27–29 August 2018

# SOLVAY WORKSHOP

## *Mechanics of slender structures in physics, biology and engineering:*

*From failure to functionality*

# ABSTRACT BOOK

## INVITED TALKS

### Curves, strings, rods, filaments, and strips: elasticity, morphoelasticity, and configurational elasticity.

Alain Goriely
University of Oxford, UK

The theory of elastic curves dates back to the 18th century and is a pillar of all mechanics and applied mathematics. While the classic theory of rods was fully formulated by the end of the19th century, there was a strong revival in the 1980s when it was understood that these structures could be used to model DNA. More recently, elastic rods and its multiple generalizations are again an exciting field of study motivated by a host of new applications in multiple fields and elegant experiments. In this talk, I will give a general overview of the topic and discuss in more depth the case of morphoelastic rods where curves are allowed to o grow and remodel.

### Geometrically incompatible confinement and generalized tension field theory: from Euler elastica to Gauss-Euler elastica

Benny Davidovitch
University of Massachussetts, USA

The mechanics of elastic sheets is described by a rather simple energy: $U_{elas} = U_{strain} + U_{bend}$, both of these terms are harmonic functions of strain and curvature, respectively. Nevertheless, even under small deviations from planarity, the physics is highly nontrivial, leading to the formation of complex patterns of wrinkles, crumples, and folds that emerge to release the highly energetic strain. The origin of this complexity stems from the geometric coupling between strain and curvature, and the lack of a general “virial theorem” that fixes the ratio between $U_{bend}$ and $U_{strain}$. When the deformed shape is developable (*i.e.* no Gaussian curvature), the geometric nonlinearity is resolved by the *Euler elastica*, whose variational principle is: Solve $\delta\, U_{bend} = 0$ under the constraint: $U_{strain} = 0$ (and suitable BCs). However, when tensile loads and/or Gaussian curvature are imposed on a sheet, *Gauss' Egregium theorem* asserts that strain is unavoidable, hence Euler *elastica* is no longer valid, and one must resort to a full-fledge variational calculus of the Föppl-von-Kármán (FvK) energy: $\delta\, U_{elas} = \delta\,[U_{strain} + U_{bend}] = 0$. An illuminating example is the “spherical stamping” problem (Hure *et al.* PRL 2012), where a thin sheet is confined into a narrow gap between two concentric, rigid spherical shells. Other examples, paramount to elasto-capillary phenomena, are the partial wetting of a stretched sheet (Huang *et al.* Science 2007, Schroll *et al.* PRL 2013, Nadderman *et al.* PNAS 2013, Schulman & Dalnoki-Verres *et al.* PRL 2015, Davidovitch & Vella Soft Matter 2018), and placing of a sheet onto a liquid meniscus (King *et al.* PNAS 2012, Paulsen *et al.* Nat. Mat. 2015). In these problems, and numerous other systems, the complex patterns reflect an interplay between avoiding the stamping-imposed strain and the cost of bending.

Focusing on wrinkle-like deformations, I will present a chain of variational principles -- the standard “tension field theory” (TFT) and its generalized version (“inverted tension field theory”, ITFT) -- that interpolate between the Euler *elastica* and the full-fledge FvK problem. The first addresses problems

in which confinement is governed by tensile loads (*e.g.* typical elasto-capillary problems), whereas the second addresses problems in which confinement is associated purely with an imposed Gaussian curvature (*e.g.* the spherical stamping problem). I will describe how each of these variational principles reduces to the full FvK equations in various asymptotic limits, characterized by the bendability of the sheet and the level of imposed confinement. I will further show how each of these principles can be employed to study wrinkle patterns using a "far from threshold" analysis.

## Geometric models for thin sheets at liquid interfaces

Vincent Démery
ESPCI & ENS Lyon, France

Understanding the response of thin sheets to complex loadings is difficult due to the large displacements involved and the interplay between mechanics and geometry owing to the two-dimensional nature of the sheet. Complex loadings are ubiquitous in elasto-capillary problems, where the sheet can be constrained to lie on a curved surface or submitted to a surface tension gradient. I will present a model that we developed to handle the gross shape of a thin (~ 100 nm) polymer sheet in such situations. This model is geometrical since it does not depend on the mechanical properties of the sheet in a wide range of parameters.

## Building with fluids, lazy design of functional materials

Pierre-Thomas Brun
Princeton University, USA

From mechanical mematerials, to photonic and phononic materials and to super-hydrophobic surfaces, the need to fabricate hierarchical and topological structures is well established. These functional materials challenge existing manufacturing paradigms and prompt the development of new fabrication methods with improved scalability, design flexibility and robustness. Here we harness the Rayleigh-Taylor instability in thin polymeric liquid films to spontaneously fabricate structured materials. The fluidic instability yields pendant drops lattices, which become solid upon curing of the polymer, thereby permanently sculpting the materials interface. We solve the so-called inverse design problem, taming the instability, so that the structures we form can be tailored, of a range of size spanning over two decades. Finally, we show that this all-in-one methodology can be extended to a broad class of capillary flow to "build with fluids" and fabricate architected soft materials.

## Elastohydrodynamics of an immersed particle near a soft wall

Thomas Salez
CNRS, University of Bordeaux, France and Hokkaido University, Japan

Soft and wet contact arises in a range of phenomena that spans many length and time scales, and includes: landslides, aquaplaning of tires, wear of industrial bearings, ageing of synovial and cartilaginous joints, cell motion in blood vessels or microfluidic devices, and atomic-force or surface-force rheology. Therein, the coupling between boundary elasticity and confined viscous flow leads to a striking zoology of counterintuitive emergent effects. From the canonical situation of a free particle that can simultaneously sediment, slide, and roll in a viscous fluid, and near a soft wall, we explore [1-3] a range of novel inertial-like (despite the low-Reynolds-number flow) features, such as: enhanced sedimentation, elastohydrodynamic bouncing, roll reversal, emergent lift and torques...

[1] Journal of Fluid Mechanics **779**, 181 (2015).
[2] Proceedings of the National Academy of Sciences of the USA **113**, 5847 (2016).
[3] Physical Review Fluids **2**, 074102 (2017).

## Liquid drops on slender structures: From partial wetting to insect adhesion

Dominic Vella
University of Oxford, UK

Soft surfaces are wetted by small liquid drops in a range of scenarios: eye-lashes get wet when we cry while insects use small scale droplets to walk on the ceiling. I will discuss a range of problems in which the wetted object is slender, and hence highly bendable. I will begin by showing that capillary-induced deformation generically induces a considerable tension in the structure itself, shedding new light on experiments that claim to measure pre-existing tensions using deviations from Young's contact. I will then discuss a couple of dynamic problems involving droplets, showing how droplet motion can be controlled at small scales using slenderness but also how capillarity leads to some new insights into the buckling of slender structures.

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## Instabilities in Blistering

Draga Pihler-Puzovic
University of Manchester, UK

Blisters form when a thin surface layer of a solid body separates/delaminates from the underlying bulk material over a finite, bounded region. It is ubiquitous in a range of industrial applications, e.g. blister test is applied to assess the strength of adhesion between thin elastic films and their solid substrates, and during natural processes, such as formation and spreading of laccoliths or retinal detachment.

We study a special case of blistering, in which a thin elastic membrane is adhered to the substrate by a thin layer of viscous fluid. In this scenario, the expansion of the newly formed blister by fluid injection occurs via a displacement flow, which peels apart the adhered surfaces through a two-way interaction between flow and deformation. Such blisters are prone to fluid and solid mechanical instabilities, which can interact with each other. If the injected fluid is less viscous than the fluid already occupying the gap, patterns of short and stubby fingers form on the propagating fluid interface in a radial geometry. This process is regulated by membrane compliance, which if increased delays the onset of fingering to higher flow rates and reduces finger amplitude. We find that the morphological features of the fingers are selected in a simple way by the local geometry of the compliant cell. In contrast, the local geometry itself is determined from a complex fluid–solid interaction, particularly in the case of rectangular blisters. Furthermore, changes to the geometry of the channel cross-section in the latter case lead to a rich variety of possible interfacial patterns.

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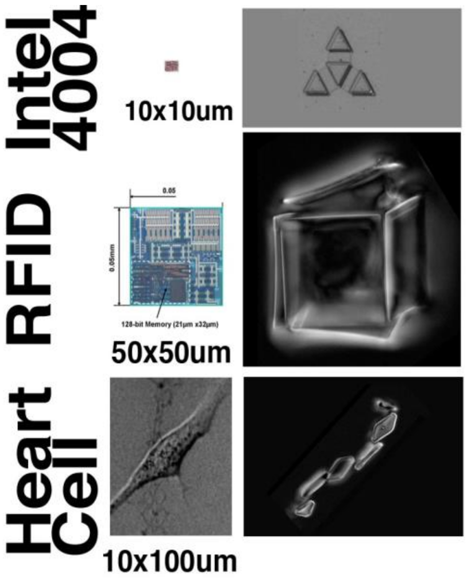
## Atomic Origami: a technology platform for nanoscale machines, sensors, and robots

Itai Cohen
Cornell, USA

What would we be able to do if we could build cell-scale machines that sense, interact, and control their micro environment? Can we develop a Moore's law for machines and robots?

In Richard Feynman's classic talk "There's Plenty of Room at the Bottom" he foretold of the coming revolution in the miniaturization of electronics components. This vision is largely being achieved and pushed to its ultimate limit as Moore's Law comes to an end. In this same lecture, Feynman also points to the possibilities that would be opened by the miniaturization of machines. This vision, while far from being realized, is equally as tantalizing. For example, even achieving miniaturization to micron length scales would open the door to machines that can interface with biological organisms through biochemical interactions, as well as machines that self-organize into superstructures with mechanical, optical, and wetting properties that can be altered in real time. If these machines can be




interfaced with electronics, then at the 10's of micron scale alone, semiconductor devices are small enough that we could put the computational power of the spaceship Voyager onto a machine that could be injected into the body. Such robots could have on board detectors, power sources, and processors that enable them to make decisions based on their local environment allowing them to be completely untethered from the outside world.

In this talk I will describe the work our collaboration is doing to develop a new platform for the construction of micron sized origami machines that change shape in fractions of a second in response to environmental stimuli. The enabling technologies behind our machines are graphene-glass and graphene-platinum bimorphs. These ultra-thin bimorphs bend to micron radii of curvature in response to small strain differentials. By patterning thick rigid panels on top of bimorphs, we localize bending to the unpatterned regions to produce folds. Using panels and bimorphs, we can scale down existing origami patterns to produce a wide range of machines. These machines can sense their environments, respond, and perform useful functions on time and length scales comparable to microscale biological organisms. With the incorporation of electronic, photonic, and chemical payloads, these basic elements will become a powerful platform for robotics at the micron scale.  As such, I will close by offering a few forward-looking proposals to use these machines as basic programmable elements for the assembly of multifunctional materials and surfaces with tunable mechanical, optical, hydrophilic properties.

## From 2D plates to 3D structures: playing with Carl Gauss

José Bico
ESPCI, France

Projecting the Earth on a planar map without distorting distances has long been a vain challenge, as rationalized two centuries ago by Carl Gauss in his seminal "theorema egregium". Similarly, transforming a 2D sheet into a 3D object can be a complicated issue when the transformation involves a change in the “Gaussian” curvature.

Plants and more generally living organism have however adopted a clever strategy to build complex patterns: differential growth. Can we find some inspiration from plant growth and develop structures as beautiful as petals or leaves? We will try to challenge Gauss remarkable theorem with macroscopic model experiments on transformable plates.

## Naturally integral

Julian Lienhard
str.ucture GmbH Stuttgart, Germany

The inseparable combination of material function and form is a criterion which is particularly true to natural systems. Due to the growing availability of high-performing materials and the rising computational power of our simulation and planning tools, it is now possible to explore structures whose forms are based on material behavior rather than pre-defined typologies. The research presented in this presentation explores such material behavior-oriented systems through the example of static and kinetic lightweight structures. From an engineering perspective design principal for lightweight structures are compared to design strategies found in natural organisms to discuss how the understanding of one cane influence the other (see table below).

| Engineering design principles | Natural design strategies |
|---|---|
| Light Materials | - Anisotropy |
| Light structures | - Heterogeneity<br>- Hierarchy |
| Light Systems | - Multifunctionality<br>- Adaptability |

*Comparison of engineering and natural design principles*

## Instabilities in Soft Structures

Ellen Kuhl
Stanford, USA

The human brain is inarguably the softest structures in our body. As we go through life, it grows, develops, degenerates, and shrinks. These changes in shape are naturally associated with mechanical instabilities and alterations in brain function. Here we revisit mechanically important events in the life cycle of the human brain—from early development to late degeneration—and discuss their impact on the deformation, strain, and stress field across the brain as a whole. Using continuum theories of finite growth and finite shrinkage, we investigate critical conditions for brain folding during neurodevelopment and for brain damage during neurodegeneration. With a view towards slender structures, we highlight the interaction of the thin outer layer of the brain, the gray matter cortex, with the soft inner white matter core. We show that the gray-and-white-matter interface is critical in the formation of the characteristic folded surface morphology of our brain and in the formation of lesions in traumatic brain injury. We discuss these events in view of our recent experiments to better characterize gray and white matter tissue, both in dead brain samples and in the living brain. Our experiments reveal that the human brain is a highly dynamic structure with markedly different rheological properties und different loading conditions. To no surprise, the dynamic environment of the brain has important implications on its failure and functionality, which we discuss in terms of selective physiological and pathological conditions.

## Drops on fibers and liquid films on membranes

Sébastien Neukirch, Paul Grandgeorge
CNRS & Sorbonne Université, France

Liquid droplets can develop capillary forces strong enough to deform thin elastic structures. For example, upon compression of its ends, a spider capture silk fiber spontaneously bends and spools inside the water droplets sitting on it. This surprising elasto-capillary coiling provides the composite system with a liquid-solid mechanical response. Indeed, capillary forces compressing the fiber inside the droplet confer a constant tension to the system, even in a globally compressed configuration, a tensile behavior typical of liquid soapy films. This one-dimensional liquid-solid fiber can be extended to a two-dimensional version: the liquid infused fibrous membrane. Again, surface tension induces wrinkling of the membrane inside the liquid film and provides a self-storing mechanism: The composite membrane adapts its surface area when compressed, always remaining under tension.

### Plant stems and ramifications: fiber-reinforced slender structures with mechanically highly efficient outer form and inner hierarchical structuring

Thomas Speck
University of Freiburg, Germany

Most plants possess slender upright stems and show various types of ramifications, which possess multiple evolutionary adaptations in outer form and inner hierarchical structure for ensuring a high load bearing capacity and a (typically) benign fracture behavior. Over the last decades we analyzed a multitude of plants stems from species of different growth forms including self-supporting trees, shrubs and sub-shrubs, semi-self-supporting scramblers, and non-self-supporting climbing lianas and vines. Quantitative analyses of the form-structure-function relationship by studying functional morphology/anatomy on various hierarchical levels and correlating it with mechanical tests revealed a pronounced adaptation to the mechanical constraints plants of different growth form face in their respective environment. This holds as well for under-critical loads in the (visco-)elastic range of the stems and branches as for the fracture behavior when exposed to over-critical mechanical loading.

