Wetting on Soft or Microstructured Surfaces

694. WE-Heraeus-Seminar

11 – 13 April 2019
Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Subject to alterations!

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de.

Scope of the 694. WE-Heraeus-Seminar:

Liquid droplets are omnipresent. This has inspired numerous studies on the wetting behavior of liquid droplets under static and dynamic conditions. Many surfaces are not flat and rigid but microstructured or soft. Soft surfaces deform as soon as a droplet is deposited. Thus, droplets are surrounded by a wetting ridge and to understand the wetting behavior of soft surfaces, the interplay between wetting and elasticity needs to be taken into account. The gel can even be replaced by a lubricant, leading to very low-friction substrates. For such lubricant infused surfaces, the surface texture is key in harnessing capillary forces that lock the lubricant in place.

The seminar will bring together experts and early stage researchers interested in the understanding of the wetting of soft or microstructured surfaces. We aim to assess the current status of this interdisciplinary field, to discuss future developments and to foster the exchange of concepts and techniques. The seminar targets researchers working experimentally and/or theoretically in this exciting domain of research.

Scientific Organizers:

Prof. Dr. Doris Vollmer (Chair)	Max Planck Institute for Polymer Research, Physics at Interfaces, Mainz, GERMANY E-mail vollmerd@mpip-mainz.mpg.de
Prof. Dr. Hans-Jürgen Butt	Max Planck Institute for Polymer Research, Physics at Interfaces, Mainz, GERMANY E-mail butt@mpip-mainz.mpg.de
Prof. Dr. Julia Yeomans	University of Oxford, Department of Physics, Oxford, UK E-mail julia.yeomans@physics.ox.ac.uk

Introduction

Administrative Organization:

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Jutta Lang

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Registration:

Jutta Lang (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Wednesday (17:00 h – 21:00 h) and
Thursday morning

Door Code:

(Key symbol button) 2 6 9 4 #
For entering the Physikzentrum
during the whole seminar

Program

Program

Wednesday, 10 April 2019

17:00 – 21:00	Registration
from 18:30	*BUFFET SUPPER / Informal get together*

Thursday, 11 April 2019

08:00	*BREAKFAST*	
09:00 – 09:10	Scientific organizers	**Opening and welcome**

Chair: Kirsten Harth

09:10 – 09:55	Periklis Papadopoulos	**Wetting of soft superhydrophobic micropillar arrays**
09:55 – 10:40	Stefan Karpitschka	**Dynamical wetting of soft solids**
10:40 – 11:00	*COFFEE BREAK*	

Chair: Barbara Wagner

11:00 – 11:45	Robert Style	**Surface stresses in soft silicone gels**
11:45 – 12:30	Jacco Snoijer	**Interactions on soft interfaces: Beyond the Cheerios effect**
12:30	**Conference Photo** (in the foyer of the lecture hall)	
12:35	*LUNCH*	

Program

Thursday, 11 April 2019

Chair: Peichun Amy Tsai

14:00 – 14:45 Dominic Vella **Droplet motion induced by geometry and flexibility**

14:45 – 15.45 **Poster flash presentations I** (2:30 min. each)

15:45 – 16:05 *COFFEE BREAK*

Chair: Sebastian Aland

16:05 – 16:50 Julia Yeomans **Bacteria: Self-motile liquid crystals?**

16:50 – 17:50 **Poster flash presentations II** (2:30 min. each)

18:00 *DINNER*

19:15 **Poster session**

Program

Friday, 12 April 2019

08:00	*BREAKFAST*	

Chair: Thomas Willers

08:45- 09:00	Stefan Jorda	**About the Wilhelm and Else Heraeus-Foundation**
09:00 – 09:45	Atsushi Hozumi	**How to realize statically hydrophilic/oleophilic but dynamically hydrophobic/oleophobic surfaces?**
09:45 – 10:30	Karin Jacobs	**Impact of interfacial properties to droplet dynamics, geometry and arrangement**
10:30 – 11:00	*COFFEE BREAK*	

Chair: Martin Brinkmann

11:00 – 11:45	Chiara Neto	**How slippery are SLIPS? Measuring effective slip on lubricated surfaces with colloidal probe atomic force microscopy**
11:45 – 12:30	Halim Kusumaatmaja	**Modelling drops on liquid infused surfaces**
12:30	*LUNCH*	

Program

Friday, 12 April 2019

Chair: Andreas Münch

14:00 – 14:45	Armelle Keiser	**Dynamics on liquid-infused surfaces**
14:45 – 15:30	Camille Duprat	**Wetting flexible fiber arrays**
15:30 – 16:15	Detlef Lohse	**Droplets and bubbles with phase transitions**
16:15 – 16:45	*COFFEE BREAK*	

Chair: Steffen Hardt

16:45 – 17:30	Dimosthenis Poulikakos	**Rational surface nanoengineering for dropwise condensation and antifogging**
17:30 – 18:15	Cameron Tropea	**Wetting questions in vehicle water management**
18:15 – 19:00	David Quéré	**tba**
19:00	*HERAEUS DINNER at the Physikzentrum* *(cold & warm buffet, free beverages)*	

Program

Saturday, 13 April 2019

08:00	*BREAKFAST*	

Chair: Bat-El Pinchasik

09:00 – 09:45	Xu Deng	**Printing surface charge as a new paradigm to program droplet transport**
09.45 – 10:30	Robin Ras	**The challenge of accurate characterization of surface wetting**
10:30 – 10:55	*COFFEE BREAK*	
10:55 – 11:00	Scientific organizers	**Poster awards**

Chair: Elmar Bonaccurso

11:00 – 11:45	Jürgen Rühe	**Robust and Sturdy: Tailormade micro- and nanostructured materials with unusual wetting properties**
11:45 – 12:30	Hans-Jürgen Butt	**Adaptive wetting**
12:30 – 12:40	Scientific organizers	**Summary and closing remarks**
12:40	*LUNCH*	

End of the seminar *and FAREWELL COFFEE* ***/ Departure***

Please note that there will be ***no*** *dinner at the Physikzentrum on Saturday evening for participants leaving the next morning.*

Posters

Program

1.	Sebastian Aland	**Efficient simulations of dynamic wetting of flexible substrates**
2.	Ahmed Aldhaleai / Peichun Amy Tsai	**Wetting, drying, and surfactant droplets on superhydrophobic surfaces**
3.	Philipp Baumli	**Flow-induced emulsion-based lubricant-replenishment**
4.	Martin Brinkmann	**Condensation and evaporation on elastic surface topographies**
5.	Joris Château	**Break-up of a viscous suspension jet**
6.	Longquan Chen	**Experimental and numerical study of droplet impact on nanostructured superhydrophobic surfaces**
7.	Ranabir Dey	**Soft electrowetting**
8.	Alexey Eremin	**Photomanipulation of the anchoring energy and its effect on the behaviour of LC colloids**
9.	Owen Ernst	**Reorganization of thin metal layers by (de)wetting phenomena for microelectronic applications**
10.	Marta Fenero	**Development of omniphobic aluminum surfaces**
11.	Mathis Fricke	**A kinematic evolution equation for the dynamic contact angle and some consequences**
12.	Diana Garcia-Gonzalez	**Elastocapillary bundling of superhydrophobic micropillar arrays**
13.	Dirk Gründing	**Capillary rise - From the continuum mechanical description to the Washburn model**
14.	Kirsten Harth	**Drop impact on hard substrates covered by a thin oil layer**
15.	Maximilian Hartmann	**Stability of evaporating droplets on chemically patterned surfaces**
16.	Dorothea Helmer	**Study of slippery liquid infused porous surfaces with different porosities under shear force**

Posters

17.	Guillaume Jaunky	**Wetting using highly branched hydrophilic additives**
18.	Hansol Jeon	**Liquid-liquid phase separation in contact with deformable surfaces**
19.	Pallav Kant	**Splitting droplet through coalescence of two different three-phase contact lines**
20.	Srinath Lakshman	**Droplet complete rebound on thin films and liquid-infused textured surfaces**
21.	Kai Liu	**Improving surface-wetting characterization**
22.	Solomon Melides	**Effects of hydrophobic surface heterogeneity on the spreading of water on soluble thin films**
23.	Himanshu Mishra	**On the assessment of omniphobicity derived from intrinsically wetting materials**
24.	Andreas Münch / Barbara Wagner	**Nonlinear visco-elastic effects of polymer and hydrogel layers sliding on liquid substrates**
25.	Abhinav Naga	**Wetting ridge on liquid-infused surfaces**
26.	Saurabh Nath	**Capillary springs**
27.	Dirk Peschka	**Dynamic contact angles via gradient flows**
28.	Bat-El Pinchasik	**Bioinspired networks for liquid diodes: From passive transport to actuated motion**
29.	Talal Qahtan	**Janus membrane for dual action: Oil-water separation and in situ water decontamination**
30.	Olinka Ramírez Soto	**Impact of compositional gradients on the dynamics of solid-liquid-vapor contact lines**
31.	Matthieu Roché	**The elastocapillary ridge as a non-integer disclination**
32.	Sriharitha Rowthu	**Self-replenishing mechanisms in abrasion-resistant alumina slippery surfaces**

Posters

33.	Muhammad Subkhi Sadullah	**Droplet binning and droplet sorting using liquid infused surfaces**
34.	Vatsal Sanjay	**Droplet encapsulation**
35.	Lothar Schimmele	**Wetting transitions of binary liquid mixtures on a nanosculptured surface**
36.	Meenaxi Sharma / Krishnacharya	**Dynamics of aqueous drops on lubricating fluid coated slippery surfaces: Sinking or slipping**
37.	Roghayeh Shiri	**Morphology of liquid-liquid dewetting**
38.	Amy Stetten	**Wetting adaptation and charge separation at the interface between polymer surfaces and rolling drops**
39.	Antonio Tinti	**Contact angle hysteresis induced by multiple nanodefects**
40.	Leon Topp	**Droplets on switchable substrates: A simulation study**
41.	Vittorio Vercillo	**Laser micro-/nano-structuring of surfaces for icephobic applications**
42.	Prashant Waghmare	**Impact and spreading dynamics of ferrofluid droplet**
43.	Thomas Willers	**Replacing the solid needle by a liquid one when measuring static and advancing contact angles**
44.	William Wong	**Revising the pendant drop model: Contactless method for analyzing contact angle hysteresis**
45.	Qin Xu	**Direct observation of dewetting process on soft substrates**
46.	Binyu Zhao	**Three-dimensional morphology and size-dependent stiffness of nanomenisci on porous alumina**
47.	Daniel Zinsmeister	**Deposited hygroscopic aerosols affect the wetting and water movement on leaf surfaces**

