag reduction is possible and above which a dynamic instability with important fluctuating loads is present. The critical dimensionless velocity is dependant on the mass number. Therefore, the optimal flexibility for the structure that leads to a drag reduction by reconfiguration while avoiding dynamic instability is also dependant on the mass number. Furthermore, experiments show that our flexible structure can exhibit two flutter modes: symmetric and anti-symmetric, depending on its mass number. The findings contribute valuable insights into the interplay of flexibility, instability, and aerodynamic performance in the dynamic behavior of flexible plates and the flow.

¹Boukor, M., Choimet, A., Laurendeau, É., Gosselin, F.P. (2023). *Flutter Limitation of Drag Reduction by Elastic Reconfiguration*. Accepted in Journal Physics of Fluids, arXiv preprint arXiv:2312.16115.

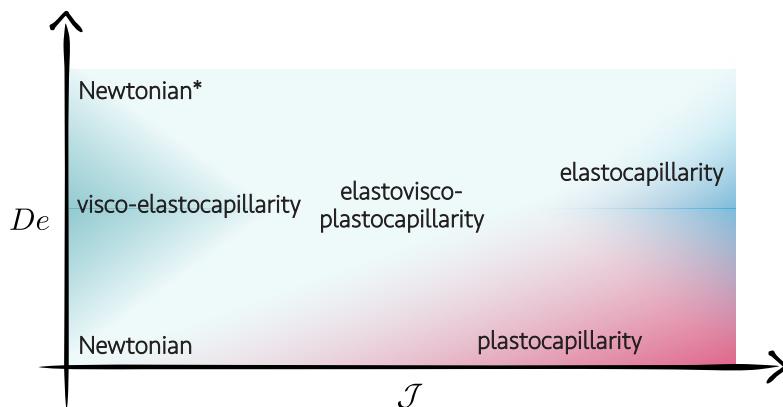
Elasto-Visco-Plastocapillarity

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Yield stress fluids such as emulsions, suspensions, gels, or foams feature peculiar mechanical properties. Below the yield stress, they behave like soft visco-elastic solids, but once sufficiently stressed, they flow like a viscoelastic liquid. Many problems in engineering and geophysics feature the free surface flow of a yield stress fluid. Although negligible at large scales (e.g. lava flows and landslides), capillary forces may become significant at small scales (e.g. coating polymeric materials and 3D printing). We refer to the phenomena in this regime as Plastocapillarity, highlighting the importance of permanent plastic deformation and surface tension forces. Here, we present a computational framework for capillary flows of yield stress fluids with elasto-viscoplastic properties ¹. Droplet spreading will be studied as the archetypal example and the effect of important dimensionless numbers (Deborah, Plastocapillary, and Ohnesorge) will be systematically analyzed. We will compare the computational results with our experiments and asymptotic solutions ². Finally, we will discuss the open problems in the field.



The general case of elasto-visco-plastic spreading reaches different regimes, depending on which rheological factor (elasticity or plasticity) dominates. Here, we will discuss these limits.

¹Franca, H.L., Jalaal, M. and Oishi, C.M., *Elasto-viscoplastic Spreading: from Plastocapillarity to Elasto-capillarity*, Physical Review Research to appear, 2024

²Jalaal, M., Stoeber, B. and Balmforth, N.J., *Spreading of viscoplastic droplets*, Journal of Fluid Mechanics, 914, p.A21. 2021

Buoyant porous thin disks fall straighter than solid ones

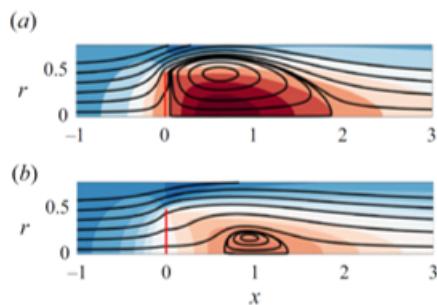
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Isocontours of the streamwise component of the base flow relative velocity for (a) low and (b) large permeabilities and $Re = 85$.

The prediction of trajectories of buoyancy-driven objects immersed in a viscous fluid is a key problem in fluid dynamics. Simple-shaped objects, such as disks, present a great variety of trajectories, ranging from zig-zag to tumbling and chaotic motions¹. Yet, similar studies are lacking when the object is permeable. We perform a linear stability analysis of the steady vertical path of a thin permeable disk, whose flow through the microstructure is modeled via a stress-jump model based on homogenization theory². The relative velocity of the flow associated with the vertical steady path presents a recirculation region detached from the body, which shrinks and eventually disappears as the disk becomes more and more permeable. In analogy

with the solid disk, one non-oscillatory and several oscillatory modes are identified and found to destabilize the fluid–solid coupled system away from its straight trajectory. Permeability progressively filters out the wake dynamics in the instability of the steady vertical path. For sufficiently large permeabilities, the disk first undergoes a non-oscillatory divergence instability, which is expected to lead to a steady oblique path with a constant disk inclination, in the nonlinear regime. A further permeability increase reduces the unstable range of all modes until quenching of all linear instabilities.

¹Ern, P., Risso, F., Fabre, D. and Magnaudet, J., *Wake-induced oscillatory paths of bodies freely rising or falling in fluids*, *Annu. Rev. Fluid Mech.* **44**, 97-121, 2012.

²Zampogna, G.A. and Gallaire, F., *Effective stress jump across membranes*, *J. Fluid Mech.* **892**, A9, 2020

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