Plant stems and ramifications proved to be promising role models for the development of unbranched and branched fiber-reinforced textile structures. These can be used as lightweight high-loadbearing structures in many technical applications and as bioinspired polymer hulls, which — after concrete filling — represent very efficient load-bearing “dendriform” pillars in architecture and constructional engineering.

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### Engineering elasticity in thin films

Stéphanie Lacour
EPFL, Switzerland

Soft bioelectronics are hybrids of soft and hard materials. Thinness enables bendability but fails to provide stretchability, i.e. multiaxial and reversible deformation, and conformability. This talk will illustrate two strategies to engineer elasticity in thin film materials based on (1) microstructuring and (2) liquid-solid thin films. Examples of their use in skin-like electronics and biomimetic electrical interfaces will be presented.

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### Embodied intelligence in soft deforming structures of robots

Fumiya Iida
Cambridge, UK

Compared to biological systems, today’s robots are still suffering from being flexible and adaptive to uncertain and unstructured tasks and environments. Humans are for example capable of handling a large variety of objects even at younger ages, even if they are not known previously. In order to fill the gap of animals and machines in terms of dexterity and adaptability, we have been investigating the notions of embodied intelligence, i.e. how well-designed physical body can simplify executions of complex tasks and enhance their adaptability. With the recent advancement in the technologies of soft functional materials and additive manufacturing, we can develop complex soft structures to be integrated into robotic systems to systematically investigate such challenging problems. In this talk, I would like to introduce the research projects in our laboratory in which we attempt to develop dexterous and adaptive robotic hands.

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### Self-healing soft robots

Bram Vanderborght
VUB, Belgium

Inspired by the soft tissue from which humans and many other organisms are made, a new generation of robots is constructed from flexible materials. Their flexibility allows soft robots to be used for countless applications. Being made from soft materials, soft robots can perform tasks in varying work environments while ensuring safe contact with humans. They are used to grab delicate and soft objects in the food industry or in minimally invasive surgery. They also play an important role in rehabilitation and arm prostheses. However, the soft materials also make them susceptible to damage from sharp objects or excessive pressure.

We implemented a novel method that enables soft robots to completely heal from such damage. We developed soft robots made from rubbery polymers with built-in healing capacity and we demonstrated the capability in three self-healing robotic components: a gripper, a robot hand, and an artificial muscle. These resilient, pneumatic components were damaged under controlled conditions to test whether the scientific principle also works in practice. Realistic damage could be healed completely without leaving any weak spots. After healing, the prototypes were able to fully resume their tasks.

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## In formation & information in living materials

Dominique Peysson
ENSAD, France

While digital gives itself a place of choice in the simulation of life, I will present my art works that, on the contrary, question the nature of living material. The limit between the complex inert matter now being conceived in our laboratories and the material of the living becomes increasingly blurred. But isn't our thought that we usually dissociate from corporeality, derived from each intimate part of our body, as well as from our grey matter? And is the genetic information that defines us not simply matter? I will present art works which are about information that can circulate and be stored in material, at different scales: molecular scale, cellular scale, body scale and environment scale. They question the fact that information IS matter... information inscribed in living matter, or living matter inscribed in information: DNA as a manufacturing material in the true sense of the word, large-scale projection of microfluidic in vivo pseudo-cells, vapor of life as a vanity, and radioactive clouds after Fukushima disaster...

## From turbulence transition to the buckling of a soda can

Tobias M. Schneider[1] and Shmuel M. Rubinstein[2]
[1]Emergent Complexity in Physical Systems Laboratory (ECPS), Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland
[2]Harvard John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

Thin-walled cylindrical shells such as rocket walls (or soda cans) offer exceptional strength-to-weight ratios yet predicting at which load the structure becomes unstable and fails remains an unsolved problem. Shells buckle and collapse at loading conditions much below those predicted by linear stability theory. This failure of linear theory is traditionally ascribed to extreme sensitivity to unavoidable shell imperfections, which modify the linear thresholds and lead to unpredictable stochastic variations of buckling loads for nominally identical shell structures.

We propose a complementary fully nonlinear dynamical systems approach inspired by successful recent descriptions of the transition to turbulence in shear flows. We show both experimentally and theoretically that unstable fully nonlinear equilibrium states located on the boundary of the unbuckled state's basin of attraction define critical perturbation amplitudes and guide the nonlinear initiation of catastrophic buckling. By following unstable equilibria including so-called edge states [1] as a function of loading conditions using both numerical continuation and non-destructive experimental probing techniques, we characterize the load-dependent variations of the basin of attraction of the unbuckled state. Specifically, we identify an experimentally accessible representation of the hyperdimensional basin of attraction in the form of a low-dimensional stability landscape [2] which fully encodes the stability of a cylindrical shell (see talk by S.M. Rubinstein). Together with a characterization of typical perturbations, the mapping of basin boundaries opens an avenue for accurately predicting when an individual shell structure buckles.

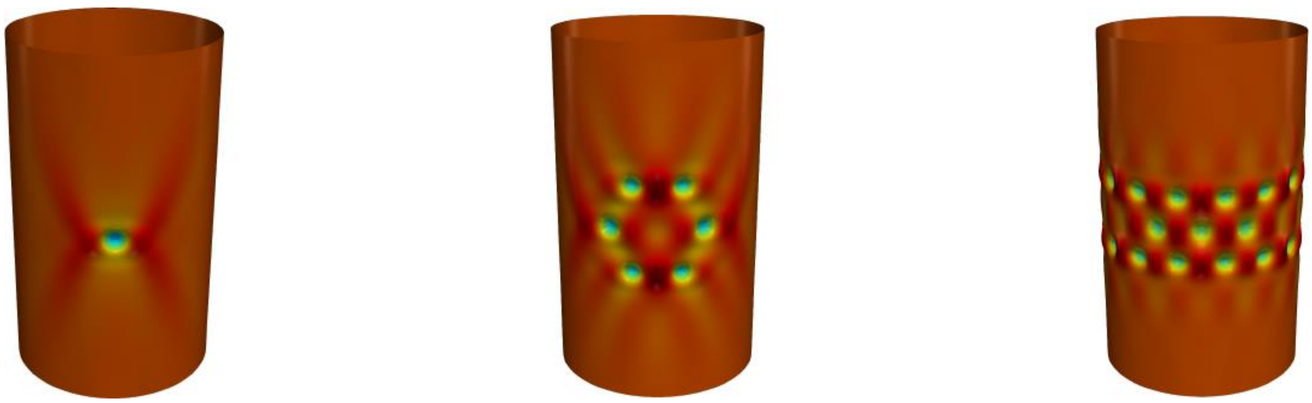

Figure: Three unstable force equilibria located on the basin boundary for an axially loaded cylinder shell.

(This is joint work with Tobias Kreilos, Emmanuel Virot, Anais Abramian & Emilio Lozano.)

[1] T. Kreilos, and T.M. Schneider. "Fully localized post-buckling states of cylindrical shells under axial compression.", Proc. R. Soc. A, **473**, 20170177 (2017).

[2] E. Virot, T. Kreilos, T.M. Schneider and S.M. Rubinstein. "Stability landscape of shell buckling", Phys. Rev. Lett. **119**, 224101 (2017).

## Tensile Instability in a Thick Elastic Body

David M. J. Dykstra,[1,2] Johannes T. B. Overvelde,[2,3] Rijk de Rooij,[2] James Weaver,[4] and Katia Bertoldi[2,5]
[1]Institute of Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
[2]John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
[3]FOM Institute AMOLF, Science Park 104, 1098 XG Amsterdam, Netherlands
[4]Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, Massachusetts 02138, USA
[5]Kavli Institute, Harvard University, Cambridge, Massachusetts 02138, USA

A range of instabilities can occur in solid structures that undergo deformation, more commonly known as buckling. While most buckling phenomena arise under compressive forces, it has previously been shown analytically that a tensile instability can occur in an elastic block subjected to equitriaxial tension [1]. Guided by this result, we conducted centimeter-scale experiments on thick elastomeric samples under generalized plane strain conditions and observed for the first time this elastic tensile instability. We found that equibiaxial stretching leads to the formation of a wavy pattern, as regions of the sample alternatively flatten and extend in the out-of-plane direction [2]. Our work uncovers a new type of instability that can be triggered in elastic bodies, enlarging the design space for smart structures that harness instabilities to enhance their functionality.

[1] Rivlin, R.S.. Large elastic deformations of isotropic materials. II. Phil. Trans. R. Soc. A **240**, 491 (1948)

[2] Overvelde, J.T., Dykstra, D.M.J., de Rooij, R., Weaver, J., Bertoldi, K. Tensile Instability in a Thick Elastic Body. Phys. Rev. Lett. **117**, 094301 (2016)

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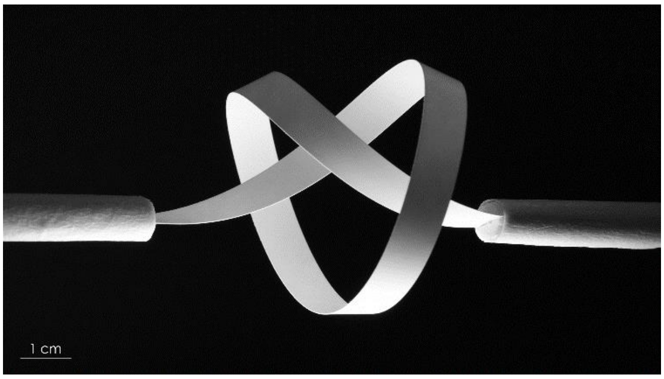
## Stable elastic knots with no self-contact

Derek E Moulton[1], Paul Grandgeorge[2], Sébastien Neukirch[2]
[1]Mathematical Institute, University of Oxford, Oxford, UK
[2]Sorbonne Université, UPMC Univ Paris 06, CNRS, UMR 7190 Institut Jean Le Rond d'Alembert, F-75005 Paris, France

Knots are widespread, universal physical structures, from shoelaces to Celtic decoration to the many variants familiar to sailors. They are often simple to construct and aesthetically appealing, yet remain topologically and mechanically quite complex. Knots are also common in biopolymers such as DNA and proteins, with numerous and significant biological implications.




While self-contact is an inevitable feature of tight knots, here we go the other direction and ask whether a knotted filament with zero points of self-contact may be realized physically. Our focus is on the simple hand-held experiment of an elastic rod bent into a trefoil knot, with the ends held clamped. The question we consider is whether there exist stable configurations for which there are no points of self-contact. This idea can be fairly easily replicated with a thin strip of paper, but is more difficult or even impossible with a flexible wire. We search for such configurations within the space of three tuning parameters related to the degrees of freedom in the simple experiment. Mathematically, we show, both within standard Kirchhoff theory as well within an elastic strip theory, that stable and contact-free knotted configurations can be found, and we classify the corresponding parametric regions. Numerical results are complemented with an asymptotic analysis that demonstrates the presence of knots near the doubly-covered ring.

In the case of the strip model, quantitative experiments of the region of good knots are also provided to validate the theory.

[1] Moulton, D. E., Grandgeorge, P., & Neukirch, S. Stable elastic knots with no selfcontact. J. Mech Phys Solids **116**, 33–53 (2018).

## Elastogranular Mechanics in Fragile Matter

D. P. Holmes
Mechanical Engineering, Boston University

Elastic bodies embedded within and deforming around discrete granular media arise in the locomotion of certain burrowing animals, the drilling of deep hydrocarbon wells, the development of root growth in plants, the design of jammed architectural structures, and in the removal of sediment from the interior walls of piped networks. The competition between a discrete granular network and a geometrically nonlinear structure results in coupled and nontrivial elastogranular interactions, and despite their familiarity, their underlying physics are still not well understood.

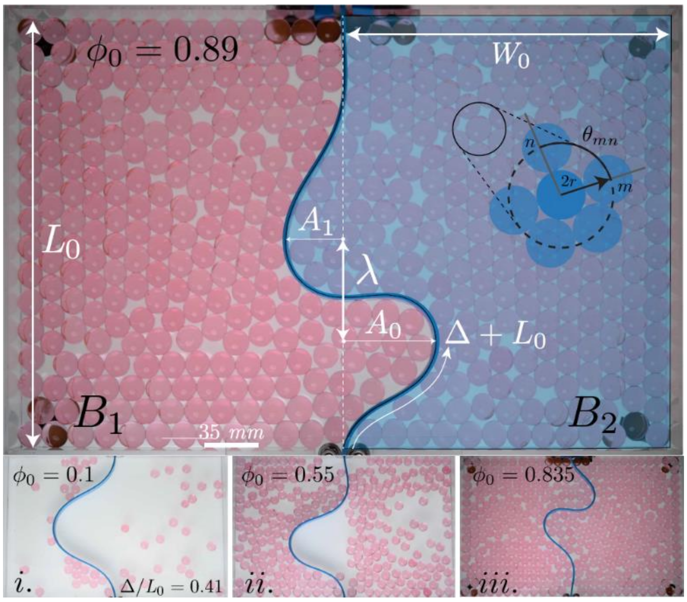



Figure: Elastogranular interactions as an elastic beam is confined in granular arrays of various initial packing fractions.

Our recent work has explored the rich phase space of the simplest elastogranular system – a planar elastica within a 2D array of spherical grains [1]. Confinement of a slender body into a granular array induces spontaneous symmetry breaking and stress localization in the geometrically nonlinear structure, and jamming, reordering, and vertical dislocation of the surrounding granular medium. Using techniques from experimental mechanics, complemented by reduced order scaling analyses, we quantify the structural deformations and granular motion as the length of a confined elastica is increased within arrays of various packing fractions. We find that at low packing fractions, minimization of the elastica's bending energy dictates the behavior of the granular array, and we determine the characteristic length of confined material necessary to induce jamming. Above the jamming point, the crystalline lattice of the beads directs the deformation and stress localization of the elastica. We find that the folds of the elastica are confined within a characteristic length corresponding to the length that diverges as the packing fraction increases. This diverging length scale is consistent with three different metrics: elastica deformation, granular displacement, and granular disorder. While it appears at first glance that these two regimes govern the elastogranular mechanics of these systems, we show that over–confinement of the elastica will induce a form of stress relaxation in the granular medium by vertically dislocating grains through two distinct mechanisms that depend on the geometry of the confined structure.

We believe this work would be a strong contribution to the Solvay Workshop on Mechanics of Slender Structures in Physics, Biology, and Engineering: From Failure to Functionality for two reasons. First, we investigate the coupling of two problems in soft condensed matter physics: stress localization and jamming, and provide a physical understanding for how these two phenomena interact in a model experimental system. Second, the work is interdisciplinary, combining elements of geometry, soft matter, and statistical physics with relevant problems in biology and engineering. We believe these results will be useful for the design of burrowing structures in complex media, such as smart, steerable needles, while providing a novel framework for studying the problem of jamming and fragile matter.