Abstracts of Lectures

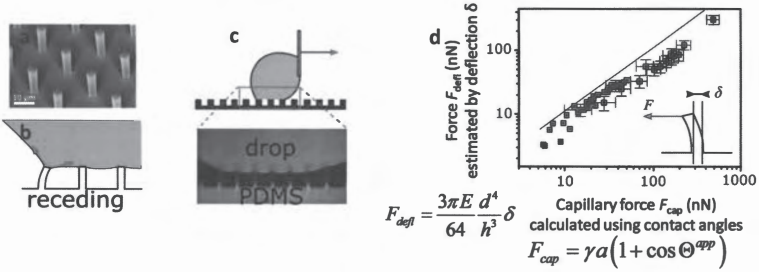
(in chronological order)

Wetting of soft superhydrophobic micropillar arrays

Periklis Papadopoulos[1], Bat-El Pinchasik[2], Martin Tress[3],
Doris Vollmer[2], Michael Kappl[2] and Hans–Jürgen Butt[2]

[1]University of Ioannina, Department of Physics, GR-45110 Ioannina, Greece
[2]Max Planck Institute for Polymer Research, D-55128 Mainz, Germany
[3]Department of Chemistry, University of Tennessee, Knoxville, TN, USA

Superhydrophobic surfaces are usually assumed to be rigid so that liquids do not deform them. Here we analyze how the relation between microstructure and wetting changes when the surface is flexible. Therefore we deposited liquid drops on arrays of flexible micropillars. We imaged the drop's surface and the bending of micropillars with confocal microscopy and analyzed the deflection of micropillars while the contact line advanced and receded. The deflection is directly proportional to the horizontal component of the capillary force acting on that particular micropillar. In the Cassie or "fakir" state, drops advance by touching down on the next top faces of micropillars, much like on rigid arrays. In contrast, on the receding side the micropillars deform. The main force hindering the slide of a drop is pinning at the receding side, while the force on the advancing side is negligible. In the Wenzel state, micropillars were deflected in both receding and advancing states.



$$F_{defl} = \frac{3\pi E}{64} \frac{d^4}{h^3} \delta$$

$$F_{cap} = \gamma a\left(1 + \cos\Theta^{app}\right)$$

Fig. 1: *(a) SEM image of an array of PDMS micropillars. (b) Side view of the receding side of a drop on the micropillars. The net force on the rim of the drop is nonzero and has a horizontal component. (c) Using confocal microscopy we imaged moving sessile drops. (d) Forces calculated by two independent ways: from pillar deflection and Young's modulus, and from capillary forces. They do not match exactly, because pillars did not bend like infinitely thin beams.*

References

[1] P. Papadopoulos, B. Pinchasik, M. Tress, D. Vollmer, M. Kappl, H.-J. Butt, Soft Matter **14**, 7429 (2018)

Dynamical Wetting of Soft Solids

M. van Gorcum[1], B. Andreotti[2], J.H. Snoeijer[1], and S. Karpitschka[3]

[1]Physics of Fluids Group, University of Twente, Enschede, Netherlands
[2]Laboratoire de Physique Statistique, Université Paris-Diderot, France
[3]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany

The contact line of a liquid drop on top of a solid surface exerts a nanometrically sharp surface traction, providing an unprecedented tool to study highly localized and dynamic deformations of soft polymer networks. The traction deforms the solid into a wetting ridge which surrounds the droplet and governs its dynamical behavior. Contact line motion and the morphology of the ridge are governed by the surface tension and the viscoelastic response of the solid [1]. One of the outstanding problems in the context of dynamical soft wetting is the stick-slip instability of a moving contact line, which is observed above a critical velocity. Time-resolved measurements of the solid deformation are challenging, and the mechanism of dynamical depinning has remained elusive. Direct optical visualizations of dynamic wetting ridges show that its opening angle increases with speed, which cannot be attributed to bulk rheology. Instead, this effect points to a dynamical increase of solid surface tension. Under this assumption we derive, and confirm experimentally, a criterion for contact line depinning on soft solids [2].

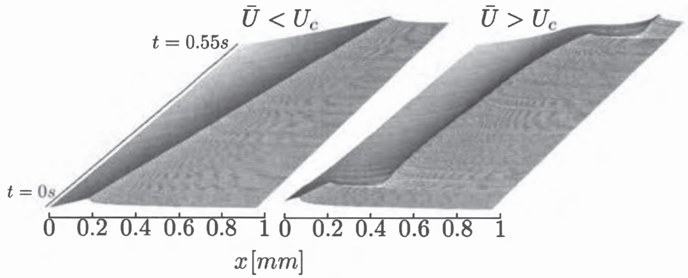


Figure 1: Moving wetting ridges below (left) and above (right) the critical velocity.

References

[1] S. Karpitschka, S. Das, M. van Gorcum, H. Perrin, B. Andreotti, and J.H. Snoeijer. *Nat. Commun.*, 6:7891, 2015.

[2] M. van Gorcum, B. Andreotti, J.H. Snoeijer, and S. Karpitschka. *Phys. Rev. Lett.*, 121:208003, 2018.

Surface stresses in soft silicone gels

Robert W. Style[1], **Qin Xu**[1], **K. E. Jensen**[2], **and Eric R. Dufresne**[1]

[1]ETH Zürich, Zürich, Switzerland
[2] Williams College, Williamstown, USA

Surface stress, also known as surface tension, is a fundamental material property of any interface. In stiff solids, it normally has a negligible effect. However, recent work has demonstrated how surface stress can significantly affect the mechanical behaviour of soft solids, including surface wetting, small-scale adhesion, and composite behaviour.

I will explain how we can characterise surface stresses in soft solids by examining the contact line of a droplet on the soft solid in question. Unexpectedly, we find that the measured values of surface stress are highly strain-dependent [1,2,3]. This means that surface stresses can play a dominant role in solid mechanics at larger length scales than previously anticipated. Our measurements are corroborated by separate micro-indentation experiments [1].

References

[1] K. E. Jensen, R. W. Style, Q. Xu, E. R. Dufresne, Phys. Rev. X **7**, 041031 (2017)
[2] Q. Xu, R. W. Style, E. R. Dufresne, Soft Matter **14**, 916 (2018)
[3] Q. Xu, K. E. Jensen, R. Boltyanskiy, R. Sarfati, R. W. Style, E. R. Dufresne, Nature Commun. **8**, 555 (2017)

Interactions on soft interfaces: Beyond the Cheerios effect

J.H. Snoeijer

[1] *Physics of Fluids Group, University of Twente, Enschede, The Netherlands*

The attractive interaction of solid particles floating on a liquid interface is popularly known as the Cheerios effect. Here we present similar interactions for particles and droplets on soft layers, mediated by viscoelastic deformations. We start with the Inverted Cheerios effect, by considering liquid drops on a solid gel [1]. Remarkably, the interaction between drops can be tuned from attractive to repulsive, as shown experimentally and theoretically. Subsequently, we turn to more general cases of particles on elastic layers and provide an overview of the various regimes of interaction [2]. Then, we discuss drops on viscous layers [3] before, finally, returning to the Cheerios effect for drops hovering above a bath in a Leidenfrost state. In the latter case, we observe a nearly frictionless dynamics and observe intricate capillary orbits [4].

References

[1] S. Karpitschka, A. Pandey, L.A. Lubbers, J.H. Weijs, L. Botto, S. Das, B. Andreotti, and J.H. Snoeijer, PNAS **113**, 7403 (2016)

[2] A. Pandey, C.L. Nawijn and J.H. Snoeijer, EPL **112**, 36006 (2018)

[3] M.A. Hack, M. Costalonga, T. Segers, S. Karpitschka, H. Wijshoff and J.H. Snoeijer, Appl. Phys. Lett. **113,** 183701 (2018)

[4] A. Gautier, D. van der Meer, J.H. Snoeijer and G. Lajoinie, in preparation.

Droplet motion induced by geometry and flexibility

A. T. Bradley[1], F. Box[1], I. J. Hewitt[1] and D. Vella[1]

[1]*Mathematical Institute, University of Oxford, Oxford, UK*

Droplets on surfaces move in response to a range of factors, from externally applied fields to substrate topography and geometry. In this talk, I shall discuss briefly how changes in surface curvature may induce droplet motion.

The focus of the talk will, however, be the motion of a droplet confined in a channel whose walls are initially flat (uncurved) and parallel. However, these walls are deformable and, via a combination of bending and capillarity, a pressure gradient is created that, in turn, drives the spontaneous movement of the droplet. This droplet motion occurs only because of the channel bends in response to the presence of the droplet itself; we call this motion *bendotaxis* [1].

We study the dynamics of bendotaxis using a combination of experiments at a macroscopic scale and a simple mathematical model; we focus in particular on the time scale associated with the motion for both wetting and non-wetting drops. Surprisingly, we find that the direction in which bendotaxis occurs is always the same, regardless of the wettability of the channel: both wetting and non-wetting droplets move towards the open end of the channel.

We suggest that bendotaxis may be a useful means of transporting droplets in technological applications, for example in developing self-cleaning surfaces, and discuss the implications of our results for such applications.

References

[1] A. T. Bradley, F. Box, I. J. Hewitt and D. Vella, Phys. Rev. Lett. (*in press*)

Bacteria: self-motile liquid crystals?

Julia M Yeomans
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We discuss recent work showing that the concepts of liquid crystal physics can give insight into the behaviour of colonies of bacteria at surfaces. Dense bacterial layers can show local nematic order with associated topological defects acting as preferential sites for biofilm formation. Less dense swimming bacterial suspensions can be focused by an underlying passive nematic, a step towards exploiting their energy for microfluidic transport.

How to realize statically hydrophilic/oleophilic but dynamically hydrophobic/oleophobic surfaces?

C. Urata and A. Hozumi

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The development of novel liquid-repellent surfaces inspired by examples from nature, including the lotus leaf, the water striders' leg, the pitcher plant, etc., have attracted considerable attention across many scientific disciplines with interest ranging from fundamental research to practical applications. Such functional surfaces have been commonly prepared by combining textured surfaces with perfluorinated compounds such as perfluoroalkylsilanes or perfluorinated fluids.

In this talk, we questioned: "Are micro/nanostructures, perfluorinated compounds, or extremely large contact angles (CAs) truly necessary to achieve excellent liquid sliding properties"? We introduce our approaches to achieving surfaces which show excellent dynamic dewetting properties against water and various low surface energy organic liquids, without relying on both complicated surface roughening techniques, or expensive and environmental damaging perfluorinated compounds. Our developed surfaces are very smooth and show unusual dynamic dewettability, that is, "statically hydrophilic/oleophilic but dynamically hydrophobic/oleophobic" properties on which water and various probe liquids can move smoothly without pinning at very low substrate tilt angles despite their fairly small CAs.

References

[1] N. Singh, H. Kakiuchida, T. Sato, R. Hönes, M. Yagihashi, C. Urata, and A. Hozumi, *Langmuir*, **2018**, 34, 11405.
[2] C. Urata, B. Masheder, D. F. Cheng, D. F. Miranda, G. J. Dunderdale, T. Miyamae, and A. Hozumi, *Langmuir*, **2014**, 30, 4049.
[3] B. Masheder, C. Urata, D. F. Cheng, and A. Hozumi, *ACS Appl. Mater. Interfaces*, **2013**, 5, 154.
[4] C. Urata, B. Masheder, D. F. Cheng, and A. Hozumi, *Langmuir*, **2012**, 28, 17681.
[5] D. F. Cheng, C. Urata, B. Masheder, and A. Hozumi, *J. Am. Chem. Soc.*, **2012**, 134, 10191.
[6] D. F. Cheng, C. Urata, M. Yagihashi, and A. Hozumi, *Angew. Chem., Int. Ed.*, **2012**, 51, 2956.

Impact of interfacial properties to droplet dynamics, geometry and arrangement

Karin Jacobs[1]

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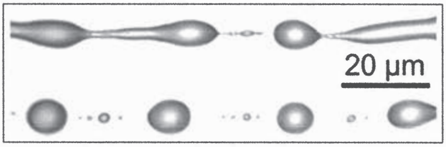

Many different parameters can influence the behavior of droplets on surfaces, e.g. the hydrodynamic boundary condition at the solid/liquid interface. For instance, for droplets formed on a cylindrical fiber due to a Rayleigh-Plateau-Instability (RPI) of a liquid film, the hydrodynamic boundary condition significantly influences the dynamics of the RPI [1] and can also make them move [2]. The boundary condition moreover influences the motion of and the flow within a droplet: Classical hydrodynamic models predict that infinite work is required to move a three-phase contact line, yet assuming a slip boundary condition, in which the liquid slides against the solid, such an unphysical prediction is avoided. Our experiments on sessile droplets demonstrate that the contact line motion is also influenced by the hydrodynamic boundary condition [3]: Spherical cap-shaped droplets, with nonequilibrium contact angle, are placed on a solid surface from which they dewet. The relaxation is monitored using *in situ* atomic force microscopy. We find that slip has a strong influence on droplet evolutions, both on the transient nonspherical shapes and contact line dynamics. The observations are in agreement with scaling analysis and boundary element numerical integration of the governing Stokes equations, including a Navier slip boundary condition. The results are also corroborated by our experiments using scattering methods [4]. Furthermore, the hydrodynamic boundary condition causes the emergence of different droplet patters after a thin film dewetted. The droplet arrays observed during the quasi-static evolution are generated by two distinct types of instabilities: droplet shedding of moving liquid ridges and satellite droplet pinch-off during the decay of stationary rims [5].

References

[1] S. Haefner et al. Nature Comm. **6**, 7409 (2015)

[2] S. Haefner, O. Bäumchen, K. Jacobs, Soft Matter **11**, 6921S (2015)

[3] J.D. McGraw et al., PNAS **113**, 1168 (2016)

[4] J.D. Mc Graw et al., J. Chem. Phys. **146**, 203326 (2017)

[5] D. Peschka et al., PNAS (in press).

How Slippery are SLIPS? Measuring Effective Slip on Lubricated Surfaces with Colloidal Probe Atomic Force Microscopy

Chiara Neto, Liam R.J. Scarratt, Liwen Zhu

School of Chemistry and University of Sydney Nano Institute, The University of Sydney, NSW 2006 Australia

Lubricant-infused surfaces have interesting anti-fouling, anti-icing and omniphobic surface properties.[1] The acronym often used in the literature - SLIPS - describes them as being "slippery" (SLIPS). Here, we studied their ability to reduce hydrodynamic drag by inducing slip at the liquid/liquid interface.[2] We quantified an effective slip length over lubricant-infused surfaces, by measuring hydrodynamic drainage forces by colloid probe atomic force microscopy (AFM) in a viscous sucrose solution. Two sets of lubricant/substrate systems were studied: the first was an ultra-thin silicone oil layer (2 nm thick) on hydrophobized [octadecyltrichlorosilane (OTS)-coated] silicon wafers. This was found to induce an average effective slip length of 29 ± 3 nm, very close to that of an uninfused OTS substrate.[3] The second set of surfaces were thicker silicone oil films (10 – 400 nm thick) stabilized over Teflon surfaces. These silicon oil films induced higher values of effective slip length, up to around 70 nm. The effect of drainage forces on film thickness was not taken into account, and the current theories of interfacial slip used do not adequately describe the experimental data at liquid/liquid interfaces, but some trends could be identified as to how slip varies with increasing lubricant film thickness on the surface. We expect that these results will contribute to improving the design of drag-reducing coatings using lubricant infusion.

References

1. C. S. Ware, T. Smith-Palmer, S. Peppou-Chapman, L. R. J. Scarratt, E. M. Humphries, D. Balzer and C. Neto, *ACS Appl. Mater. Interfaces*, 2018, **10**, 4173–4182.
2. T. Lee, E. Charrault and C. Neto, *Adv. Colloid Interface Sci.*, 2014, **210**, 21-38.
3. L. R. J. Scarratt, L. Zhu and C. Neto, *Langmuir*, 2019, DOI: 10.1021/acs.langmuir.8b03767.

Modelling Drops on Liquid Infused Surfaces

H. Kusumaatmaja[1]

[1] *Department of Physics, Durham University, Durham DH1 3LE, UK*

Inspired by pitcher plants, a novel class of functional surfaces, termed liquid infused surfaces (LIS), can be constructed by infusing rough or porous materials with a lubricant. They have been shown to exhibit a wide-range of advantageous surface properties, including self-cleaning, drag reduction, anti-icing and anti-fouling. In this talk I will discuss our recent results modelling the statics and dynamics of drops on these liquid infused surfaces. First, unlike standard wetting problems, our theory shows that the contact angle of a drop on LIS is not uniquely defined by material parameters, but also has a strong dependence on the size of the drop and the pressure of the infusing lubricant [1]. Second, using a novel ternary free energy lattice Boltzmann method to study the dynamics of drops moving across LIS, we observe a rich interplay between contact line pinning and viscous dissipation at the lubricant ridge, which become dominant at large and small apparent angles respectively [2]. Third, we employ Surface Evolver to examine the capillary force exerted by liquid bridges sandwiched between two LIS. Our hypothesis is that the action of capillary forces by the lubricant will make perpendicular displacements very difficult. As such, we can effectively have a substrate which is slippery in one direction, but sticky in another direction. Finally, we investigate the motion of drops on LIS with texture gradients. When the LIS is under-filled by the lubricant, we observe that the drops can move across large distances, many lengths of their size. This feature is unique and highlights the desirable property that contact line pinning is very weak on LIS. When the lubricant is only partially wetting the solid surface, we will also demonstrate how bi-directional droplet motion may be achieved with the same surface texture.

References

[1] C. Semprebon, G. McHale and H. Kusumaatmaja, Soft Matter **13**, 101 (2017)

[2] M. S. Sadullah, C. Semprebon and H. Kusumaatmaja, Langmuir **34**, 8112 (2018)

Dynamics on liquid-infused surfaces

Armelle Keiser (1), Philipp Baumli (2), Doris Vollmer (2), David Quéré (3)

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Trapping a thin liquid film in the micro-textures of a rough material creates a surface that is partially solid and partially liquid, referred to as a lubricant-impregnated surface (LIS) [1-2]. Such surfaces have recently raised a great interest, owing to their promising industrial applications. Indeed, they proved to drastically reduce adhesion of a broad range of liquids, leading to enhanced mobility [3], and strong anti-biofouling, anti-fogging, and in some cases anti-icing properties [4]. In addition, they can self-heal and resist drop impact [5].

In the first part of the talk, I will illustrate how the combination of textures and lubricant leads to very unique dynamics. Focusing on the friction of a drop going down an inclined LIS, a special attention will be given to the meniscus that surrounds the drop [6]. Then, through canonical experiments (dewetting of a thin film, drops confined in a Hele-Shaw cell, pearling instability), I will highlight the original dynamics exhibited by liquids on those surfaces, dramatically different from the behaviors classically reported on solid substrates.

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Wetting flexible fiber arrays

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Capillary forces play an important role in liquid-textile interactions. A small amount of liquid between two fibers can locally deform the fibers, and indeed induce the collapse, or sticking, of adjacent fibers. At the scale of a textile, this elastocapillary effect can lead to a global shrinkage upon drying, as well as a modification of the wetting properties, since the arrangement of the fibers, i.e. the microstructure of the surface, is modified.

Mist collection on a fiber array : collapse of adjacent fibers and formation of liquid columns

We study the wetting/drying of flexible fiber arrays with model experiments, either with a single drop deposited on parallel fibers, or by placing the microstructure in a mist of micron-size droplets to study the collection of drops, i.e. the growth/coalescence dynamics on an fiber array. We study how the zipping, i.e. the collapse of adjacent fibers, and the resulting formation of continuous liquid columns, affect the adhesive strength, the drying rate and the collection efficiency. In addition, we show how these changes in the fibrous structure may be controlled by adjusting the tension of the fibers.

Droplets and bubbles with phase transitions

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In this talk I will describe and explain several simple experiments in which phase transitions in and around single droplets and bubbles play an important role. The talk will cover vapor bubbles and freezing and boiling droplets, on cold and hot surfaces, and in cold and hot surrounding liquid, showing beautiful and often unexpected phenomena.

One example consists of a drop of water that freezes from the outside: the expansion of water upon freezing is incompatible with the self-confinement by a rigid ice shell. Using high-speed imaging we show that this conundrum is resolved through an intermittent fracturing of the brittle ice shell and cavitation in the enclosed liquid, culminating in an explosion of the partially frozen droplet. We propose a basic model to elucidate the interplay between a steady buildup of stresses and their fast release. The model reveals that for millimetric droplets the fragment velocities upon explosion are independent of the droplet size and only depend on material properties (such as the tensile stress of the ice and the bulk modulus of water). For small (submillimetric) droplets, on the other hand, surface tension starts to play a role. In this regime we predict that water droplets with radii below 50 μm are unlikely to explode at all. We expect our findings to be relevant in the modeling of freezing cloud and rain droplets.

Another example is a liquid droplet that impacts a solid surface so hot that enough vapor is generated under it to prevent its contact with the solid. The minimum solid temperature for this so-called Leidenfrost effect to occur is termed the Leidenfrost temperature. We observe the wetting or drying and the levitation dynamics of the droplet using high-speed total internal reflection imaging, which enables us to observe the droplet base up to about 100 nm above the substrate surface. By this method we are able to reveal the processes responsible for the transitional regime between the fully wetting and the fully levitated droplet as the solid temperature increases, thus shedding light on the characteristic time and length scales setting the dynamic Leidenfrost temperature for droplet impact on an isothermal substrate.