[1] D. J. Schunter Jr *et al.*, Phys. Rev. Lett. **120**, 078002 (2018).

## Wrinkle-to-crumple transition in thin films on curved surfaces

Yousra Timounay, Joseph D. Paulsen
Syracuse University

When a thin yet stiff film is placed on a liquid droplet, a deformation structure emerges, termed “crumples” [1]. These crumples occur as wrinkles break up into segments, and they appear to focus stress at their tips. However, their mechanism and threshold are not known. To address this problem, we study the behavior of thin polystyrene sheets (thickness ~ 100 nm) placed on a cylindrical liquid-air interface that is subjected to longitudinal compression. This setup allows us to independently control both the curvature of the cylindrical meniscus and lateral confinement. We find that wrinkles give way to crumples beyond a threshold value of curvature. We study how this threshold depends on other parameters such as compression, surface tension, aspect ratio and sheet thickness. Our results are summarized in phase diagrams that demarcate wrinkles, crumples, and folds.

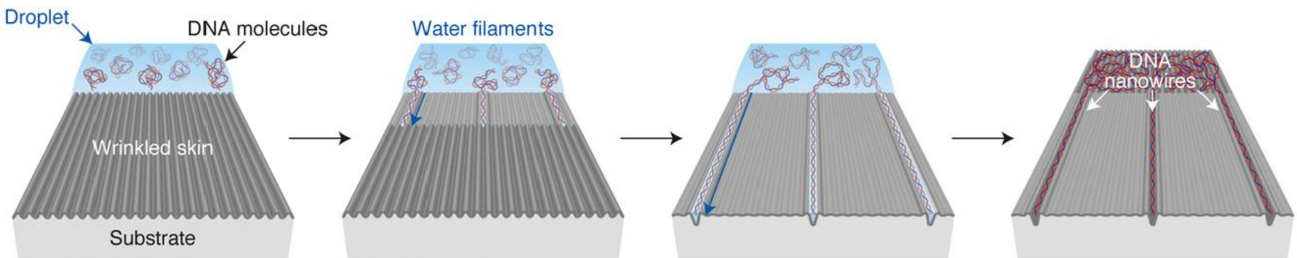
[1] King, Schroll, Davidovitch, & Menon, PNAS **109** (2012).

## Capillarity-induced Folding of Wrinkled Skin

Andrej Kosmrlj[1], So Nagashima[2], Howard A. Stone[1], Myoung-Woon Moon[2]
[1]Princeton
[2]KIST

We investigate what happens when a liquid droplet is placed on a wrinkled surface that is obtained via the wrinkling instability of compressed stiff skin on a soft substrate. Two different scenarios were observed. Liquid remains in a droplet when the contact angle between the liquid and the skin is larger than some critical angle, which depends on the aspect ratio of wrinkles, i.e. the ratio between the height amplitude and the wavelength of wrinkles.

However, if the contact angle is smaller than the critical angle, then the liquid from droplet starts




entering wrinkled channels. Interestingly, we observed that liquid didn’t enter all wrinkled channels, but it formed periodically spaced liquid filaments, when both the contact angle and the critical angle were small. This is because at the onset of the wrinkling instability, system is extremely sensitive to additional surface forces. Once the first liquid filament is formed, capillary forces from the liquid squeeze that wrinkle to a tight fold and they also flatten neighboring wrinkles. The reduced aspect ratio of neighboring wrinkles decreases the critical angle and prevents formation of new liquid filaments in nearby wrinkles. The next liquid filament can thus form only some distance away, where the flattening effect is diminished. Finally, we exploited this effect for the fabrication of periodic array of DNA nanowires by using the liquid solution with DNA molecules.

## Dynamic wrinkling and strengthening of a filament in a viscous fluid

Julien Chopin[1], Moumita Dasgupta[2], Arshad Kudrolli[3]
[1]Instituto de Fisica, Universidade Federal da Bahia (Brazil)
[2]Physics Department, Clark University (USA)

Slender structures embedded in complex fluids which buckle and fold as a result of mechanical compression are commonly found as in F-actin and microtubules in cell mechanics, flagella in swimming organisms, fibers in paper processing, and the earth's crust in orogenesis. While buckling typically occurs in the fundamental mode corresponding to the lowest strain, higher modes can occur depending on the constraints along the filament which may be static or dynamic. We investigate the wrinkling dynamics of an elastic filament immersed in a viscous fluid submitted to compression at a finite rate with experiments and by combining geometric nonlinearities, elasticity, and slender body theory [1]. The drag induces a dynamic lateral reinforcement of the filament leading to growth of wrinkles that coarsen over time. We discover a new dynamical regime characterized by a time scale with a nontrivial dependence on the loading rate, where the growth of the instability is superexponential and the wave number is an increasing function of the loading rate. We find that this time scale can be interpreted as the characteristic time over which the filament transitions from the extensible to the inextensible regime. In contrast with our analysis with moving boundary conditions, traditional Biot's analysis in the limit of infinitely fast loading leads to rate independent exponential growth and wavelength.

[1] Chopin, J., Dasgupta, M., and Kudrolli, A., "Dynamic wrinkling and strengthening of a filament in a viscous fluid," Phys. Rev. Lett. **119**, 088001 (2017).

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## Finding the mechanical stable states of prismatic architected materials

Agustin Iniguez-Rabago, Yun Li, Johannes T.B. Overvelde

Advances in fabrication technologies are enabling the production of architected materials with unprecedented properties. While most of these materials are characterized by a fixed geometry, an intriguing avenue is to add internal mechanisms capable of reconfiguring their spatial architecture enabling tuneable functionality. Previously we proposed a design strategy based on space-filling extruded polyhedra to create 3D reconfigurable materials comprising a periodic assembly of rigid plates and elastic hinges. Interestingly, when the rigidity constraint of the faces is softened, new folding pathways open up that lead to multiple mechanically stable states.

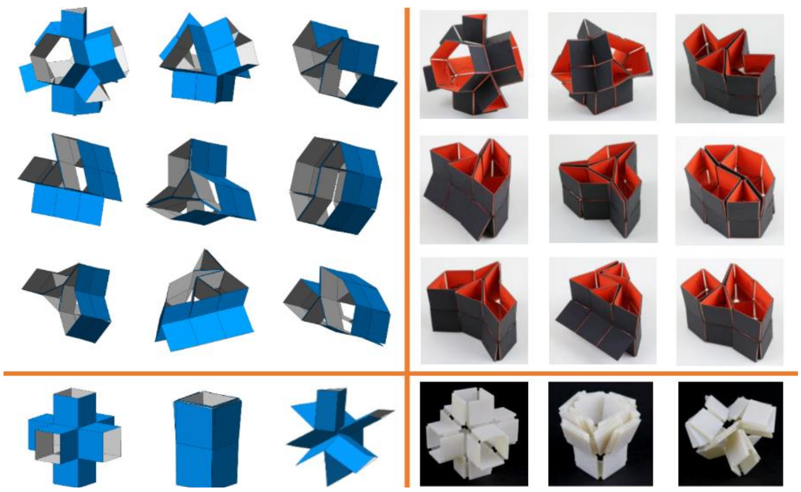

Figure: Stable states of extruded polyhedra found through simulations (left) and in prototypes (right), respectively. Simulations are performed by allowing the faces to stretch and by exploring all the possible symmetric unique folding combinations. Two types of prototypes were created: paper faces with double side tape as hinge for the truncated tetrahedron (up) and 3D printed faces with silicon sheets as hinge for the cube (down).

By performing numerical analysis and harnessing symmetries that exits in these geometries, we systematically explore the energy landscape to find the possible stable states. Additionally, we manufactured prototypes of the unit cells that can undergo the necessary deformations to change between these stable states as seen in Figure 1. The final goal is to understand and design a wealth of multistable materials by tiling these unit cells and by actuating them with local or global stimuli to switch between different mesostructures, and thus enable multiple functionalities in one material.

### The elastocapillary adhesion of a wet beam: A model for the terrestrial locomotion of insects

Tristan Gilet, Sophie Marie Gernay, Pierre Lambert

Most insects can walk on smooth substrates in any orientation (Fig. 1 - left). The adhesion force that they generate must switch within a fraction of second at each step. Like many other species, the dock beetle gains this controllable adhesion from hairy pads on its feet. These pads are covered with hundreds of micrometer-sized spatulated setae (Fig. 1 - middle), at the tip of which some liquid is dispensed. In a recent work [1], we have observed the deflection of these individual seta tips and we have shown that it could be attributed to their bending in response to the wedge-shaped capillary bridge that they form with the substrate. This capillary bridge can provide the levels of adhesion required during the free walk of the beetle [2].

In this talk, we will present the elastocapillary regimes experienced by seta tips during insect locomotion. These regimes are characterized experimentally, among others through adhesion force measurements on millimeter-sized slender beams clamped at one end and with a capillary wedge at the other end (Fig. 1 - right). A model inspired from [3] can explain most of our observations. We will finally discuss how the adhesion force can be controlled, and cancelled at some point, through modifications of the clamping angle and the volume of liquid in the wedge.

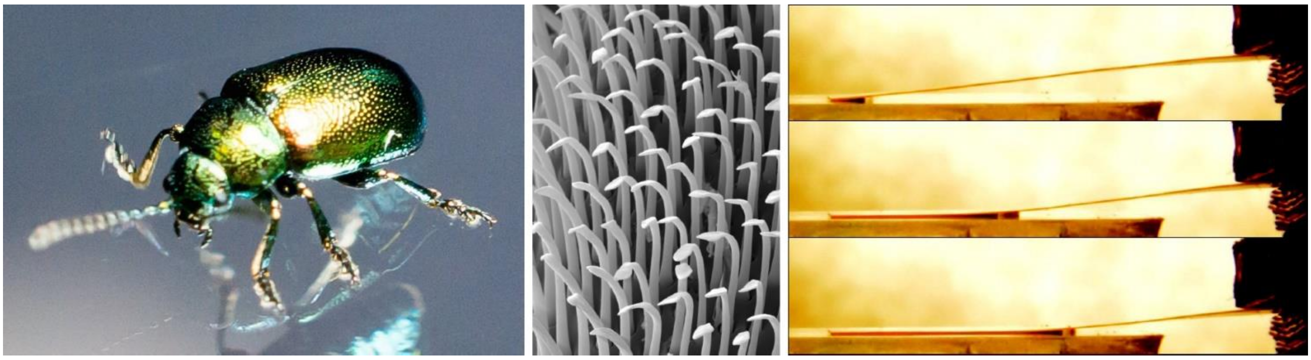

Figure: (Left) A dock beetle, like many insects, can walk on a wide variety of substrates in any orientation. (Middle) Hundreds of wet spatulated setae provide adhesion on smooth substrates. (Right) The adhesion mechanism of setae can be modeled and understood with a wet beam in elastocapillary equilibrium.

[1] S.M. Gernay, W. Federle, P. Lambert and T. Gilet, Elasto-capillarity in insect fibrillar adhesion, J.R. Soc. Interface **13**, 20160371 (2016)

[2] S.M. Gernay, S. Labousse, P. Lambert, P. Compère and T. Gilet, Multi-scale tarsal adhesion of freelywalking dock beetles, J. R. Soc. Interface **14**, 20170493 (2017)

[3] H.-M. Kwon, H.-Y. Kim, J. Puëll and L. Mahadevan, Equilibrium of an elastically confined liquid drop, J. Appl. Phys. **103**, 093519 (2008)

### Capture of viscous fluids in living organisms

Amandine Lechantre[1], Denis Michez[2], Pascal Damman[1]
[1]Laboratoire Interfaces et fluides complexes, UMons
[2]Laboratoire de Zoologie, UMons

Some insects, birds and mammals use flower nectar as their energy resources. For this purpose, they developed specific skills to ingest high viscous fluids. Depending on the sugar content in the nectar, different strategies are observed: some animals like bees and some bats exhibit a specific papillary structure well-suited to viscous dipping; in contrast hummingbirds have a tongue made from two thin flexible sheets that bend to form a tube when immersed in the nectar.

In the first case, bees and some bats possess a tongue decorated with complex structures that, according biologists, are optimized for fluid capture. In this talk, we first make an extensive investigation of the viscous drag with smooth rods and we will confront the actual physical model of viscous dipping with a visco-gravitational model for experiments with high capillary number. From combined experiments and theoretical analysis, the nature of the relevant forces has been determined. Then experiments on structured rods that mimic biological morphologies were performed. For this study we artificial tongues decorated with lateral protrusions and we determined the influence of the structure on the viscous dipping and the drainage. Finally, we compared results to the capture of nectar for living bees.

In the second case, hummingbirds use their tongue as a semi-open tube. The physical model for this capture of viscous fluid is unknown. To understand it, biological experiments have been done on living hummingbirds.

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## Nonlinear flow response of a channel with asymmetric valves inspired from the lymphatic system.

M. Brandenbourger, Adriaan Schiphorst, Corentin Coulais

Machine Material Lab, Van der Waals-Zeeman Instituut, Institute of Physics, University of Amsterdam, Amsterdam, Netherlands.

Fluid-structure interactions are often the centerpiece of different tools and mechanisms developed by nature (e.g. insect wings, fish fins, human heart valves, human vocal folds, etc.). In this study, we take the example of the lymphatic system to explore how asymmetric valves within a channel allow an ingenious and low energy consuming pumping system. The study aims at better understand how non-oriented actuations generate a net flow thanks to the asymmetry and the mechanical properties of the surrounding system.

We focus our work on the interdependence between the low Reynolds flow within a square channel and asymmetric valves (see Fig. 1). The experiment consists in a centimetric-scale channel where different numbers and geometries of valves can be added. The different valve geometries are fast prototyped by laser cutting. For a given flow rate, the influence of the flow on the valve opening/closing is imaged and pressure sensors measure the pressure variation due to the valve displacement. We first study how a system of two valves facing each other react to forward and backward flows and how pressure in the channel is affected by the opening or the closing of the valves. From this calibration, we then study how a flow actuation between two double valves structures generates a net flow in the channel.