Rational surface nanoengineering for dropwise condensation and antifogging

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In this lecture, I will focus on the rational, physics-derived, surface nanoengineering for condensation applications, focusing on two distinct aspects: Power generation targeting high efficiency of metallic condenser surfaces and sunlight-driven fogging retardation and rapid defogging of transparent materials.

With reference to condenser surfaces, I will present a spontaneous and naturally-emerging microfluidic mechanism during condensation, that is able to sweep microscale droplets from simply hydrophobic surfaces, without the need for already explored droplet removal pathways. The mechanism involves a self-generated, sustained and directional cascading coalescence sequence of micro-droplets along standard hydrophobic microgrooves, that removes droplets in a zipping-like process, at speeds of up to ~1m/s and for lengths more than 100 times the microgroove width. Additionally, the standard microgrooved surfaces, upon which this mechanism manifest itself, can be realized with conventional and scalable surface fabrication methods on a broad range of materials in addition to metals.

Condensation is also responsible for fogging, affecting the performance of a wide range of everyday applications including windshields, visors, displays, cameras, and eyeglasses. I will present a novel approach, based on sunlight absorbing, yet transparent metasurfaces, nanoengineered by varying the concentration of embedded plasmonically enhanced light absorbing nanoparticles in an ultra-thin titania film, to yield broadband absorption with tunable transparency. Such surfaces upon illumination induce significant heating at the air-substrate interface where fog is most likely to form and can rapidly de-fog or completely inhibit fog nucleation altogether. For the same environmental conditions, we demonstrate that such metasurfaces are able to reduce defogging time by up to four-fold compared to reference samples and markedly outperform the most widely implemented solution in anti-fogging, namely, superhydrophilic surfaces. This approach work paves the way for large-scale, low-cost manufacturing that can be applied to a versatile range of materials, including polymers and other flexible substrates, which can further be combined with state-of-the-art technology to overcome remaining impracticalities, safety, and energy-related costs related to fogging.

Wetting Questions in Vehicle Water Management

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Predictive capabilities of film, rivulet and drop transport on vehicle surfaces are desirable, since experimental investigations are complex and only possible at late stages of vehicle design. However, simulations and/or experiments remain essential, either related to wing-mirror sight demands or, more recently, to insure proper operation of sensors and/or imaging devices. Major difficulties are presently apparent with such predictions, because physical models describing basic wetting phenomena encountered on typical vehicle surfaces and geometries are lacking or are not implemented in numerical codes. These include processes such as wettability influence on drop impact and splashing, shear-driven film-rivulet-drop transition, incipient motion of drops, drop interaction with grooves and material discontinuities, film/rivulet/drop stripping from edges, etc. Improvements to present models implemented in simulation codes can only be expected once a basic physical understanding of these processes is acquired. The present contribution summarizes the main challenges in developing models and outlines a series of generic experiments with the express purpose of meeting these challenges. The structure of such models at the micro through to the macro scale is described. Implementation of these models in existing codes is also discussed and the outlook for a prediction of external water management is drawn.

(tba)

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Printing surface charge as a new paradigm to program droplet transport

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Directed, long-range and self-propelled transport of droplets on solid surfaces, especially on water repellent surfaces, is crucial for many applications from water harvesting to bio-analytical devices. One appealing strategy to achieve the preferential transport is to passively control the surface wetting gradients, topological or chemical, to break the asymmetric contact line and overcome the resistance force. Despite extensive progress, the directional droplet transport is limited to small transport velocity and short transport distance due to the fundamental trade-off: rapid transport of droplet demands a large wetting gradient, whereas long-range transport necessitates a relatively small wetting gradient. Here, we report a radically new strategy that resolves the bottleneck through the creation of an unexplored gradient in surface charge density (SCD). By leveraging on a facile droplet printing on superamphiphobic surfaces as well as the fundamental understanding of the mechanisms underpinning the creation of the preferential SCD, we demonstrate the self-propulsion of droplets with a record-high velocity over an ultra-long distance without the need for additional energy input. Such a Leidenfrost-like droplet transport, manifested at ambient condition, is also genetic, which can occur on a variety of substrates such as flexible and vertically placed surfaces. We envision that our work enriches and extends our capability in the manipulation of droplet transport and would find numerous potential applications otherwise impossible.

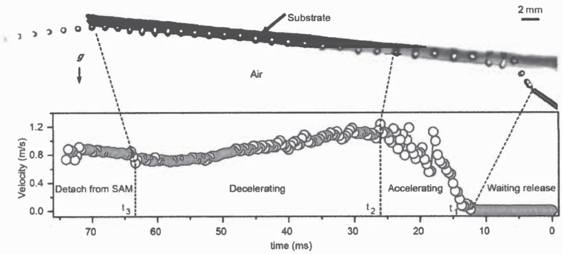

Fig.1 The gravity against droplet transportation on an upside down placed EPGS surface and evaluated the transport velocity vs time

The challenge of accurate characterization of surface wetting

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Wetting is typically characterized from a sessile droplet by evaluating the angle at the contact line where liquid, air and solid meet.[1] Contact angle goniometry is considered as the gold standard of wetting characterization, however, is prone to inaccuracies, especially towards high contact angles.[2-4]

In this talk, I will describe the problem and present state-of-the-art methodologies for evaluating wetting of hydrophobic surfaces with enhanced accuracy. Oscillations of magnetic water droplets allow measurement of friction forces between droplet and surface with nanonewton sensitivity.[5] Adhesion forces between droplet and surface can be measured by scanning droplet adhesion microscopy with sensitivity down to nanonewton (Figure 1).[6]

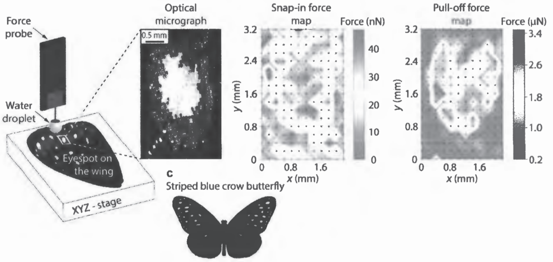

Figure 1. Scanning droplet adhesion microscopy allows to obtain wetting maps, a new concept for hydrophobic surface characterization, visualizing wettability variations with micronscale spatial resolution.[5]

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Robust and Sturdy: Tailormade micro- and nanostructured materials with unusual wetting properties

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We describe the generation of well defined micro- and nanostructured surfaces with tailor-made surface chemistries. To this high aspect ratio micro- and nanostructured surfaces are generated in silicon through lithography, the Bosch process or a cryro-DRIE process. In the first case well defined post structures, in the latter silicon nanograss structures are obtained (Fig. 1). The silicon structures are coated with polymer layers of different polarity. It is found, that such surfaces show very distinct wetting transitions, where even minor changes in the surface energy of the coating cause huge changes in the contact angle.

A serious problem for any practical application of superhydrophobic surfaces is the mechanical fragility of the nanostructures. Even moderate forces caused by touching or rubbing the surfaces are frequently enough to destroy the nanostructures and lead to the loss of the superhydrophobic properties. We study the mechanical stability of superhydrophobic surfaces with three different topographies i.e. with nano- and microscale features and surfaces carrying a combination of both. We perform controlled wear tests on the different surfaces and discuss the impact of wear on the wetting properties of the different surfaces.

Additionally, superhydrophobic surfaces (SHS) have gained a reputation to exhibit self-cleaning behavior ("Lotos effect") as drops rolling off the surface take along loosely adhering durst particles. However, this self-cleaning process reaches its limits when such surfaces are brought in contact with sticky contaminants like oils and smaller particles. Once intimate contact between the surface and a small particle is established, it will be almost impossible to remove it because of strong surface interactions. Such contaminations, however, lead to contact line pinning and destroy the superhydrophobic effect. Because the fragility of the micro- and nanostructures prohibits any mechanical cleaning, the sample is then usually doomed. We describe mechanisms to repair such surfaces. We demonstrate this principle by deliberately soiling the surface with various model contaminants, such as oily substances and particles, and study the repair process.

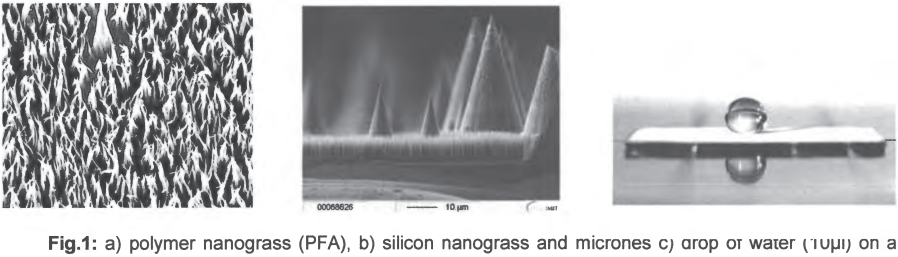

Fig.1: a) polymer nanograss (PFA), b) silicon nanograss and micrones c) drop of water (10µl) on a silicon nanograss covered surface

Adaptive wetting

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The dynamic process of liquids that wet or dewet surface is not only ubiquitous in everyday life. It is also of key importance in many technological applications. Existing work mostly focuses on the influence of the topography and composition of rigid and inert substrates. Here, we discuss the wetting of adaptive surface. Adaptive substrates change their physico-chemical properties due to the presence of a liquid or its vapor. As it turns out, not only specifically designed substrates adapt, but adaptation to the liquid is a rather general phenomenon. Adaptation can explain contact angle hysteresis.

We propose a first order kinetic model to describe dynamic contact angles of such adaptive surfaces (Langmuir 2018, 34, 11292). The model is relatively general and does not refer to a particular adaptation process. The aim of the proposed model is to provide a quantitative description of adaptive wetting and to link changes in contact angles to microscopic adaptation processes. By introducing exponentially relaxing interfacial energies and applying Young's equation locally, we predict a change of advancing □a and receding contact angles □r depending on the velocity of the contact line. Even for perfectly homogeneous and smooth surfaces, a dynamic contact angle hysteresis is obtained. As possible adaptations we discuss changes in the surface state reconstruction of polymers or monolayers, diffusion and swelling, adsorption of surfactants, reorientation of liquid molecules or the formation of an electric double-layer.

Abstracts of Posters

(in alphabetical order)

Efficient simulations of dynamic wetting of flexible substrates

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Wetting of elastic substrates (soft wetting) plays a major role in a broad variety of phenomena in nature and technology. Yet, the continuum modeling and simulation of soft wetting has remained essentially unexplored [1].

The poster presents an idea for a numerical method coupling two-phase flow to elastic bodies and substrates. Thereby, we combine phase-field modeling of moving contact lines [2] with methods for fluid-structure interaction to develop an efficient numerical framework for simulating various aspects of soft wetting.

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Wetting, Drying, and Surfactant Droplets on Superhydrophobic Surfaces

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We experimentally investigate the wetting state and evaporation dynamics of droplets on superhydrophobic (SH) surfaces of different roughness. In particular, by exploring new parameter regime, we study the influences of nanofluids, surfactants, and nanograss-liked SH on the wetting and evaporation of aqueous droplets. The time evolution of the contact angle, base diameter, droplet height, and droplet volume on various superhydrophobic substrates are measured. The experimental data indicates that all the water droplets formed gas-trapping Cassie-Baxter state on the nanograss SH samples. We found that for small droplets similar evaporation dynamics were observed, and the droplets began with constant contact angle mode, followed by a mixed mode at the end of the droplet lifetime. Contrary, for relatively large droplets, two distinct evaporation dynamics were reported. Some of the droplets were initially in a constant contact angle mode as in the small droplets, while other droplets began with constant contact radius regime and finally, all the droplets underwent a mixed mode. Stick-slip motions of the contact line for large droplets were observed and attributed to the adhesion work between the solid and the liquid interface. Our experimental data for the evolution of both the contact angle and the droplet mass flux roughly collapse onto one universal curve for different droplets sizes and initial contact angles and agreed better with an evaporative cooling model. Finally, we will also discuss the effects of additive nanoparticles and surfactants on contact angle and evaporation dynamics on SH microstructures.

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Flow-Induced Emulsion-Based Lubricant-Replenishment

Philipp Baumli†,1, **Hannu Teisala**†,1, **Hoimar Bauer**1, **Diana Garcia-Gonzalez**2, **Viraj Damle**3, **Florian Geyer**1, **Maria D´Acunzi**1, **Anke Kaltbeitzel**1, **Hans-Jürgen Butt**1, **and Doris Vollmer***,1

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Slippery lubricant-infused surfaces allow easy removal of liquid droplets on surfaces. They consist of textured or porous substrates infiltrated with a chemically compatible lubricant [1]. Capillary forces help to keep the lubricant in place. Slippery surfaces hold promising prospects in applications including drag reduction in pipes or food packages, anti-corrosion, anti-biofouling, or anti-icing. However, a critical drawback is that shear forces induced by flow lead to depletion of the lubricant [2, 3]. In this work, a way to overcome the shear-induced lubricant depletion by replenishing the lubricant from the flow of oil-in-water emulsions is presented and investigated theoretically and experimentally. Laser scanning confocal microscopy and advanced image processing reveals that the attachment and coalescence of oil droplets from the emulsion at the substrate surface fills the structure with the lubricant. That is, the flow-induced lubricant-replenishment prevails over the shear-induced depletion. Flow-induced lubrication of textured surfaces can be generalized to a broad range of lubricant-solid combinations using minimal amounts of oil.

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Condensation and evaporation on elastic surface topographies

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While elasto-capillary bundling of slender surface features during the evaporation of a wetting liquid are amply described in literature [1,2], only few studies address the effect of wettability on the dynamics of pattern formation during condensation. The example shown in Fig.1 illustrates that the interaction mediated by deformations of high aspect ratio ridges of a hydrophobic material can lead to a spontaneous droplet ordering. The kinetics of this process can be understood from the enhancement or suppression of coalescences with neighboring droplets located in the same groove which is influenced by the positions of droplets in neighboring grooves. Numerical energy minimizations to compute the droplet shapes at given sinusoidal deformations of the ridges reveal that the droplets in the same grooves can only coalesce up to a certain maximum volume. Beyond this volume the droplets "pop out" and start to merge with other droplets across the ridges. To study the coupling between liquid transport, ridge deformation, and droplet coalescence we propose a one dimensional model that accounts for the wetting conditions and the geometry of the linear surface topographies.

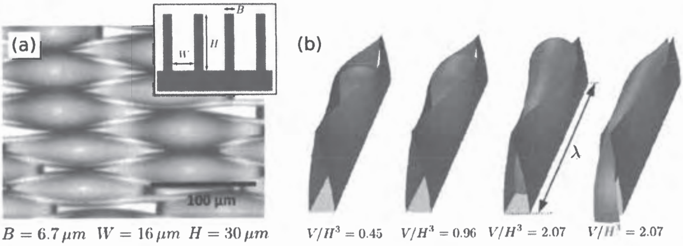

Fig. 1 (a): Droplet pattern observed during condensation of water vapor between hydrophobic silicone rubber ridges. (b): Numerically computed droplet shapes for various liquid volumes and a material contact angle 105°.

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Break-up of a viscous suspension jet. Joris CHÂTEAU, & Henri LHUISSIER (*IUSTI, Aix-Marseille Univ. & CNRS, France*). As viscosity is increased, a liquid capillary jet accelerated by gravity stretches over increasingly large distances before eventually breaking up. This Newtonian behavior is profoundly altered for particulate suspensions. Adding solid particles to a liquid, which increases the effective viscosity, can paradoxically shorten the jet considerably. This apparent contradiction is rationalized by considering finite size effects occurring at the scale of a few particles. A model is presented which captures the breakup length of suspension jets observed experimentally for a broad range of liquid viscosities, particle sizes and extrusion velocities of the jet, and recovers the Newtonian case for vanishing particle sizes. These results can be readily extended to any stretched jet configuration and potentially to other fluid media having a granularity.

Experimental and numerical study of droplet impact on nanostructured superhydrophobic surfaces

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We experimentally and numerically investigated the impact of diverse viscous droplets on nanostructured superhydrophobic surfaces. We showed that an increase in liquid viscosity will slow down the impact process and cause bouncing droplets to rebound lower and fewer times. The critical impact velocity, above which droplets can rebound from the superamphiphobic surface, was found to linearly increase with the liquid viscosity, which can be explained by a scaling argument. Moreover, we found that the maximum spreading factor, which increases with impact velocity but decreases with liquid viscosity, cannot be well described by the theoretical models developed at a level of scaling analysis in the literature. Based on numerical simulations, we analyze the temporal evolution of all energy terms involved in the dynamics, and demonstrate that the deviation of the theoretical predictions from experimental results is due to the neglect of the residual kinetic energy and improper estimation of the interfacial and viscous dissipation energies in the theoretical models.

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Soft electrowetting

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The application of an external electrical voltage to a conducting sessile droplet, resting on a hydrophobic dielectric film covering an electrode, results in enhanced wetting of the droplet on the dielectric film. Such electrically controlled partial wetting of a sessile liquid drop on a dielectric film is referred to as 'electrowetting' (EW). During EW, the presence of surface charges gives rise to a Maxwell stress, pulling on the liquid-vapor interface and pushing down on the liquid-solid interface. The Maxwell stress is distributed over a region having a length scale comparable to the dielectric thickness (d). Hence, when the droplet length scale is much larger than d, the increased curvature of the droplet surface close to the contact line (due to the balance of Maxwell stress and Laplace pressure) manifests in a lowering of the macroscopic droplet contact angle as given by the classical Lippmann-Young equation. The interesting thing to see now is how this scenario is altered if the dielectric layer is made soft.

Wetting on soft surfaces lead to elastic deformations, altering the geometry near the contact line by creating a ridge on the soft substrate. The size of this wetting ridge can be of the order of the elastocapillary length, which for silicone-based gels can easily be tens of microns. For the physical situations when the elastocapillary length is comparable to d, or larger, it is reasonable to expect an interesting interplay between elasticity and electrostatics which may eventually culminate in a change of the EW effect as classically established solely for rigid dielectrics. We therefore investigate here the statics and dynamics of *Soft Electrowetting*. We perform a systematic study of the variations of the macroscopic contact angles of the liquid drop, as a function of voltage and contact line speed. This is complemented with confocal microscopy experiments, where we show the first images of wetting ridges in the presence of strong Maxwell stresses. Furthermore, EW also provides an active way to probe the mechanics of soft structured substrates, by imposing a highly localized forcing near the droplet contact line. We utilize this to understand the behavior of flexible superhydrophobic striped surfaces during droplet wetting.

Photomanipulation of the anchoring energy and its effect on the behaviour of LC colloids

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Recently, photo-switchable azo-dendrimers spontaneously adsorbed at glass/LC interfaces have been shown to switch reversibly between homeotropic and planar anchoring conditions when exposed to UV [1-3]. In colloidal LC systems, this effect results in the photo-switching of the director field in the vicinity of LC droplets, or even mechanical motion of the colloidal particles in the nematic matrix [4,5]. We demonstrated that these effects are determined by a light-driven change of the anchoring energy of the glass/LC interface [4].

Here, we report measurements of the interfacial surface tension anisotropy (anchoring energy) at an ITO-glass/5CB interface under exposure to UV and VIS light illumination. We demonstrate that the anchoring strength depends on the ratio of the intensities in the UV and VIS bands. A simple model is developed to qualitatively explain the dependence of the anchoring energy on the light intensity. These results are then applied to describe the light-driven kinetics of the opto-mechanical effect which has been explored in the dependence of *both* UV and VIS illumination. Additionally, we report the structure and the order in the dendrimer layer at the glass/LC interface. Using Second Harmonic Generation and Attenuated Total Reflection IR Spectroscopy, it is shown that the dendrimer molecules adopt a polar structure, which can be reversibly suppressed by the UV illumination, and restored by the VIS illumination. Unusual behaviour is found in liquid crystalline droplets in an isotropic matrix. In case of bent-core nematics, the droplets with the LC/dendrimer mixture exhibit a spiral texture in polarising microscopy. We show that the spiral handedness can be switched by exposure to UV. We discuss a possible director configuration which can explain this behaviour.

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Reorganization of thin metal layers by (de)wetting phenomena for microelectronic applications

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Nano- and microstructures of metals and semiconductors are essential for novel electronic components. Top-down approaches for these structures are well established, but suffer from several limitations such as high material loss, undesirable surface modifications and high costs due to many process steps. As a result, reliable large-scale bottom-up methods without material waste are required. We have developed two methods of bottom-up growth using a change in the surface texture of the substrate: The first method requires a shadow mask for gentle pre-structuring of less than 10 nanometers, the second method uses a gentle surface roughening by femtosecond laser treatment. These surface and roughness changes cause a reorganization of a deposited thin film by controlled dewetting, surface diffusion and condensation. A fundamental description of the underlying mechanisms for micro- and nanostructure formation is also part of our research. In this case there are two mechanisms possible: The local growth of the material and the surface controlled collapse of a thin film. First demonstrations of these phenomena are large area arrays of indium microdroplets on molybdenum and gold nanodroplets on silicon and silicon/silicon oxide wafers. These simple systems shall be transformed into more complex systems of functional materials. The indium islands can be converted into CIGSe islands for microconcentrator energy conversion cells. Gold nanodroplets are suitable for the production of silicon/germanium nanowires for thermoelectric applications.