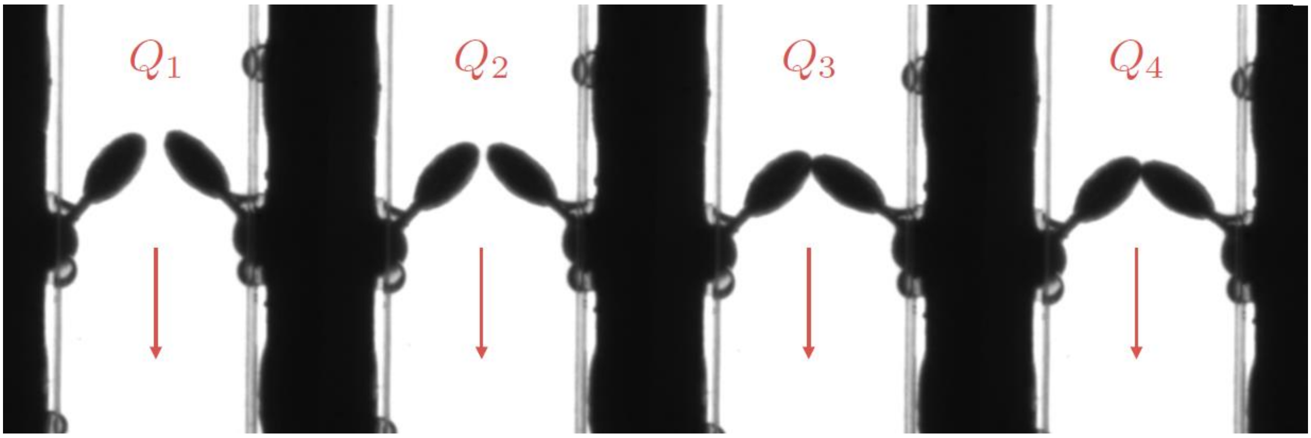


Figure: Variation in the opening of a double valve structure as a function of the flow $Q$.

The nonlinear interdependence between the channel pressure and the liquid flow is modeled as a function of the mechanical properties and geometry of the valve (stiffness, size relative to the channel, etc...). From an analysis of the pressure- ow relationship, we analytically describe which mechanical parameters lead to an optimization of the flow. We then compare our experimental results to our theoretical approach. Finally, we study both experimentally and theoretically how to maximize the net flow produced by a system of 5 valves thanks to random actuation in between each valve.

## Exploiting magnetocapillary interactions for swimming along liquid interfaces

Nicolas Vandewalle
GRASP, CESAM, Department of Physics, University of Liege, Belgium.

When soft ferromagnetic particles are suspended at air-water interfaces in the presence of a vertical magnetic field, dipole-dipole repulsion competes with capillary attraction such that 2d structures self-assemble. The complex arrangements of such floating bodies are emphasized. The equilibrium distance between particles exhibits hysteresis when the applied magnetic field is modified. Irreversible processes are evidenced. By adding a horizontal and oscillating magnetic field, periodic deformations of the assembly are induced. We show herein that collective particle motions induce locomotion at low Reynolds number. The physical mechanisms and geometrical ingredients behind this cooperative locomotion are identified. These physical mechanisms can be exploited to much smaller scales, offering the possibility to create artificial and versatile microscopic swimmers. Moreover, we show that it is possible to generate complex structures that are able to capture particles, perform cargo transport, fluid mixing, etc.

## Reprogramming the Elastic Properties of Mechanical Metamaterials by Amplifying Imperfections

G. Oliveri, J.T.B. Overvelde
AMOLF

Researchers have started to explore the use of compliance in the design of soft robotic devices that have the potential to be more robust, adaptable and safer for human interaction than traditional rigid systems. However, the field of soft robotics is still in its development phase and advances in control and tunability of soft actuators' response are needed. A promising direction to embed and control multiple functionalities in a single actuator is to use mechanical metamaterials. In these designed materials, elastic instabilities are often harnessed to enable switching between two modes of deformation. By embedding these metamaterials in soft actuators, they could benefit in a similar way from elastic instabilities associated with different functionalities.

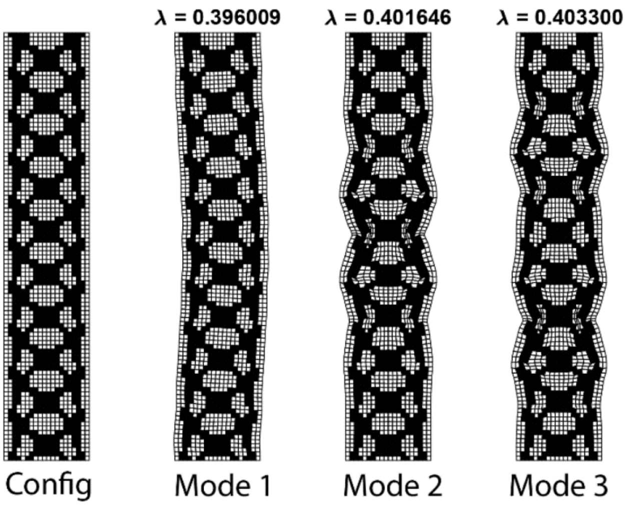


Figure: Example of an optimized topology of a beam with the first three buckling modes occurring at bifurcation points close to the assigned value of $\hat{\lambda} = 0.4$. Black and white cells represent material and void points respectively.

To design frustrated mechanical metamaterials, in which multiple post-buckling behaviors can be triggered that each starts at the same bifurcation point, we developed a stochastic topology optimization algorithm. As an example, we optimized the shape of a beam such that the first three buckling modes occur at the same bifurcation point (see Figure 1, in which $\lambda$ indicates the force at the bifurcation points). To favor one deformation mode over another, reversible imperfections (pneumatic actuation, sound pressure) can be applied to the mechanical metamaterial, so that multiple mechanical shapes and functionalities can be triggered.

This research will open up exciting opportunities for the design of soft robots with different and improved functionalities, bringing these soft systems closer to real world applications.

## Plastic fluctuations in a knitted fabric

Poincloux Samuel[1], Mokhtar Adda-Bedia[2], Frédéric Lechenault[1]
[1]Laboratoire de Physique Statistique, Ecole Normale Supérieure, Paris, France
[2]Laboratoire de Physique, Ecole Normale Supérieure de Lyon, Lyon, France

A knitted fabric is a topologically constrained elastic yarn following a periodic path. The mechanical behavior of the fabric appears to be drastically different from the yarn it is made of. To explain this discrepancy, we introduced a network model which features three ingredients, a dominant bending energy, an unaltered topology and yarn length conservation. This model provides a quantitative comparison with experiments done on a model knitted fabric, both in the force-elongation response and in the deformation field [1]. However, a knitted fabric also deforms plastically by avalanching stick-slip events owing to inter-yarn friction at the crossing points. Experimental footprints of those avalanches are abrupt drops of the force signal and strongly localized deformation. While the first provides a global estimation of the avalanche size, the second identifies a local one. Extensive tensile experiments allow us to measure the probability distribution of the avalanche size. Both local and global estimations exhibit a power law distribution with consistent exponents [2]. Despite their underlying topological order, knitted fabrics demonstrate surprisingly strong similarities in their mechanical response with seemingly different systems such as granular media or earthquakes.

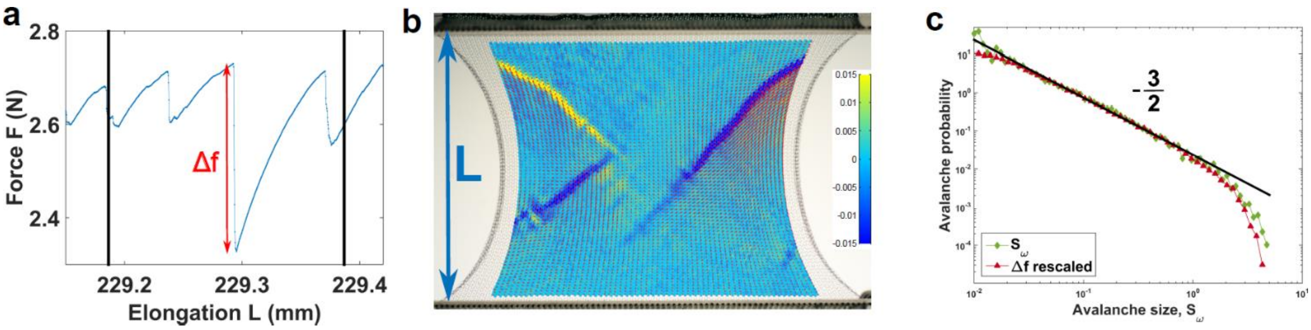


Figure: **a**, Focus on the force needed to pull the fabric along its longitudinal direction $L$. The force slowly increases until it drops of a quantity $\Delta f$, signature of a stick-slip avalanche. **b**, Typical image of a knitted fabric with the displacement field of the stitches between the interval marked by vertical black lines in **a**. The colormap is the vorticity $\omega$ of the displacement field, slip avalanches are characterized by a high vorticity. An avalanche size $S_\omega$ can be estimated from $\omega$. **c**, Probability distribution of the estimated avalanche size from a global quantity $\Delta f$ and a local one $S_\omega$. They both show a power law distribution with an exponent close to $-1{:}50$.

[1] Poincloux, S., Adda-Bedia, M. & Lechenault, F. Geometry and elasticity of a knitted fabric. Preprint on ArXiv (2018).

[2] Poincloux, S., Adda-Bedia, M. & Lechenault, F. Knits: an archetype of soft amorphous materials. Preprint on ArXiv (2018).

# POSTER

## An Asymptotic Variational Problem Modeling a Thin Elastic Sheet on a Liquid, Lifted at One End

David Padilla-Garza
Courant Institute of Mathematical Sciences, New York University

We discuss a 1D variational problem modeling an elastic sheet on water, lifted at one end. Its terms include the membrane and bending energy of the sheet as well as terms due to gravity and surface tension. By studying a suitable Gamma-limit, we identify a parameter regime in which the sheet is inextensible, and the bending energy and weight of the sheet are negligible. After the Gamma limit is proved, we use Lagrange multipliers to study the limiting problem; this allows us to prove a reflexion symmetry observed experimentally, arising from an effective surface tension due to the constraint of inextensibility. In this regime, the problem simplifies to one with a simple and explicit solution. From a mathematical perspective, this problem poses the challenge of working in a unbounded domain, and a non-reflexive Sobolev space. This project was motivated by discussions with Benjamin Davidovitch (who is currently analyzing the same problem using different methods).

## Harnessing Interfacial Instabilities in Polymer Melts

Lingzhi Cai and Pierre-Thomas Brun
Department of Chemical and Biological Engineering, Princeton University

Recent technological advancements call for the developments of hierarchical and topological structures. In this project, we aim to use interfacial instabilities, such as the Rayleigh-Plateau instability, to fabricate structures. Specifically, we propose to deposit a thread of viscous fluid into a bath of polymer. Capillary forces yield to the breakup of the thread into a collection of drops. As the polymer cures these drops are permanently captured into the matrix, thereby forming a composite material. By tuning the spacing between successive threads, we are able to fabricate crystal-like structure in these composite materials. The pattern formation process is robust: the crystal structure exhibits self-healing property of any initial or accidental defects.

We study the fundamental aspects of the Rayleigh-Plateau instability in this 3D printing context and adapt existing theories, for example, spatio-temporal stability analysis, to rationalize our

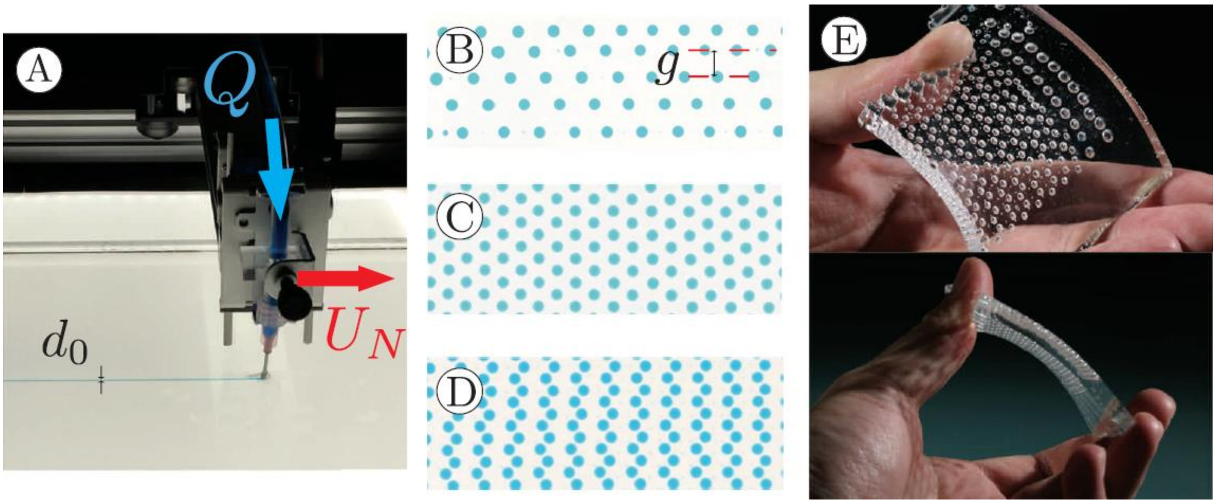


Figure: (A) The experimental setup. Glycerol colored with a blue dye is being discharged with a volumetric flowrate, $Q$, into a matrix of transparent liquid polydimethylsiloxane (PDMS). The print head is moving at a constant speed $U_N$. The flow is convectively unstable so that a viscous jet of diameter $d_0$ forms before breakup. (B-C) Crystal-like pattern emerges when successive threads are drawn close to previous ones. In (B), the gap size between successive threads, $g \gg d_0$; in (C), $g \sim d_0$. (D) Further reduction in gap size, $g < d_0$, leads to shearing effects with a change in crystal structure. (E) A sample of the cured polymer matrix.

experimental results. In turn, we aim to take advantage of our model for the directed control of the instability toward the design of material with prescribed properties and function. This will require us to solve the inverse problem: identifying the set of initial and boundary conditions so that desired structure will emerge without any external intervention.

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### Two-dimensional dynamics of self-alignment including shift, lift and tilt

Youen Vitry[1], Benoit Scheid[1], Sam Dehaeck[1], François Gallaire[2], Pierre Colinet[1] and Pierre Lambert[1]
[1]TIPs Department, CP 165/67, Université Libre de Bruxelles, 50 av. FD Roosevelt, B-1050 Brussels
[2]LFMI, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne

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### Single fold local mechanics

Théo Jules[12], Frédéric Lechenault[2] & Mokhtar Adda-Bedia[2]
[1]Laboratoire de Physique, Ecole Normale Supérieur de Lyon, 65 Allée d'Italie 69007 Lyon
[2]Laboratoire de Physique Statistique, Ecole Normale Supérieure de Paris, 24 Rue Lhomond 75005 Paris

Folds and origamis find numerous natural or industrial applications at multiple scales, from DNA strands to large solar panels deployed in space. To better understand the behavior of complex folded systems, one should decipher the mechanics of a single fold. So far, this system is described as two flexible faces linked by an elastic hinge, the crease. However, this model fails to link the elasticity of the hinge to the sheet plasticity and the material properties.

To go beyond this simple model, we carefully shape and anneal a crease within a polymer sheet. We clamp it and record both the shape of the fold and the force needed to deform it in various loading configurations. Then, the experimental shape is fitted to that predicted by an elastic model for the fold. This model rests on the continuous description of both the faces and the crease as one unique thin sheet with a non-flat reference configuration. It yields the local fold properties and explains the significant differences we observe between the tensile and the compressional regime. Furthermore, an asymptotic study of the fold deformation enables the characterization of the local shape of the crease, the origin of its linear elasticity and its spatial extension.