Development of omniphobic aluminum surfaces

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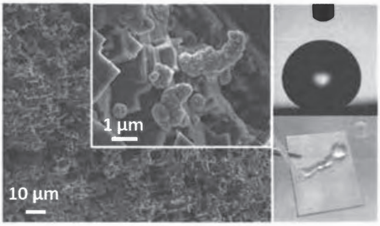
On one hand, omniphobic surfaces offer the potential to repel both high and low surface tension liquids, including water, oils and alcohols. This property has attracted huge interest in recent years due to its broad impact on industrial applications, including self-cleaning, corrosion resistance, anti-fouling, anti-icing and water-oil separation. On the other hand, aluminum is one of the most used metals in the industry. Its low specific weight, excellent thermal and electrical conductivity and low cost have made it an attractive metal as engineering material. Therefore, significant impact for omniphobic aluminium surfaces can be anticipated.

In this poster, an omniphobic aluminium surface developed by combining chemical etching and surface modification will be presented. At the first steps of this strategy, a hierarchically micro/nanostructure was obtained through chemical etching using ferric chloride as dislocant agent. Afterwards, benefiting from previous experience on material modification,[1] chemical surface modification with a low surface energy material was performed in order to grant omniphobic properties to the system. High contact angles values for water (158°) and hexadecane (75°), combined with good slippery, onto these surfaces were obtained. The anti-icing functionality of the developed surfaces will be discussed.



Surface morphology of aluminum substrate after chemical etching and its water repellent behavior.

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A Kinematic Evolution Equation for the Dynamic Contact Angle and some Consequences

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We investigate the moving contact line problem for two-phase incompressible flows with a kinematic approach. The key idea is to derive an evolution equation for the contact angle in terms of the transporting velocity field. It turns out that the resulting equation has a simple structure and expresses the time derivative of the contact angle in terms of the velocity gradient at the solid wall. Together with the additionally imposed boundary conditions for the velocity, it yields a more specific form of the contact angle evolution. Thus, the kinematic evolution equation is a tool to analyze the evolution of the contact angle. Since the transporting velocity field is required only on the moving interface, the kinematic evolution equation also applies when the interface moves with its own velocity independent of the fluid velocity.

We apply the developed tool to a class of moving contact line models which employ the Navier slip boundary condition. We derive an explicit form of the contact angle evolution for sufficiently regular solutions, showing that such solutions are unphysical. Within the simplest model, this rigorously shows that the contact angle can only relax to equilibrium if some kind of singularity is present at the contact line. Moreover, we analyze more general models including surface tension gradients at the contact line, slip at the fluid-fluid interface and mass transfer across the fluid-fluid interface.

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Elastocapillary bundling of superhydrophobic micropillar arrays

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The water-repellent properties of superhydrophobic surfaces are only achieved, when the drop is in the Cassie state. In that state, the bottom side of the drop is only in contact with the top face of hydrophobic protrusions. A transition to the Wenzel state, in which the water contacts the entire solid surface needs to be prevented as it implies the loss of high apparent contact angles, low sliding angles and self-cleaning properties. To prevent the Cassie-to-Wenzel transition one parameter of the surface which has not been fully explored is the elasticity of the surface.

Capillary forces can lead to significant mechanical deformations of elastic materials; think about the solid meniscus that forms around a liquid drop when sitting on top of a soft material[1] or, a wet paint brush in which the bristles agglomerate due to surface tension forces[2]. In a similar way to the paint brush, when using superhydrophobic surfaces fabricated with soft materials there is a deflection of the polymer structures in contact with a moving droplet[3].

In this work, we focus on studying the Cassie-to-Wenzel transition of an evaporating droplet on top of a superhydrophobic surface, fabricated with a soft material. We observe that as the droplet starts to evaporate, its inner pressure grows resulting in a selective impalement on the structure and consecutive elastocapillary bundling of the structures underneath[4]. The process, imaged under laser scanning confocal microscopy, allows us to correlate the infiltration of water within the pillars, with the pillars' elastic response and as a result we are able to characterize the transition and final state of the substrates in high detail.

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CAPILLARY RISE

FROM THE CONTINUUM MECHANICAL DESCRIPTION TO THE WASHBURN MODEL

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A classical experiment to analyze the phenomenon of wetting, is the rise of a liquid in a capillary against gravity forces. While the most popular description of this phenomenon is the Washburn square-root-dependency, an ordinary differential equation, describing the rise height over time, has also been available for almost a century. It is based on a comparably simple one-dimensional force balance and has been extended to incorporate various effects such as surfactants, varying contact angles, and various geometric specifics, e.g. the reservoir or the capillary shape.

The classical model for the rise of liquid in a capillary has been derived from the full continuum mechanical free surface model. The derivation allows for example to use the correct stationary rise height (not Jurin's height). Furthermore, incorporating the correct mass in the capillary also allows to remove the singularity that arises in the classical model for small times. This is contrast to the argument from literature where the liquid reservoir has to be considered.

Modeling the liquid wall boundary condition by a no slip condition is a widely accepted approach for single phase flows. It does however yield diverging pressure and viscous dissipation towards the moving three phase contact line. Hence, the classical model is extended to include the effect of a Navier slip boundary condition on the capillary walls. The resulting equation is compared to the numerical solution of the full continuum mechanical free surface description.

Drop impact on hard substrates covered by a thin oil layer

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Droplets impacting on dry solid substrates or on deep pools of liquids have been studied extensively. Drop impact on a thin film of the same liquid is well studied. However, the case of different or even immiscible liquids attracted comparatively little attention until recently. Lubricant infused textured surfaces have attracted substantial attention due to their low contact angle hysteresis and resulting self-cleaning or antibacterial properties. However, the lubricant's dynamics during dynamic interaction with liquid interfaces is so far insufficiently characterized and understood.

We study the dynamics of impacting water drops on thin oil layers (from few micrometers to tens of micrometers thickness) prepared by spin-coating using optical methods, combining high-speed side view imaging with bottom view interferometry or Total Internal Reflection (TIR) imaging. The latter allows us to precisely determine the presence of air layers and the eventual formation of oil-water contact, and to relate it to the overall droplet behavior. This includes spreading / retraction dynamics and drop decomposition.

Stability of Evaporating Droplets on Chemically Patterned Surfaces

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The stability of evaporating water droplets on chemically patterned surfaces with alternating hydrophilic and hydrophobic stripes is studied experimentally, numerically and using a scaling model. Different stripe widths, width ratios and wettabilities are considered. Numerical studies with *Surface Evolver* show that a critical contact angle contrast exists above which an evaporating droplet breaks up. For smaller contrasts, the droplet stays intact. This critical value increases with increasing hydrophobic contact angle. Experimental studies confirm the existence of a stable and an unstable regime.

In the unstable regime it is found that a configuration with two liquid fingers on the hydrophilic stripes connected by a capillary bridge on the separating hydrophobic stripe is formed. With ongoing evaporation, the width of this bridge decreases until a critical value is reached. This is when the droplet breaks up, leaving two disconnected liquid volumes above the hydrophilic stripes. For increasing ratio of the hydrophilic and the hydrophobic stripe width, the critical width increases.

The critical width of the capillary bridge can be predicted by a simple scaling model based on the Young-Laplace equation. According to the model, the critical width is reached when the Laplace pressure inside the bridge exceeds the maximum achievable pressure inside the liquid fingers on the hydrophilic stripes.

Acknowledgements

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Study of Slippery Liquid Infused Porous Surfaces with Different Porosities under Shear Force

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Slippery Liquid Infused Porous Surfaces (SLIPS) consist of a lubricant spread on a nano-/microstructured surface [1]. Due to the liquid on top, SLIPS substrates can be construed as soft surfaces, i.e. the surface deforms upon deposition of a droplet, forming a wetting ridge [2]. The macroscopic behavior of such surfaces under shear stress can be studied by determining the roughness, because loss of the lubricant exposes the underlying rough material. We have previously reported the formation of superhydrophobic fluoropolymer foam “Fluoropor” with adjustable pore sizes [3]. Infusion of Fluoropor with fluorinated oils results in Fluoropor-SLIPS of different transparency. The influence of shear stress on these SLIPS was studied by white light interferometry [4]. After seven days of high shear force, the SLIPS lost a significant amount of lubricant, while they stayed intact at low shear forces, if the pores were small enough (see Figure 1). The attachment of biofilm-forming bacteria *p. aeruginosa* was more effectively reduced on Fluoropor-SLIPS with smaller pore sizes. WLI measurements could be an effective tool for analyzing SLIPS and understanding the macroscopic behavior of soft surfaces.

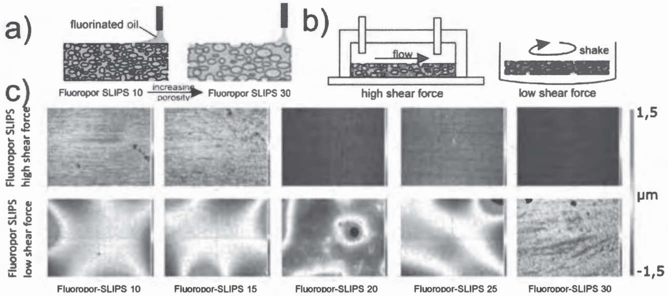

Figure 1: White light interferometry (WLI) study of Fluoropor polymers with different porosities. **a)** infusion of Fluoropor with fluorinated oil gives Fluoropor-SLIPS with increasing pore sizes. **b)** incubation of Fluoropor-SLIPS under high shear force (microfluidic setup) and low shear force (shaker). **c)** WLI data shows a significant loss of lubricant after seven days under high shear force. Under low shear force, the Fluoropor-SLIPS with smaller pores stay intact, while Fluoropor-SLIPS with larger pores also lose the lubricant and expose the surface roughness

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Wetting using Highly Branched Hydrophilic Additives

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Modern waterborne and conventional solvent-based coatings face a number of technical and commercial challenges. Additives are increasingly important for enabling the coating formulator to reach these ever-growing demands and advance the technology. Wetting, leveling, slip, recoatability or easy-to-clean properties are strongly influenced by surface-active additives.

The classic approach to improve substrate wetting is to use an additive, which reduces the surface tension of the coating to be applied. Fluorinated surfactants and silicone surfactants are the most effective substances in this group of additives. Even in small quantities, they reduce the static surface tension of the coating and favor the spreading. For many years, coating formulators primarily used these tools to improve substrate wetting and also wetting over primers, basecoats, middle coats etc. This is still the first approach to improve the wetting of cured coating films, but the method has many disadvantages in multi-layer coatings. First, a low surface tension of the coatings is not ideal for achieving the best possible leveling. Secondly, it is necessary to consider the wetting process of the different layers between each other and with a given substrate. The adjustment of the surface tension with additives in multilayer coatings can be problematic if the underlying layers have relatively low surface energies.

A unique opportunity for multi-layer coating systems is to not use a substrate wetting additive, but to raise the surface energy of the underlying coating (or primer), so that no conventional wetting additive is needed for the subsequent coating. For the first time, a new generation of hydrophilic additives has been developed, which – unlike other surface additives – is able to raise the surface energy of the cured coating film substantially. This results in perfect wetting of the subsequent coating and good intercoat adhesion when recoated. We believe that this technology could also be used in various industrial applications to enhance wetting on soft surfaces.