[1] F. Lechenault, B. Thiria and M. Adda-Bedia, "Mechanical Response of a Creased Sheet", Phys. Rev. Lett. **112**, 24 (2014).

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### Detachment Transition in a Model of Convexification of Clusters of Discs

David Martin-Calle & Olivier Pierre-Louis
Institut Lumière Matière (ILM), Univ. Claude Bernard Lyon 1

Adhesion controlled by the rugosity of the surfaces in contact, or by adding third bodies to the interface, is a recurring problem in contact physics, as well as in its applications, ranging from geophysics to nanosciences. Being inspired by experiments displaying a detachment transition when one increases the density of nanoparticles inserted between a graphene sheet and a at substrate, we propose a simple statistical model, which displays an analogous transition. Experimental observations reveal that the observed transition results from collective effects, that expand detachment zones by convexificating them. Thus we builded a model based on the convexification of percolation clusters associated with individual detachment areas induced by each particle. This transition occurs discontinuously when we bring it about by adding new particles. We study this transition's properties with numerical simulations, with a great number of discs. A lot of questions remain unanswered, of which are links with explosive percolation models, or with models of depinning of fronts in random media.

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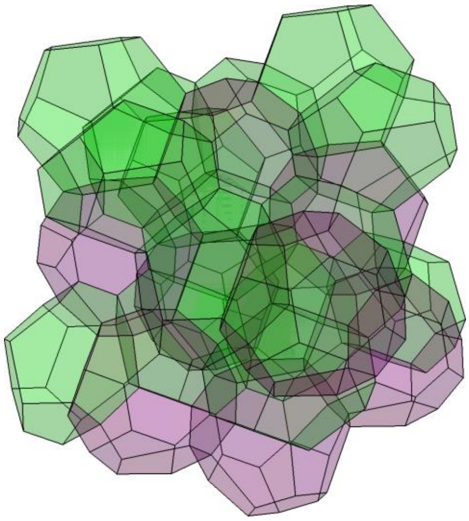
## The Optimal Space Partition

E. Opsomer and N. Vandewalle
GRASP, CESAM, Department of Physics, University of Liege, Belgium.



The pursuit of the optimal space partition (i.e. the partition with minimum surface area) is a challenging endeavor, that has been fascinating researchers in various scientific fields for a long time. In 1887, Lord Kelvin conjectured that the optimal partition would be realized by a 14-faced polyhedron called tetrakaidecahedron (W. Thomson, "On the division of space with minimum partitional area", in Phil. Mag., vol. 24, 503, 1887). This partition was considered optimal until 1994, when Weaire and Phelan obtained by computer simulations a new structure, made of eight equal-volume polyhedra, and presenting less surface area (D. Weaire and R. Phelan, "A counter-example to Kelvin's conjecture on minimal surfaces", in Phil. Mag. Lett., vol. 69, 107-10, 1994).

Here, we propose a stochastic method, to search for polyhedral structures maximizing the mean isoperimeter. New promising structures with non-equal cell volumes arise and one in particular, made of 24 polyhedra, is found to surpass previous kwon partitions. Our work (E. Opsomer and N. Vandewalle, "Novel structures for optimal space partitions", in New J. Phys., vol. 18, 103008, 2016) suggests that other structures with large isoperimeters are still to be discovered.

## Influence of Bénard-Marangoni instability on the morphology of drying colloidal films

B. Sobac[1], P. Colinet[1] and L. Pauchard[2]
[1]TIPs Lab - Université libre de Bruxelles, Bruxelles, Belgium
[2]FAST Lab UMR 7608 CNRS, Orsay, France

Film formation by drying of colloidal solutions is a widely used process in many industrial applications. The drying of such a system is a very complex process leading to a sol-gel transition induced by solvent evaporation. The resulting film can even crack and delaminate. In this study, we investigate the drying process of a colloidal suspension with a highly volatile solvent and we show that the resulting pattern of delaminated plates drastically differs from what is usually observed for aqueous colloidal suspensions. Visualization using an IR camera reveals that hexagonal convection cells can develop during the drying of solutions with highly volatile solvent. The convective cells may persist all along the film consolidation. Thus, we highlight the importance of the hydrodynamics during the first phase of strong solvent evaporation and the consequences on the following drying steps. A criterion predicting whether or not Bénard-Marangoni instability effectively occurs will be discussed.

## Shaping compliant origami via snap-through instabilities

Anne S. Meeussen and Martin van Hecke
Huygens-Kamerlingh Onnes Laboratory, Universiteit Leiden, Leiden, the Netherlands; Designer Matter Department, AMOLF, Amsterdam, the Netherlands

Real origami structures are not rigid; plates and hinges may bend and stretch. Adding such compliance to rigid origami models enriches their behaviour, leading especially to the creation of mechanically multistable structures [1]. Compliance thus opens up a rich design space to control shape-morphing in thin materials.

We explore this new design space starting from a compliant, undulating origami sheet, consisting of soft plates connected by parallel hinges. This simple material switches reversibly between many stable shapes via snap-through instabilities. Its reshaping results from a hierarchical, geometry-mediated competition between different sources of compliance, which we demonstrate via experiments and minimal computational models.


Figure: An undulating origami sheet undergoes a rapid, elastic snap-through transition to a new stable configuration when edge point loads are applied. Viewing the structure between crossed polarizers emphasizes the difference between the two stable shapes via optical birefringence of the sheet material.

[1] J. Silverberg, J.H. Na, A.A. Evans, B. Liu, T.C. Hull, C.D. Santangelo, R.J. Lang, R.C. Hayward, and I. Cohen. Nat. Mater. **14**, 389 (2015).

## Magnetoelastic instability in soft thin films

M. Poty, F. Weyer, G. Grosjean, G. Lumay, and N. Vandewalle
GRASP, Institute of Physics B5a, University of Liège, B4000 Liège, Belgium

Our main motivation is to create thin soft elastic films sensitive to the presence of a magnetic field. Ferromagnetic particles are incorporated in a thin soft elastic matrix. A lamella, made of this smart material, is studied experimentally and modeled. That thin films can be actuated using an external magnetic field applied through the system. The system is found to be switchable since subcritical pitchfork bifurcation is discovered in the beam shape when the magnetic field orientation is modified. Strong magnetoelastic effects can be obtained depending on both field strength and orientation. Our results provide versatile ways to contribute to many applications from the microfabrication of actuators to soft robotics. As an example, we created a small synthetic octopus piloted by an external magnetic field.

[1] M. Poty, F. Weyer, G. Grosjean, G. Lumay & N. Vandewalle, EPJE **40** (2017).

## Adhesion and swelling of an elastic loop

M. Curatolo[1], P. Nardinocchi[2], L. Teresi[1], D. P Holmes[3]
[1]Roma Tre University, [2]Sapienza University of Rome, [3]Boston University

Adhesion is a mechanism used in many fields such as biomedicine [1], tissue engineering [2] and polymer science [3]. In nature we find several proofs of adhesion-based mechanisms such as the adhesion of single bacterial cells that revealed to be the strongest of all the biological adhesives [4]. Another noteworthy example is the adhesion mechanism of gecko toes that use capillarity as important contribution for adhesion [5].

Here, we investigate the adhesion mechanism between a vinylpolysiloxane (VPS) thin elastica, bent in a racquet-like shape, and a thick VPS substrate (see Fig.1). In the experiments, a small silicone oil

Cst-5 is posed with a syringe on the substrate which is not in contact with the elastica. Then, an electromechanical system creates a contact between the tip of the elastic loop and the substrate. The contact is kept for different times and the droplet is absorbed by both the solids until the system starts to pull back the elastic loop. Before breaking the contact, the elastica strongly changes its configuration by bending. A breaking force is measured and strongly depends on the time of contact. The experiments are compared with a model that describes the force that breaks the contact and its relation with the interfacial surface energy that changes over time. Our study reveals that swelling, if used with wisdom, can be very useful to enhance adhesion with the possibility to obtain very interesting results and important consequences for future applications.

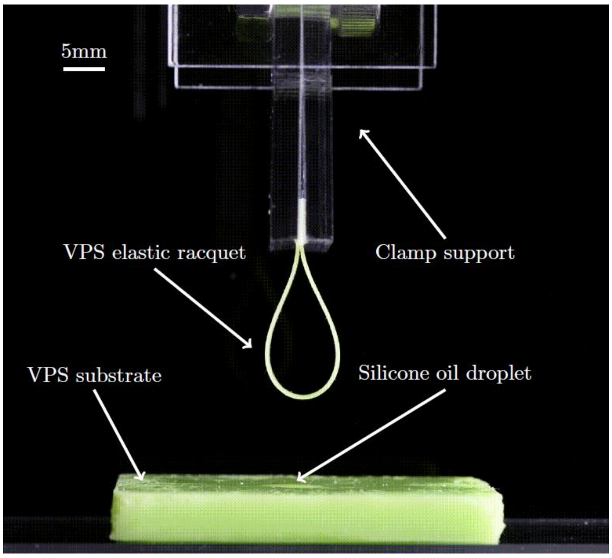


Figure: Experimental setup. A thin elastica in a racquet like shape is clamped by an acrylic support. The vertical position of the acrylic support is controlled by the Instron machine. A droplet of silicon oil is posed on a VPS substrate to realize the contact between the surfaces.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[2] Nikolovski J, Mooney DJ. 2000 Smooth muscle cell adhesion to tissue engineering scaffolds. Biomaterials **21**, 2025-2032 (2000).

[3] Awaja F, Gilbert M, Kelly G, Fox B, Pigram PJ. Adhesion of polymers. Progress in polymer science **34**, 948-968 (2009).

[4] Tsang PH, Li G, Brun YV, Freund LB, Tang JX. Adhesion of single bacterial cells in the micronewton range. PNAS **103**, 5764-5768 (2006).

[5] Huber G, Mantz H, Spolenak R, Arzt E. Evidence for capillarity contributions to gecko adhesion from single spatula nanomechanical measurements. PNAS **102**, 16293-16296 (2006).


## Reconfigurable fog nets


Pierre-Brice Bintein[1], Axel Cornu[1], Nicolas Vandewalle[2], Denis Terwagne[1]

[1]trioS.lab ULB, Bruxelles, Belgium

[2]GRASP ULG, Liège, Belgium


The increasing water scarcity brings attention to alternative sources of fresh water, among which fog is already harvested in numerous arid coastal regions [1]. Nets placed in dominant winds are used to catch fog water droplets, with yields resulting from interplay between aerodynamic, capture and drainage efficiencies [2,3].

The most common nets are the available food packing “Raschel meshes”. Innovations to increase water yield mainly consist in making hydrophobic coatings [3] and 3D-textiles [4], which respectively improve drainage and capture. But a recent field study moderates these enhancements and shows that they do not hold at various wind velocities [5].

We propose to use flexible meshes that adapts their shapes to wind in order to stay efficient in a wider range of wind velocities, and investigate experimentally the performances of such reconfigurable nets in controlled fog flows.


[1] O. Klemm, R.S. Schemenauer, A. Lummerich, P. Cereceda, V. Marzol, D. Corell, J. van Heerden, D. Reinhard, T. Gherezghiher, J. Olivier, P. Osses, J. Sarsour, E. Frost, M. J. Estrela, J. A. Valiente and G.M. Fessehaye, Fog as a fresh-water resource: overview and perspectives. Ambio. **41**, 221–234 (2012).

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[3] K.C. Park, S.S. Chhatre, S. Srinivasan, R.E. Cohen and G.H. McKinley, Optimal design of permeable fiber network structures for fog harvesting. Langmuir **29**, 13269–13277 (2013).
[4] J. Sarsour, T. Stegmaier, M. Linke, H. Planck, Bionic development of textile materials for harvesting water from fog, 5th International Conference on Fog, Fog Collection and Dew (2010).
[5] D.M. Fernandez, A. Torregrosa, P.S. Weiss-Penzias, B.J. Zhang, D. Sorensen, R.E. Cohen, G. McKinley, J. Kleingartner, A. Oliphant, M. Bowman, Fog Water Collection Effectiveness: Mesh Intercomparisons, Aerosol and Air Quality Research **18**, 270–283 (2018).

## Mechanical governing rules of mesenchymal cell aggregation on fibrous extracellular matrix

Fazil Emre Uslu[1], Christopher Davidson[2], Nikolaos Bouklas[3], Brendon M. Baker[2], Mahmut Selman Sakar[1]
[1]Institute of Mechanical Engineering, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland
[2]Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI 48109
[3]Department of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY 14853

Sculpturing compartmentalized three-dimensional biological structures during development is primarily a mechanical process, and recent work has started to decipher the design and interaction principles [1]. For example, mesenchymal stem cells (MSCs) aggregate and form clusters by applying traction forces and remodeling the surrounding matrix. These microscale clusters act as actuators that collectively deform tissues and define macroscale organ shape. The elastic moduli of the individual fibers are in general much higher than those of the resulting network from a continuum perspective. The architecture of the network controls the range of transmission of cellular forces and mechanosensing. Synthetic fiber networks provide a controllable environment to study how tissue organization depends on mechanical and topological cues. In vitro experiments with MSCs cultured on synthetic fiber networks have shown that the density and degree of connectivity of the network and the stiffness of individual fibers control cell proliferation and spreading [2]. While contracting, cells apply traction forces to the fibers they have already engaged with, and through spreading and further contractions this process leads to fiber recruitment and re-organization.

We developed a microrobotic manipulation platform along with a computational framework to explore the evolution of cellular organization on a synthetic fiber network. We record spatial and temporal changes in the distribution and shape of cultured cells along with the topological map of the fiber network using time-lapse confocal microscopy. We constructed an experimentally validated finite element model, replicating the exact network topologies and cell configurations, using a network of flexible beams interacting with contractile elements, that can recapitulate the evolution process. We first process acquired images of the network to identify the geometry and connectivity of the structural elements of the network as well as initial cell positions. The list of elements and nodes are imported to the finite element model along with the initial position of the cells. The fibers are modeled as flexible beams and the cells as rigid disks to which a constant torque is applied in order to facilitate fiber recruitment. Application of well-defined forces to the fibers using a magnetically controlled microactuator facilitates the characterization of the constitutive properties of the structures. The combined experimental and computational approach may reveal the role of initial cell pattern and fiber properties (stiffness, density, degree of connectivity) on the transient and steady state network architecture, and preliminary results demonstrated the feasibility.

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## Unusual Coupled Deformation and Supercoiling of Bio-Molecules

Raushan Singh and Ajeet Kumar
Dept. of Applied Mechanics, IIT Delhi, Hauz Khas, New Delhi, 110016

We present a thin tube formulation for coupled extension-torsion-inflation deformation in helically reinforced pressurized circular tubes. Both compressible and incompressible tubes are considered. On applying thin tube limit, the nonlinear ordinary differential equation to obtain the in-plane radial displacement is converted into a set of two simple algebraic equations for the compressible case and one equation for the incompressible case. This allows us to obtain simple analytical expressions for coupling stiffnesses corresponding to extension-twist, twist-inflation and extension-inflation couplings, in terms of the tube's intrinsic twist, material constants and the applied pressure.

These analytical expressions can predict whether such tubes would overwind/unwind on being infinitesimally stretched or exhibit positive/negative Poisson's effect. We further show numerically that such tubes can be tuned to generate initial overwinding followed by rapid unwinding as observed during finite stretching of a torsionally relaxed DNA.

Supercoiling of charged biomolecules is another topic of interest for biological and mechanics community. The challenge here is to model the electrostatic coulomb interaction which has inverse square singularity in the equivalent continuum approach. In the context of DNA supercoiling, researchers employ discrete approach and model DNA at base-pair level (Westcott et al., 1997). It automatically eliminates singularity. However, as the length of the DNA increases, the ratio of the distance between neighboring base-pairs and the total DNA length approaches zero and even the discrete approach starts sensing singularity. We re-look at the equivalent continuum problem and propose a singularity free numerical scheme for supercoiling of Kirchhoff rods under continuously distributed charge. We show that our singular-free numerical scheme turns out to be very efficient when compared to the existing discrete approach.

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## Fluid-structure interactions with 2D nanosheets suspended in a shear flow

Catherine Kamal[1], Simon Gravelle[2], Giulia Salussolia[1], Lorenzo Botto[1]
[1]School of Engineering and Material Science, Queen Mary University of London, UK
[2]Facilatd de Ingenieria y Cinecias, Universidad Adolfo Ibanez, Vina del Mar, Chile

Optimising the production of 2D nanomaterials such as graphene requires an understanding of how 2D nanosheets interact with non-uniform flows. Shear flows are often associated with liquid-phase exfoliation processes, where fluid forces are used to gently break the van der Waals bonds that keep 2D multilayer together. The interaction of the 2D nanosheets with the shear flow is known to result in important morphological changes (for example due to the sheets scrolling up into nanoscrolls). These changes can alter the performance of the nanosheets in nanocomposites or other applications.

To get insights into this fluid-structure interaction problem, we have built a continuum model of nanosheets dynamics in a shear flow, coupling the Stokes flow equations for the hydrodynamic load on the nanosheets, to the thin-plate elasticity equation for the deformation of the sheets. The thickness of 2D nanosheets can be comparable to the size of the solvent molecules. To quantify molecular effects on hydrodynamics, we compare molecular dynamics (MD) of rigid and flat graphene multilayer in water with the continuum predictions, reducing the number of layers progressively to reach atomic thickness. The MD simulations reveal important slip effects both at the flat solid boundaries and near the edges, with slip lengths much larger than the thickness of a typical nanosheet. We show, by comparing MD with two-dimensional boundary integral simulations, that for relatively short graphene layers even small slip can result in qualitative changes in the rotational dynamics of the sheets.

We also present preliminary boundary integral simulations incorporating nanosheet deformability. The simulation accounts for the slip length predicted by the molecular dynamics calculations. The continuum simulations provide insights into the microhydrodynamics of 2D nanosheets suspended in shear flow for realistic values of the non-dimensional ratio of elastic and viscous forces.

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### Numerical simulation of the spontaneous imbibition of a set of randomly spaced parallel lamellæ

Jean-Baptiste Charpentier, Laurent Bizet, and Abdelghani Saouab
Laboratoire Ondes et Milieux Complexes, UMR CNRS 6294, 53 rue Prony, 76600 Le Havre, France

Elasto-capillarity appears as soon as capillary action overcomes bending stiffness and induces a deflexion comparable to the system size $L$. This competition may be summarized in the ratio of the elasto-capillary length $L_{ec} = (B/\gamma)^{1/2}$, related to bending stiffness $B$ and surface tension $\gamma$, to $L$. For slender systems, deflexion must be in the order of the system width $r$ and a slender capillary length $L_s = (Br^2/\gamma)^{1/2}$ replaces $L_{ec}$. This length is relevant to various applications such as imbibition of paint brushes, failures in microelectromechanical systems fabrication, droplet capture by hair, etc. What about composite material processes? In Liquid Composite Molding (LCM), a liquid resin imbibes some bundles of fibers, i.e., yarns. Considering a standard carbon fiber, $L_s \sim 500\mu$m is much smaller than the characteristic length in a fabric $L \sim 5$mm. So elasto-capillarity is expected to come into play! The aim of this study is to understand how elasto-capillarity influences the flow. More specifically a very idealized problem is considered: the spontaneous imbibition of a set of randomly spaced flexible lamellæ. A coupled set of equations is used to describe the imbibition in the case of a very slender system. This set is solved using finite element method varying both $L/Ls$ and the spacing standard deviation. Two cases are investigated, embedding of the lamellæ on the liquid bath side and on the opposite side. If the embedding of the lamellæ is on the liquid bath side, then clusters of lamellæ are formed and grow with time. Clusters are closed structures which stop the imbibition inside them. However, the imbibition is still running in the diverging capillary formed between them. This leads to a slow imbibition which can be modeled analytically. The evolution of the average front position with time and volume of fluid in the system is therefore strongly different from Wahsburn's law. The imbibition slows down as the $L/Ls$ ratio and as the spacing standard deviation increase. Assuming no adhesion between the lamellæ, long time evolution leads to a partial destruction of clusters. If the embedding is made on the opposite side, the dynamic is completely different, non-hierarchical clusters appear in the first stage of the imbibition and converging capillaries are formed between them. Converging capillaries improve the imbibition dynamic, leading to empty clusters surrounded by liquid. Following this quick evolution, clusters evolve dynamically to form hierarchical structures. These results show that the imbibition dynamic is indeed strongly influenced by elasto-capillarity.

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## Instabilities of slender structures in periodic elastic states: From failure to functionality?

Arnaud Lazarus

Department of Mechanical Engineering, Institut Jean Le Rond d'Alembert, Sorbonne Université

Nowadays, from the benefit of fluttering flags for energy harvesting [1], to the use of buckling for folding [2,3] or the control of microstructural instabilities for wave filtering [4], elastic instabilities eventually occurring in slender elastic structures are often seen as an opportunity to seize rather than a failure to avoid. Currently, the type of instabilities that are used for functionalities are mainly based on diverging and fluttering that are two mechanisms possibly encountered with structures in equilibrium state, i.e. whose elastic state varies very slowly as compared to the natural scale of instability. We believe instabilities of slender structures whose elastic state varies with a period of the same order as the natural scale of instability (sometimes denoted as parametric instabilities), although usually avoided in practical engineering problems, could also be promising for functionalities.

In this presentation we introduce the concepts of linear stability of systems in periodic states such as Floquet normal forms and frequency or wavenumber lock-in [5], through the numerical study of two archetypal examples : a bi-articulated bar in periodic compressive elastic state (initial value problem in time) and a compressed beam lying on spatially-varying elastic foundations (boundary problem in space). We show the differences between the elastic instabilities of structures in equilibrium or in periodic states and highlight the features of Floquet forms that should give opportunities for functionalities. Finally, we present three possible applications of slender elastic structures where those instabilities could be promising: i) for vibration absorption, iii) for random number generation, and iii) for multiple wavelength emergence at the onset of wrinkling.

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## Stability landscape of cylindrical shell buckling

Emmanuel Virot, Tobias Kreilos, Tobias M. Schneider, Shmuel M. Rubinstein

From the legs of spiders to the stability of space rockets, the mechanical stability of thin cylindrical shells under compression is of critical important in a plethora of industrial and natural process. Nevertheless, shell buckling is hard to predict systematically because of defect sensitivity, which makes the buckling threshold very detail-dependent.

By systematically poking cylindrical shells under different axial loads, we identify a universal stability landscape which fully characterizes the stability of shells in the case where one single defect dominates. Our results suggest that this is a generic description of shell stability, indicating the critical poking for any loading conditions.

We provide a physical interpretation for an old problem in mechanical engineering: the existence of a minimal load below which thin-walled structures never collapse, for any degree of imperfection. Initially introduced by NASA as an empirical design rule, we demonstrate that this is a natural feature

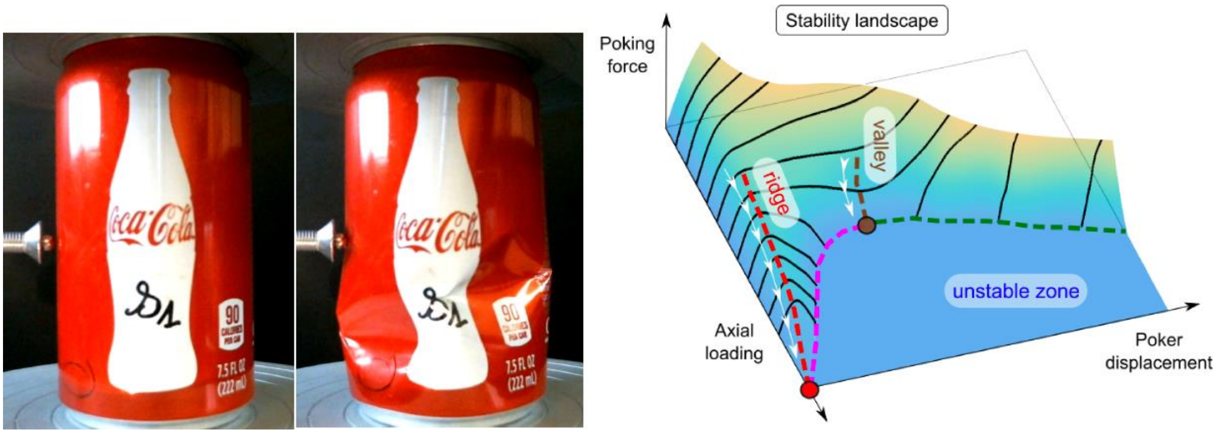


Figure: (Left) A soda can before and after buckling. (Right) Stability landscape. The ridge is defined as the trajectory of the maxima of poker force. The valley is defined as the trajectory of the minima of poker force.

of the landscape of stability. On the other hand, poking imperfect shells may allow to accurately estimate their spontaneous buckling loads, and to potentially classify the type and degree of imperfection of the tested shells. This new approach could drastically decrease the costs associated to classical full-scale destructive tests.

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## On the elastic description of granular rafts

Etienne Jambon-Puillet,[1,2] Christophe Josserand,[1,3] and Suzie Protière[1]

[1]Sorbonne Universités, UPMC Univ Paris 06, CNRS, UMR 7190, Institut Jean Le Rond d'Alembert, F-75005 Paris, France

[2]Institute of Physics, Van der Waals-Zeeman Institute, University of Amsterdam, Science Park 904, Amsterdam, the Netherlands

[3]Laboratoire d'Hydrodynamique (LadHyX), UMR7646 CNRS-Ecole Polytechnique, 91128 Palaiseau CEDEX, France

Buckling of slender objects has been traditionally associated with structural failure and avoided. However, recently there has been renewed interest in taking control of elastic instabilities to engineer innovative materials. In particular, thin films attached to solid or liquid substrates wrinkle and fold under compression, producing complex patterns which have been widely used by Nature and are now finding technological applications. Though, many practical situations involve complex membranes formed of discrete objects such as surfactants, proteins or solid particles whose mechanical properties are not well understood. Here, we probe the mechanical response of one of these complex membranes: a monolayer of large and dense particles at a liquid interface that we call a granular raft.

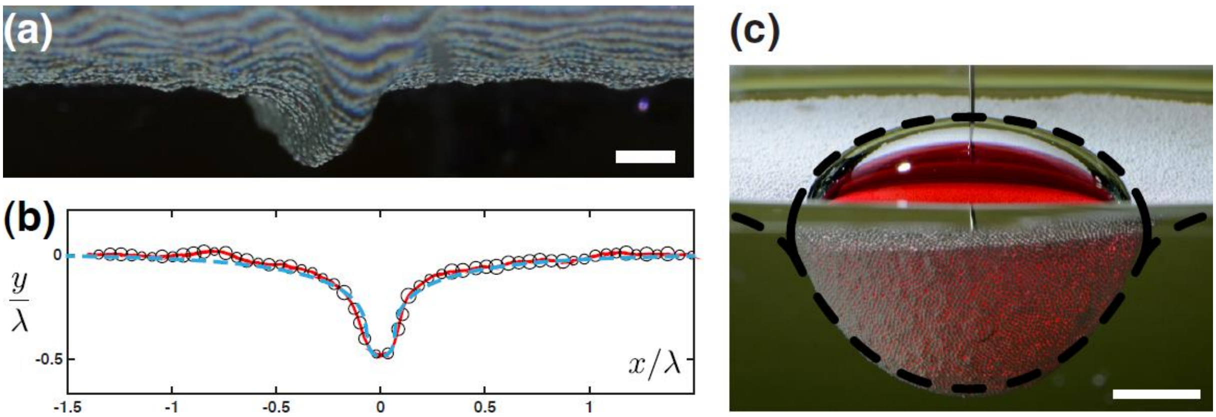


Figure: (a) Granular raft folded under compression. Scale bar 1 mm. (b) Comparison between experimental (red solid line) and theoretical fold profile (blue dashed line). The black circles schematically represent the particles. (c) Water drop (dyed red) floating on a granular raft. The heavy membrane model is overlaid as the black dashed line. Scale bar 5 mm.

We first compress rafts uniaxially and observe the formation of wrinkles which localize in a fold upon further compression (Fig. 1 (a)). Using a continuous elastic sheet description for the raft we analyze this buckling pattern (Fig. 1 (b)) and explore the limits of this elastic model. Indeed, the intrinsic discrete and frictional nature of granular rafts resurface in the finer details of the experiments. In particular, for large deformations, what seems to be at first a pure elastic response is in fact an irreversible plastic transition that can only be rejuvenated through an annealing stirring process [1].

We then deposit water drops on granular rafts floating at an oil-water interface. If the particles are hydrophobic, they trap a thin oil layer which prevents the drop coalescence with the underlying water bath [2]. Increasing the drop volume (and thus its weight) loads the raft which consequently deforms (Fig. 1 (c)). At a critical drop volume a mechanical instability sinks the raft, encapsulating the floating water drop in the underlying water bath to form an armored capsule. By modeling the raft as a heavy membrane, we predict the raft deformation and its destabilization [3]. Since armored capsules content is isolated, transportable and easily releasable, the raft mechanical failure thus appears as an opportunity to easily produce inexpensive water-in-water capsules for liquid transport and delivery.


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## Shape of an heavy ribbon held curved at one extremity


Gwenn Boedec, Julien Deschamps

Aix Marseille Univ, CNRS, Centrale Marseille, IRPHE UMR 7342, 13384, Marseille, France


Holding a thin ribbon of elastic material at one extremity, one can observe characteristic shapes governed by competition between gravity and bending rigidity. If the ribbon is held flat, the only parameters are a dimensionless parameter measuring this competition between gravity and bending and the angle of the clamp with respect to gravity. However, if instead of holding the ribbon flat, one holds its extremity curved, the geometry-induced rigidity can help it to increase its reach. An additional parameter is thus introduced in the system.