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Liquid-liquid phase separation in contact with deformable surfaces

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The capillary forces of droplets on top of soft solids deform the solid surface into sharp wetting ridges. The amplitude of the wetting ridge is governed by elasto-capillary length, the ratio of liquid surface tension to the solid's shear modulus. Previous experiments on soft wetting used large liquid-vapour surface tensions and thus were in a highly nonlinear regime regarding the response of the solid. This led to debates in the literature regarding the effects of strain dependent solid surface tensions or the dynamics of soft wetting. Liquid interfaces with small surface tensions could instead probe the linear regime of soft wetting and shed new light onto the static and dynamic behaviours of solid surface tension. Thus we investigate the liquid-immersed case of soft wetting, aiming for a control of the liquid and solid surface tensions. Near the critical point of a phase-separating binary fluid mixture, surface tension can become arbitrarily small. Here, phase separation should occur through a long wave instability rather than nucleation and growth, which would be expected away from the critical point. In contact with solid surfaces, phase separation would then occur through heterogeneous nucleation, since the energetic barriers of surface tension are typically lower than in the bulk. Therefore we also investigate experimentally how liquid-liquid phase separation processes are affected by the softness of the substrate.

Splitting droplet through coalescence of two different three-phase contact lines

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Moving contact lines of more than two phases dictate a large number of interfacial phenomena. Despite of its significance to fundamental and applied processes, the contact lines at a junction of four-phases (two immiscible liquids, solid and gas) have been addressed only in a few investigations. Here, we report an intriguing phenomenon that follows after the four phases of oil, water, solid and gas make contact through the coalescence of two different three-phase contact lines. We combine experimental study and theoretical analysis to reveal and rationalize the dynamics exhibited upon the coalescence between the contact line of a micron-sized oil droplet and the receding contact line of a millimeter-sized water drop that covers the oil droplet on the substrate. We find that after the coalescence a four-phase contact line is formed for a brief period. However this quadruple contact line is not stable, leading to a `droplet splitting' effect and eventually expulsion of the oil droplet from the water drop.

Droplet complete rebound on thin films and liquid-infused textured surfaces

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Liquid-infused textured surfaces exhibit very low adhesion and hence are promising for applications that involve self-cleaning, anti-icing or anti-fouling properties. Of particular interest is the dynamics of impacting drops on such surfaces. Here we report experiments of drop impact on thin films and liquid-infused textured surfaces. We image the deformations of the thin films during and after impact using Digital Holographic Microscopy. This is complemented by simulations based on lubrication theory, providing a direct comparison to the experimental profiles.

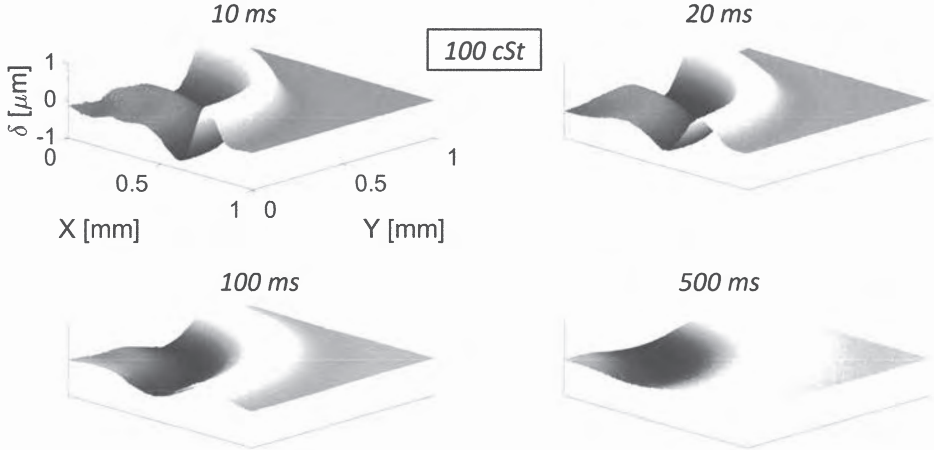

Fig: Relaxation of thin film deformations upon droplet impact. Drop diameter D = 1.25 mm, impact speed v = 0.13 m/s and initial film thickness h_0 = 15 µm.

Improving surface-wetting characterization

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Highly hydrophobic surfaces have numerous useful properties—for example, they can shed water, be self-cleaning and prevent fogging. The measurements of contact angles was and still is serving to benchmark surfaces cross the entire wettability spectrum from superhydrophilic (CA of 0°) to superhydrophobic (CA of 150°-180°). However, apart from a few reports, including (1–4), the measurement inaccuracy has been largely overlooked by users of the CA goniometer. The errors in CA resulting from one-pixel displacement of the baseline can be larger than 10° when CA is reaching to the high limitation (180°), especially with droplet images in low resolutions. Raising awareness of the limitations of CA measurements and developing more sensitive methods are essential for the development of next-generation liquid-repellent coatings for advanced applications. We encourage researchers to rethink the relevance of contact angles in hydrophobic surface characterization and propose force as the next-generation benchmark quantity (5, 6).

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Effects of Hydrophobic Surface Heterogeneity on the Spreading of Water on Soluble Thin Films

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Fat located at the surface of food powders is well understood as the cause of poor dissolution and wetting of many food products such as instant beverages, soups and sauces as well as particular impact of dairy formulas.

Wetting of homogeneous soluble films has been studied by previous authors[1,2] where evaporation and condensation have been found to be the dominant mechanism of hydration ahead of the contact line impacting contact angle (θ) and contact line speed (U), dependent on thickness and water volume fraction.

This research introduces surface heterogeneity by printing hydrophobic droplets (cocoa butter) onto hydrophilic films (maltodextrin DE19) to observe the impacts on spreading. Droplets of cocoa butter (diameter 60µm) were deposited by controlled area fractions (0-30%), as shown in Figure 1, and the water spreading dynamics evaluated (2µL droplets at 55% RH). Increasing area coverage increased θ as a function of U. Area fractions lower than 1% were found not to impact spreading in the experiments conducted. Coverage of 26.3% was found to over triple θ after 10s of experiments and U was found to be nearly halved. Evaluation of the edge of the droplet indicates water surrounds fat altering the contact line shape and contact area.

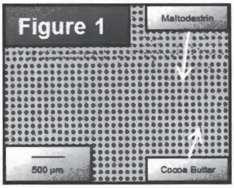

Figure 2

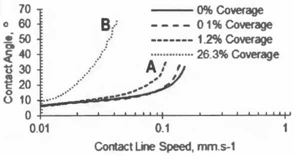

Figure 1. Micrograph of a typical heterogeneous thin film (26.3% coverage). **Figure 2.** θ vs U for 0, 0.1, 1.2 & 26.3% area coverage of 60µm deposited cocoa butter on 275nm maltodextrin films at 55% RH. **Figure 3.** Images of point A and B from Figure 2 of water droplets spreading on 1.2 and 26.3.% after 0.5s spreading

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On the Assessment of Omniphobicity derived from Intrinsically Wetting Materials

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The combination of water-repellent chemicals and surface roughness is the *recipe* for superhydrophobicity, characterized by advancing (θ_{A}) and receding (θ_{A}) contact angles as, $\theta_{\mathrm{A}} > 150°$ and as $\theta_{\mathrm{A}} - \theta_{\mathrm{R}} \leq 5°$. Superhydrophobic surfaces are routinely utilized for desalination, water-proofing, and reducing hydrodynamic drag. However, water-repellent chemicals - typically perfluorocarbons - pose economic and environmental concerns, and they are vulnerable to fouling and operational damage due to abrasion and/or harsh temperature-fields and cleaning protocols. As a result, new ways of achieving liquid-repellence - omniphobicity, characterized by apparaent contact angles, $\theta_{\mathrm{r}} \geq 90°$ - are being explored that could exploit common wetting materials, i.e., with the intrinsic contact angles, $\theta_{\mathrm{o}} < 90°$.[1-3] This feat has been achieved by carving microtextures comprising mushroom-shaped pillars or cavities, inspired by cuticles and hairs of ocean-skaters (*Halobates*) and springtails (Collembola) respectively.[1] Here, we compare assessments of omniphobicity of such surfaces through the *lenses* of (i) contact angles (advancing/receding/as-paced), and (ii) the entrapment of air on immersion. Specifically, we demonstrate that the assessment of omniphobicity can be misleading, if solely based on contact angles.[2] For pillar-based microtextures, localized defects or boundaries of microtextures may lead to the spontaneous loss of omniphobicity, and detecting them through contact angles can be difficult. We demonstrate that immersion of such surfaces into probe liquids could serve as a simple and robust "litmus" test for omniphobicity. These findings might advance the rational engineering of omniphobic surfaces using common wetting materials, such as polyethylene terephthalate (PET).

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Nonlinear visco-elastic effects of polymer and hydrogel layers sliding on liquid substrates

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We consider the interaction between a high-viscosity liquid layer in contact with a Newtonian liquid, where the layer is treated as a hydrophobic co-rotational Jeffreys' type liquid, and develop new models that explain how the dewetting leads to new friction- and stress-related patterns. In addition we consider and present a new model for the case of a hydrogel layer that allows for additional stress-related phase separation.

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Wetting ridge on liquid-infused surfaces

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Slippery liquid infused porous surfaces (SLIPS) form a new class of functional materials that repel almost any type of liquid. Inspired by the Nepenthes pitcher plant, these surfaces can be used in anti-icing, anti-biofouling, and to make easy-to-clean materials. A simple way to produce SLIPS is to infiltrate textured surfaces with a lubricant. We study the interactions and fluid reorganization which take place when an immiscible drop is placed on the lubricant. Despite the already-existing technological applications in the medical, food and packaging industries, a fundamental understanding of how the lubricant reorganizes when drops are placed on SLIPS is still lacking. Of interest is the wetting ridge surrounding the drop-lubricant interface, which is a result of the interplay of interfacial tensions between the different media. Using confocal laser scanning microscopy, we aim to image and understand the formation of the wetting ridge. The results will help us understand and predict the properties of different SLIPS, thus guiding both academic and industrial research in a more efficient direction.

Capillary Springs

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In this work, we revisit the classical experiment of Joseph Plateau from the 1840-s, where he showed a liquid cylinder between two flat plates becomes increasingly unstable when pulled apart [1]. The liquid cylinder eventually breaks into two drops when the ratio of length to diameter for the cylinder becomes π. A critical criterion in the classical version of the experiment is that the two contact lines on the plates remained pinned throughout. Here we wonder what happens in the absence of pinning. Experimentally this can be achieved by using a textured solid infused with an oil for the two plates which bound a capillary bridge made of water [2]. We observe that all liquid cylinders as in Plateau's experiment behave as capillary springs, but their characteristics critically depend on the pinning properties of the plates.