Shape of a ribbon under the joint influence of gravity and bending rigidity have been studied theoretically by [1], while the stiffening of an elastic sheet by an imposed curvature has been studied experimentally, theoretically and numerically by [2], but influence of an external force like gravity was not considered in this work. On the other hand, recently [3] demonstrated how bending of one of the extremity of a thin sheet can stiffen the sheet, and how it induces an asymmetric response under gravity load. Nonetheless, to our knowledge the problem of the shape of an elastic ribbon held curved at one extremity and submitted to gravity load has not been studied extensively yet.

We approach this problem by a combination of experiments and numerical simulations: experiments are conducted using thin ribbons made of Mylar, clamped onto a cylinder at one extremity to impose a known curvature. Influence of the angle of the axis of the cylinder with respect to gravity, thickness of Mylar, and imposed curvature are studied. We also consider a homogeneous transverse curvature of the ribbon. Simulations are based on an in-house code based on a Kirchoff-Love description of the ribbon, and discretized using subdivision elements (Loop, Catmull-Clark) in an isogeometric fashion.


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## Adsorption in monoatomic graphene induces a new type of wrinkling instability

Hervé Elettro, Francisco Melo
Soft Matter Research and Technology Center (SMAT-C), Departamento de Fisica, Universidad de Santiago de Chile, Avenida Ecuador 3493, Estacion central, Santiago, Chile

Emerging 2D materials are excellent candidates for next generation technologies such as supercapacitors, highly efficient filtration membranes and flexible solar cells. From a fundamental point of view, 2D materials represent an intriguing opportunity to bring the classical laws of continuum mechanics in new light. Only an atom (of carbon) thin, graphene shows important deviation from the plate phenomenology, crystallized into the decoupling of bending and stretching modes.

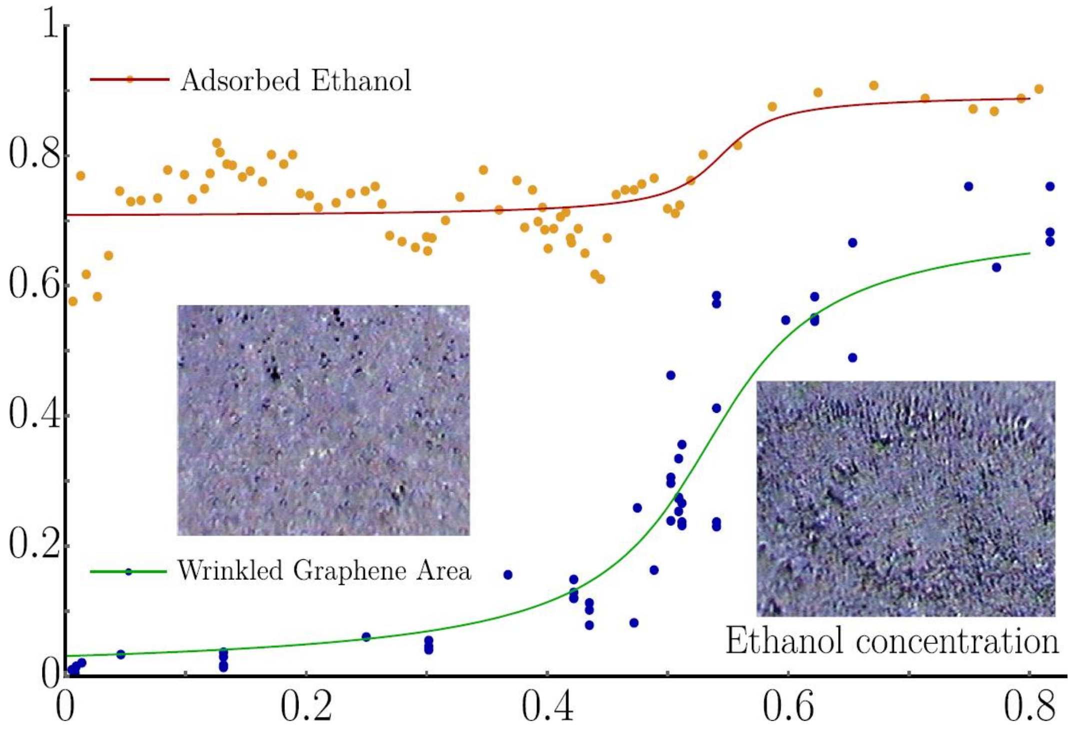


Figure: The atomic pinching mechanism, due to bond mismatch between graphene and ethanol, induces a new type of adsorption-dominated wrinkles.

Here we measure experimentally the bending rigidity of monolayer graphene by inducing the wrinkling of a floating graphene sheet under physical compression. Our results show that adsorption of liquid molecules dramatically disrupts graphene mechanics, yielding new records of flexibility on the scale of 0.01 kT. Furthermore, the addition of alcohols promotes spontaneous wrinkling, no compression needed. We characterize this new adsorption-induced wrinkling transition by coupled optical microscopy and Raman confocal spectroscopy (see Figure 1). We find that the mismatch in C-C bond length in graphene and alcohol produces a spontaneous curvature of the graphene sheet, under an atomic pinchers scenario. This also represents a cost-efficient setup to measure the interaction energy between graphene and relevant molecules. Our results open possibilities to engineer the equilibrium mechanics and geometry of large scale graphene-based devices.

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## Numerical and Experimental Developments in Nonlinear Structures

R.M.J. Groh, R.M. Neville, M. Schenk, A. Pirrera
Bristol Composites Institute (ACCIS), University of Bristol, United Kingdom

Our work aims to exploit structural nonlinearity in engineering, with a particular focus on aerospace applications, to develop well-behaved nonlinear structures [1]. To achieve this, we are developing novel numerical and experimental methods. Generalised path-following methods are used to numerically investigate the properties of nonlinear structures [2], and have been applied to thin-walled shells, slender frames, and beam structures. In addition to improved numerical methods, experimental validation of nonlinear structures is critical in ensuring their use in engineering applications, especially in conservative industries such as commercial aviation. Existing experimental techniques are unable to fully characterise the nonlinear response of even simple nonlinear structures, as they cannot measure structures with force-displacement responses that include limit points and snapping behaviour. An experimental method has been developed to extend our ability to measure the structural response of nonlinear structures [3]. In this presentation we will present our recent developments in both numerical and experimental work on nonlinear structures.

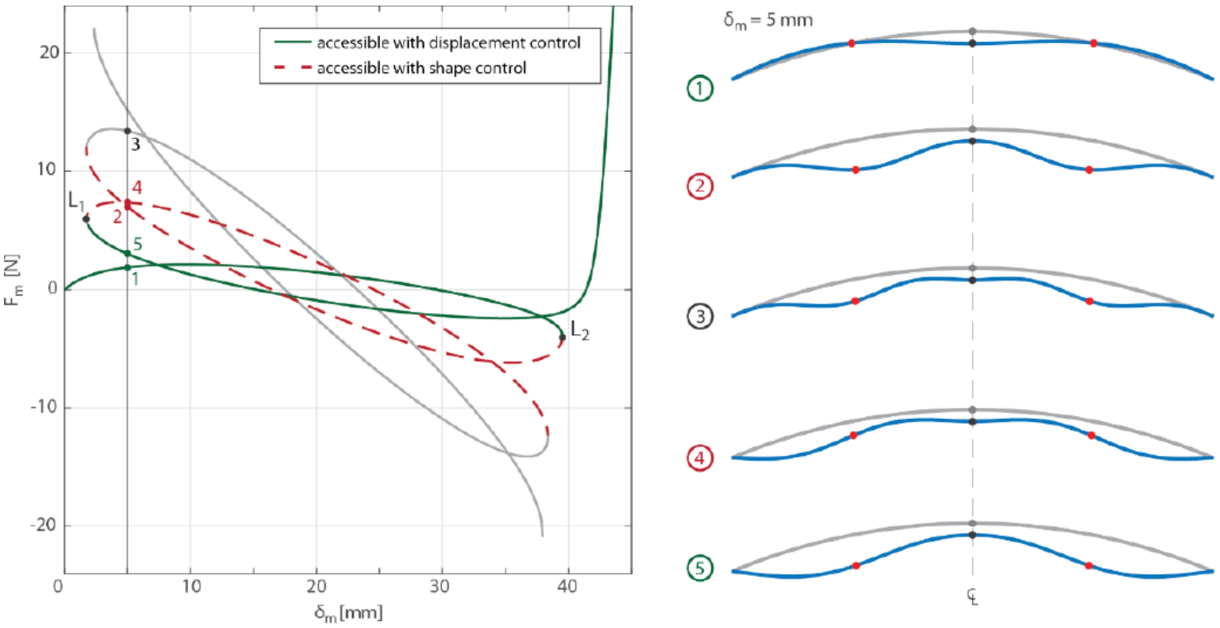


Figure: force-displacement response of shallow arch, with deformed shapes. Existing experimental techniques are unable to measure beyond the displacement limit points (L1, L2), but a new experimental method is able to capture more of the structural response.

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## Collapse of granular column: Static zone and influence of particle shape

D. Dumont, P. Rambach, P. Damman
Laboratoire InFluX, University of Mons

In spite of a large effort of the scientific community, a global description of the rheology of granular assembly remains largely elusive. For instance, a systematic study of the influence of particle shape and polydispersity is still lacking while their drastic influence has been demonstrated. To gain a better insight into the mechanical behavior of granular matter, we focus on a canonical set-up: the collapse of columns under gravity. We carried on 3D DEM numerical simulations and experiments of collapses for various granular columns on a frictional plane. Our observations accurately reproduce the previously reported data, the height and run-out distance are determined by the aspect ratio, a=Hi/Ri, of the column [1,2]. It appears however that the final morphology of the pile is dictated by the existence of a small region of static grains at the bottom of the column. The collapse occurs by a dense flow of falling grains onto the cone of static grains. In this presentation, we will discuss the origin of this static zone and how it influences all the properties of the granular pile during the collapse. A peculiar attention will be drawn to the particle shape.

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## Breaking spaghetti in two: twist controlled fracture of slender rods

Vishal Patil[1], Ronald H. Heisser[2], Norbert Stoop[1], Jörn Dunkel[1]

[1]Department of Mathematics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

[2]Sibley School of Mechanical and Aerospace Engineering Cornell University, 105 Upson Hall, Ithaca, NY 14853, USA

Fracture limits the structural stability of macroscopic and microscopic materials, from beams, bones and alloys to microtubules and carbon nanotubes. Despite recent progress, fracture control continues to present profound practical and theoretical challenges. A famous longstanding problem posed by Feynman asks why brittle elastic rods appear to fragment into at least three pieces when placed under large bending stresses. Feynman's observation raises fundamental questions about the existence of protocols that could robustly induce binary fracture in brittle materials. Using experiments, simulations and analytical scaling arguments, we demonstrate controlled binary fracture of brittle elastic rods for two distinct protocols based on twisting and nonadiabatic quenching. Our experimental data for twist-controlled fracture agree quantitatively with a theoretically predicted phase diagram. Furthermore, we establish novel asymptotic scaling relations for quenched fracture. Due to their generic character, these results are expected to apply to torsional and kinetic fracture processes in a wide range of systems.

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## Design and morphology of active elastomers

A. Zakharov, L. Pismen

Technion – Israel Institute of Technology, Haifa 32000, Israel

Reshaping of nemato-elastic sheets or shells opens ways of creating a variety of forms that can be manipulated by boundary anchoring, positioning of defects, and topological changes. Besides static reshaping, the forms can be actuated dynamically, thereby creating crawling and swimming micro robots.Firstly, we consider three-dimensional reshaping of thin nemato-elastic sheets containing halfcharged defects upon nematic-isotropic transition and show representative particular cases: a vicinity of isolated defects, an elliptic sheet and a sheet with two holes. Then we demonstrate a novel strategy of patterning nematic elastomers that does not require inscribing the texture directly and is based on varying the dopant concentration that, beside shifting the phase transition point, affects the nematic director field via coupling between the gradients of concentration and nematic order parameter. We found that the strategy provides an important qualitative effect - topological modification, which allows one to change the number of defects by adding circulation around a point

source of the dopant or absorbing defects in an isotropic domain. Besides, we consider reshaping of nematoelastic films upon imbibing an isotropic solvent under conditions when isotropic and nematic phases coexist and demonstrate that the folding patterns emerging due to differential extension or contraction can be compared with folding and wrinkling patterns of different physical origin in soft materials, but their distinguished feature is, on the one hand, anisotropy specific to soft nematic solids, and on the other hand, spatial inhomogeneity that allows one to manipulate them by external inputs. Functionality and some applications of active elastomers are discussed as well. We consider the motion of the various configurations of nematoelastic crawlers made of slender rods and thin stripes with both uniform and splayed nematic order in cross-section and detect the dependence of the gait and speed on flexural rigidity and substrate friction. Also we demonstrate the motion of a flexible Stokesian flagellar swimmer realised as a yarn made of two intertwined elastomer fibres, one active and the other one passive. Finally, reshaping of active textiles actuated by bending of Janus fibres is described. We show a great variety of shapes, determined by minimising the overall energy of the fabric, that can be produced by varying bending directions determined by the orientation of Janus fibres. Under certain conditions, alternative equilibrium states, one absolutely stable and the other metastable coexist, and their relative energy may flip its sign as system parameters, such as the extension upon actuation, change. A snap-through reshaping in a specially structured textile reproduces the Venus flytrap effect.

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## Effect of material property on relaxation dynamics and mechanical memory of crumpled sheets

Eric van Bruggen, Mehdi Habibi
Laboratory of Physics and Physical Chemistry, Wageningen University, Wageningen, The Netherlands

Crumpled structures combine low-density structures with surprising mechanical strength and the ability to absorb mechanical energy. This combination of properties opens doors to use them as mechanical metamaterials for a variety of applications. However, to rationally design metamaterials, a thorough physical understanding of their unique features is needed. One remarkable physical property observed in crumpled structures is their slow mechanical relaxation and their ability to carry a long lasting memory of previous mechanical states. We experimentally investigate the role of material properties (ductility and friction) on relaxation dynamics of crumpled sheets. A variety of sheet materials including regular printing paper, biaxially oriented polypropylene (BOPP), rubber, aluminum and brass sheets are used representing a wide range of elasto-plastic response and friction coefficient. To adjust the friction coefficient in a single sheet, it is either treated with a fine powder or roughened with sandpaper. We show that relaxation rates are not only dependent on material's elasto-plastic properties, but also rely on friction and adhesion between surfaces. We study the material dependency of the non-monotonic aging in a crumpled sheet. This is further explored by using a two-step compaction protocol introduced by Lahini et al. (Lahini et al. PRL, 2017), that allowed us to probe deeper into the material's relaxation behavior. In this process compression of the material for a specific time (waiting time) follows by decompression to a certain degree, and results in a pick in the relaxation of the forces at a time called pick time. These time scales are proportional indicating that the material can remember the previous state of deformation. We find that the ratio of the waiting time over the pick time vs. the ratio of the compaction forces shows a universal trend independent of the material property. However, the normalized height of the non-monotonic aging peak depends linearly on the time at which it arose with a slope that revealed a material property and seemed to be correlated with the material dependent relaxation constant. Using this approach, we determine quantitative variables measuring the ductility of the martial. Our results can help in further tailoring the relaxation dynamics and/or programming the response of crumpled sheets and disordered metamaterials, for example by choosing the ductility and friction in a crumpled based shock absorber its functionality can be controlled.

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## Bistability in arches and shells: designing for "failure"

Safvan Palathingal, G. K. Ananthasuresh
Department of Mechanical Engineering, Indian Institute of Science, Bengaluru, India

Growing interest in bistable structures in the past two decades is a remarkable turnaround in the field of structural mechanics to design for instabilities rather than to prevent them. Bistable arches and shells are designed to "fail", so that they can switch between their force-free stable equilibrium states. In fact, the mode of "failure" between their two stable equilibrium states is not unique. They exhibit multimodality by assuming multiple modes of switching, each corresponding to a different potential energy landscape. The ability of bistable structures to maintain two stable configurations without an active power source find a wide range of applications in literature as well as in nifty consumer goods such as clips. However, substantive engineering applications based on their multimodal switching are untapped. In this work, we explain multimodal bistability and four applications that employ multimodal bistability for their functionality: (1) an assistive easy-chair for the elderly; (2) miniature circuit-breaker; (3) RF-MEMS switch; (4) bistable shell-based monolithic compliant gripper.

The analysis, design, and optimization of multimodal bistability in planar arches, spatial arches, and shells are discussed as following: (1) a semi-analytical method for analysis and shape-synthesis of planar bistable arches with general boundary conditions by numerically determining critical points in the force-displacement curve [1]; (2) a bilateral analytical closed-form relationship between the initial and toggled profiles of bistable arches [2]; (3) shape, width, and depth optimization with the aid of the critical-point method that we have developed recently [1]; (4) an analytical model for capturing the interplay among bending, torsional and axial compression in spatially deforming arches; (5) shape optimization in shallow-thin bistable shells using three different approaches.

The first application presented in this work that is based on multimodal bistability is an assistive easy-chair for the elderly and the people suffering from arthritis [3]. Here, the strain energy stored in the bistable element when the user sits on the chair is used to assist the user to rise from the chair without using any external power sources. The second application is a miniature circuit-breaker where bistable elements are used in conjunction with other compliant elements. The reduction in total number of parts compared to a rigid-linkages based circuit-breaker improves manufacturability without compromising on features such as tripping, re-latching, and trip-free functionalities. The third is the design of a RF-MEMS switch that comprises a pair of arches, a V-beam electrothermal actuator, and a heatuator, all monolithically integrated into a single planar releasable layer to ease microfabrication. The novel feature of the design is the pulsed voltage actuation between a single pair of electrodes to switch between ON and OFF states using bimodal bistability. A monolithic compliant grasping mechanism consists of grasping arms made of beam and shell segments that work together with a bistable shell is the fourth design example. The grasper can pick up both stiff and flexible objects of any shape up to a maximum size and weight. The arms have distributed compliance so that they can conform to the shape of the object without applying undue force on it.

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## Stochastic buckling of a colloidal chain using optical tweezers

Simon Stuij[1], Jan Maarten van Doorn[2], Thomas Kodger[2], Joris Sprakel[2], Corentin Coulais[1], Peter Schall[1]
[1]University of Amsterdam
[2]Wageningen University

Mechanical instabilities occur when structures spontaneously deform or change conformation under stress, and are relevant for all materials, at scales from ~10meters to nanometers. So far, they have been mostly considered in a pure mechanical context, where thermal fluctuations are negligible. However, these latter become important when the mechanical structures become small as is the case e.g. for filaments or membranes in soft and biological materials. Here, we study the buckling of a colloidal chain in the presence of thermal noise and unveil a new mechanical critical transition at the chain buckling points.

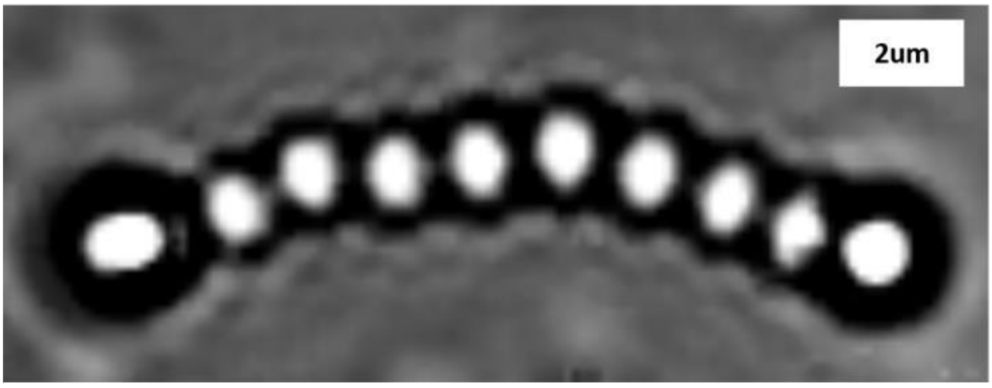


Figure: A buckled colloidal chain.

We assemble short colloidal chains by critical Casimir forces. These solvent-mediated forces allow us to vary the attractive particle interactions and thus tune the chain stiffness with temperature. Two laser tweezers are used to hold the chain at its ends, and to push on it. When compressing the chain to a critical state we observe buckling reminiscent of macroscopic structures, see figure. However thermal fluctuations and bond slippage introduce a crucial new element: multiple buckling modes occur in sequences, accompanied by a divergence of bending fluctuations when a new buckling point is reached. Our results provide new insights for understanding the mechanical response of filament and network structures as abundant in soft materials and biology.

## Using capillarity to assemble bio-inspired swimming micro-robots

G. Grosjean, M. Hubert and N. Vandewalle
GRASP, Institute of Physics B5a, University of Liège, B4000 Liège, Belgium

Magnetocapillary self-assemblies form when magnetic dipoles are induced in floating particles. Under periodic forcing, the cooperative dance of these particles can lead to locomotion at low Reynolds number. These floating structures and their motion have been the focus of recent experimental and theoretical work. Rich non-linear dynamics have been observed, which are key to the breaking of symmetry required for locomotion. Various aspects of the problem have been covered, ranging from the dynamics of a pair of particles to the symmetries of large assemblies, and including the remote control of the swimming trajectories. Some of the often-cited goals in the field of microswimmers were explored experimentally, including the transport of a cargo, with possible applications in microfabrication, microbiology or targeted drug delivery, and the manipulation of fluids, as in micropumps, micromixers or microfluidic flow control.

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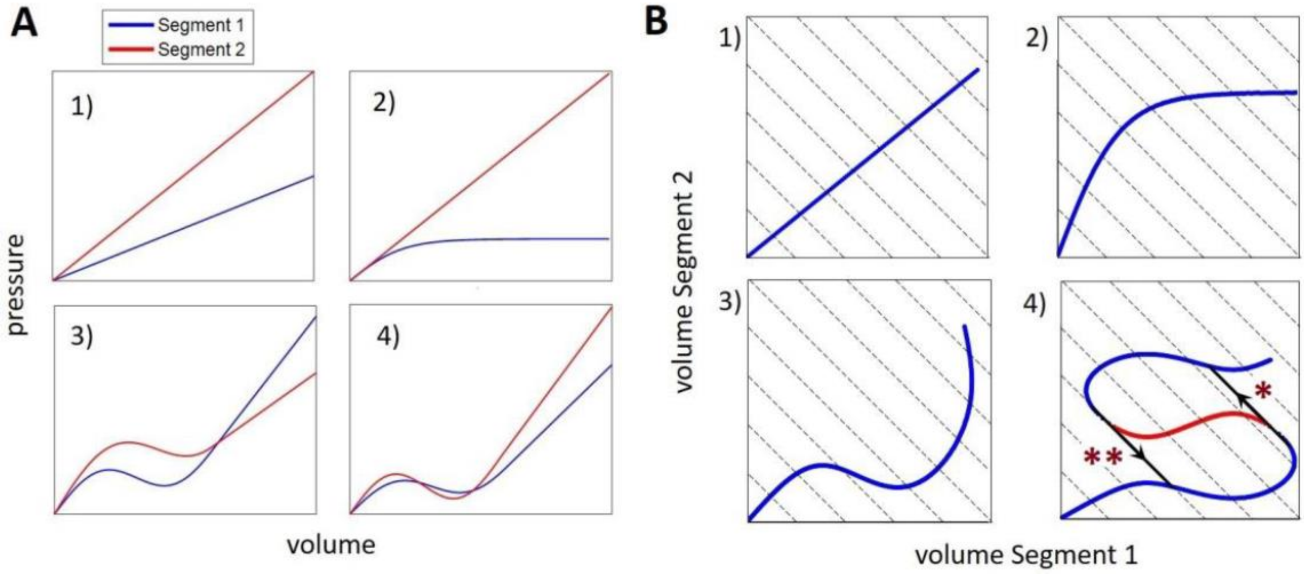
## Hardware encoded inflation sequence with nonlinear soft actuators

Edoardo Milana, Benjamin Gorissen, Michael De Volder, Dominiek Reynaerts
Department of Mechanical Engineering, KU Leuven, Members Flanders Make, Leuven, Belgium

Highly deformable soft structures can exhibit reversible elastic instabilities, that are caused by nonlinearities that originate from material properties at very large strains (rubber membranes and balloons) or from particular geometrical configurations (buckling of beams and bi-stable shells). A particular type of soft actuators are Elastic Inflatable Actuators (EIAs), where internal cavities are present within a highly elastic structure. The pressurization of these fluidic cavities generates volume variations that are transformed by the surrounding elastic structure into an overall functional deformation. As such, bending, twisting, contracting or extending actuators can be distinguished. A recent trend in soft robotics consists on harnessing actuator elastic instabilities to boost their performance, and to enable new functionalities. In this work, we focus on merging multiple EIAs into a multi-segment design, with an embedded hardware encoded actuating sequence. This form of valveless hardware intelligences is caused by triggering snap-through and snap-back instabilities of the multi-segment robot, where these originate from nonlinearities in the pressure vs. volume (PV) characteristic of each individual segment. Based on three archetypes of model PV curves (see figure left), four types of actuation sequence can emerge (see figure right), where sequence 4 is extremely important. This sequencing enables asymmetric motions that are found in natural locomotion such as walking, crawling and even flagellar and ciliary propulsion of microorganisms.




## Swelling induced actuation of thin gel beams and sheets


Eric Puntel[1], Paola Nardinocchi[2], Daniele Battista[3], Michele Curatolo[4]

[1]Università di Udine, eric.puntel@uniud.it

[2]Sapienza Università di Roma, paola.nardinocchi@uniroma1.it

[3]Sapienza Università di Roma, daniele.battista@uniroma1.it

[4]Università di Roma Tre, michele.curatolo@uniroma3.it


The versatility and bio-compatibility of gels promotes their usage in biomechanical devices. In this work we focus on actuation and structural morphing triggered by solvent induced swelling. To this end we start from a well validated stress diffusion model and we deal with two order of problems.

In the first we have a solvent bath with uniform chemical potential and we tune the material and geometric properties of a bi-layer beam to obtain simple design formulas for desired finite-strain curvature and elongation. We also discuss the occurrence of surface instability in a specific domain of the parameter space.

Secondly, motivated by "gel pumps", we exploit the obtained results in a thin sheet subject to a through-thickness, steady-state solvent flux. In order to characterize its flat-to-curved transition, we adopt an equivalent simplified approach by which the sheet is seen as composed of two uniformly swollen layers.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### Cellular extrusion induced by osmotic delamination

Horacio López-Menéndez[1], Leyla Kocgozlu[2], Jacques Prost[2,3], Benoit Ladoux[1,2]
[1]Institut Jacques Monod (IJM), Université Paris Diderot, CNRS, UMR 7592, Paris 75013, France
[2]Mechanobiology Institute, T-Lab, Singapore 117411, Singapore
[3]Physico Chimie Curie, Institut Curie, CNRS, UMR 168, Paris 75005, France

The size of a biological tissue is defined by the balance between the rate of cellular division and extrusion of live or dying (apoptotic) cells. This balance is defined as the tissue homeostasis, and it has strong implications in morphogenesis and pathological processes like tumor spreading. Previous works showed that apoptotic cell extrusion occurs by the formation of a contractile ring created either by the neighboring cells or by the apoptotic cell. Nevertheless, the relationship between the structural remodeling during the apoptosis and the extrusion process is not clear. We show that apoptotic cell extrusion within epithelial tissues arises from a mechanical instability, namely "Osmotic delamination", driven by the osmotic pressure. According to our early observations, this mechanism takes place when the cells are spread (in a low-density tissue) where they adopt a slender shape. We develop theoretical models that capture the physical origin of these observations. Where it couples the dynamics of ions and water pores, which set the osmotic pressure, with the membrane mechanics, the cell-substrate adhesion. Our approach provides mechanisms that can lead to efficient apoptotic homeostatic regulation in epithelial tissues.

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### Emergent Strain Stiffening in Interlocked Granular Chains

Denis Dumont[1], Maurine Houze[1], Paul Rambach[1,2], Thomas Salez[2-4], Sylvain Patinet[5], Pascal Damman[1]
[1]Laboratoire Interfaces et Fluides Complexes, Université de Mons, Belgium
[2]Laboratoire de Physico-Chimie Théorique, UMR CNRS Gulliver 7083, ESPCI Paris, France
[3]Université de Bordeaux, CNRS, LOMA, UMR 5798, F-33405 Talence, France
[4]Global Station for Soft Matter, Hokkaido University, Sapporo, Japan
[5]PMMH, ESPCI Paris/CNRS-UMR 7636/Université Paris 6 UPMC/Université Paris 7 Diderot, France

Granular chain packings exhibit a striking emergent strain-stiffening behavior despite the individual looseness of the constitutive chains. Using indentation experiments on such assemblies, we measure an exponential increase in the collective resistance force $F$ with the indentation depth $z$ and with the square root of the number $N$ of beads per chain. These two observations are, respectively, reminiscent of the self-amplification of friction in a capstan or in interleaved books, as well as the physics of polymers. The experimental data are well captured by a novel model based on these two ingredients. Specifically the resistance force is found to vary according to the universal relation $\log F \sim \mu\, N^{1/2}\, \Phi^{11/8}\, z/b$, where $\mu$ is the friction coefficient between two elementary beads, b is their size, and $\Phi$ is the volume fraction of chain beads when semi-diluted in a surrounding medium of unconnected beads. Our study suggests that theories normally confined to the realm of polymer physics at a molecular level can be used to explain phenomena at a macroscopic level. This class of systems enables the study of friction in complex assemblies, with practical implications for the design of new materials, the textile industry, and biology.