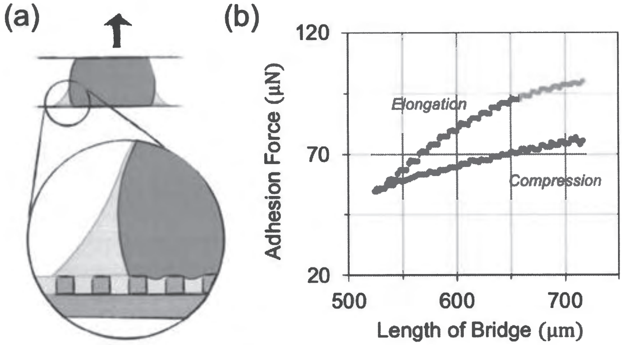

Figure: 1 (a) Schematic of a water droplet between a liquid-infused surface at the bottom and a hydrophobic plate at the top. The top plate is pulled up slowly (typically at 10μm/s) and the force at the top plate is measured with a sensitive tensiometer. Inset shows how the droplet extracts a meniscus from the lubricant infused texture. (b) A typical force-distance curve for a capillary bridge of 2 μL

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Dynamic contact angles via gradient flows

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The *poster* describes an energetic variational approach to introduce *contact angle dynamics* in a viscous fluid flow. For a corresponding Stokes free boundary problem the reduction to a thin-film equation and its variational structure are presented. The viability of this modeling approach is demonstrated by providing numerical schemes for the Stokes flow and the reduced thin-film model. Some implications and possible extensions of the contact angle model and properties of the numerical scheme are highlighted.

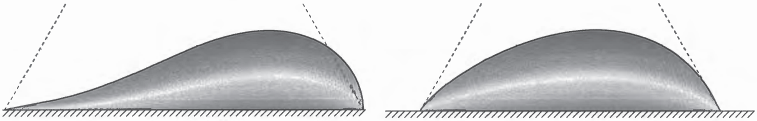

Figure: sliding 2D droplet (**left**) with dynamic contact angle (**right**) with equilibrium contact angle

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Bioinspired Networks for Liquid Diodes: from Passive Transport to Actuated Motion

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Capillary forces produce spontaneous flow, also known as 'secondary active transport'. Controlled self-propulsion of liquids has extensive application prospects in the fields of microfluidic devices, industrial filtration equipment, fog-harvesting,[1] anti-icing and condensing apparatus.[2] In nature, one can find fantastic examples of directional liquid transport in so-called "fluidic diodes" due to unique structuring and surface physiochemical properties. For example, the Texas horned lizard solves the problem of water shortage in the desert by directing condensed water on its back to the mouth via a 2D network created by the scales.[3] Another example is the spermatheca of female insects, especially designed to store or guide sperm in the direction of the reproductive system.[4] Although previous studies showed examples of directional capillary flow in 2D open networks, they still lack the predictive tools for designing highly efficient fluidic diodes. In this study, we use 3D printing to expand the scope of network design for directional liquid transport, and numeric simulations (Surface Evolver)[5] to provide guiding lines for the design of such transporting channels. Finally, despite many materials in nature being soft or flexible and the frequent appearance of flexural deformations in nature, the influence of such deformations on liquid transport in 2D networks has not been systematically studied and quantified. Here, we use soft materials to examine "bendotaxis"- liquid self-propulsion due to the combination of capillarity and surface deformations.[6]

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Janus Membrane for Dual Action: Oil-Water Separation and In Situ Water Decontamination

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An ideal remediation system for produced water (mixture of oil and organic pollutants) should include the oil-water separation and the decontamination of organic pollutants simultaneously. Although, membranes with a selective wettability of water over oil are of particular interest due to their high oil-water separation efficiency in a gravity driven ~~operation, the full remediation of oily wastewater is not possible with such membranes as~~ they are incapable of degrading organic pollutants in the permeate (i.e., water-rich permeate). In this work, a facile spray coating method was successfully applied to fabricate a novel two-faced membrane, precisely called as Janus membrane due to its dual functionality. The Janus membrane is coated with two different materials on either side of the porous membrane that enables the separation of free/emulsified oil-water mixtures in a gravity driven system and the simultaneous decontamination of organic pollutants in situ. The surface on the feed side of the Janus membrane is a superhydrophilic-superoleophobic in nature, which allows the water phase to pass through it, while retaining the oil phase with a high percentage of rejection (>99.9%) for free and emulsified oil-water mixtures. The permeate side of the Janus membrane is coated with a semiconducting material, whose primary function is to photo- catalytically decontaminate the organic pollutants present in the water-rich permeate under UV light irradiation. A theoretical model was also developed to study and predict the photo-decontamination performance of the Janus membrane as a function of relevant system parameters compared to our empirical results for the decontamination of organic dye and sulfate reducing bacteria. Our theoretical model provides the optimum operational conditions and figure of merit for the Janus membrane systems that can be used to optimize the performance of similar systems for large-scale applications.

Impact of compositional gradients on the dynamics of solid-liquid-vapor contact lines

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Marangoni contraction of binary-mixture drops on solid surfaces is being investigated. Our focus is the mechanism that gives rise to the contracted state. Previous studies have observed the dependency of the drops shape with the relative humidity of the ambient atmosphere when the drops are in the Marangoni contracted state. One theoretical approach that has been proposed follows a hydrodynamic-evaporative model, from which the contraction of the drop results as a balance between capillary and Marangoni flows.[1] We present preliminary experimental results of the internal flow fields at different ambient conditions. The relation between the internal flows and the equilibrium contact angle is studied. Additionally, the influence of the liquid composition is explored.

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The elastocapillary ridge as a non-integer disclination

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In his founding paper on the thermodynamics of interfaces [1], Gibbs defines the surface energy γ of a material as the work required to create a unit area by bringing new molecules in contact with the atmosphere, cutting bulk interatomic bonds and maintaining a constant intermolecular distance. Also, he highlights the conceptual difference between γ and the surface tension Υ of the interface, defined as the work required to create a unit surface by stretching the material at constant number of molecules in the interface (see ref. [2] for a concise summary). The difference stems from the ability of molecules to rearrange under stretch, *e.g.* $\gamma = \Upsilon$ in liquids [3, 4]. Molecules in an elastic solid cannot move. Stretching a solid alters the intermolecular distance so that $\gamma \neq \Upsilon$ in general. These two quantities are related through the Shuttleworth-Herring equation [4]: $\Upsilon(\hat{\lambda}) = \gamma(\hat{\lambda}) + \partial\gamma/\partial\hat{\lambda}$ where $\hat{\lambda}$ is a two-dimensional strain tensor in the plane of the interface. Reliable measurements of $\Upsilon(\hat{\lambda})$ and $\gamma(\hat{\lambda})$ exist for various metals [3, 5–8].

The surface energy of a material can be adjusted with a chemical treatment, such as monolayer deposition or coating. In this perspective, elastomers, *i.e.* crosslinked polymer melts, have attracted interest in recent years [9–17]. However, the definition of γ for these amorphous layers poses challenges that have yet to be met. In particular, studies of the dependence of $\gamma(\lambda)$ in the context of elastomer wetting (or elastowetting) have led to contradictory conclusions [10, 14, 15].

Here, we show that a finite-deformation model of elastomers under the assumption of a strain-independent surface energy provides an excellent description of the wetting and adhesion of elastomers. First we motivate the need for a non-linear mechanical model and we justify the assumption of strain-independent surface energy on molecular grounds. Then, we present our model. A central result of our rationale is that the deformation of the solid below the contact line has the features of a disclination. This result opens the possibility of studying wetting ridges as defects induced by the presence of contact lines. We demonstrate that our model is in very good agreement with available experimental data. Finally, we discuss the validity of other assumptions used in linear models of elastowetting.

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Self-replenishing mechanisms in abrasion-resistant alumina slippery surfaces

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We have recently shown that perfluoropolyether impregnated mesoporous alumina surfaces have exhibited excellent slippery character when contacted with water, alkanes, and acrylic paints [1]. The extremely high hardness of polar Al_2O_3 matrix, mesopores acting as reservoirs and the surfaces intentionally kept free from protruding textures have resulted in low wear-coefficients of $\leq 10^{-8}$ $mm^3.N^{-1}.m^{-1}$ as well as three orders of magnitude higher load bearing capacity (up to 350 MPa) when compared to conventional omniphobic surfaces [1,2]. These surfaces have immediately lost slippery character post abrasion, often leading to superhydrophilicity and oleophilicity as demonstrated by 0° and 10° static contact angles by water and hexadecane respectively due to the strong polarity of alumina. Indeed, these liquids have also penetrated into the mesoporous alumina demonstrating that the surface perfluorpolyether film has been removed during the wear.

The key self-replenishing mechanisms in these composites are capillary forces and the surface diffusion of the perfluoropolyether on bare Al_2O_3 surfaces. These liquid transport phenomena are responsible for nourishing the bare alumina and regaining the slipepry properties after suffiicent self-healing time. We will quantify the liquid flux rates due to various healing phenomena and eventually predict the healing time in these composites.

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Droplet Binning and Droplet Sorting Using Liquid Infused Surfaces

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Liquid infused surfaces have been demonstrated to possess excellent liquid repellent properties by having low contact angle hysteresis for virtually any liquids [1,2]. Interestingly, when the lubricant partially wets the solid, there exists a bidirectional droplet motion in the presence of a structural gradient, as shown in Figure 1. The droplet can move either toward the denser or sparser solid fraction region depending on the surface tensions of the liquids and the wettability of the lubricant to the solid. In this contribution, we explain the origin of the driving force that pushes the droplet in either direction and confirm this phenomenon using lattice Boltzmann simulations [3,4]. We further show that this bidirectional motion opens up new possibilities for microfluidic applications using liquid infused surfaces. For instance, here we show that we can sort and bin droplets based on their size and surface tension at the same time.

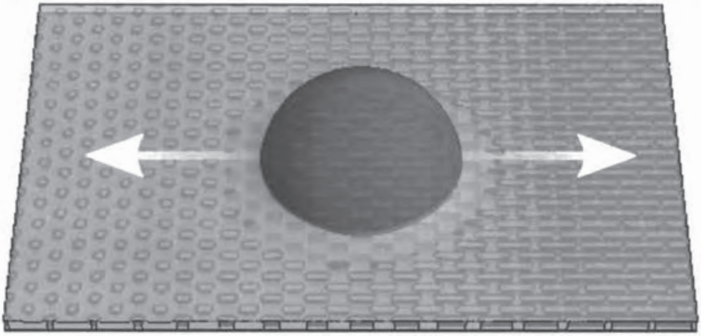

Figure 1: Bidirectional motion on a liquid infused surface with texture gradient.

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DROPLET ENCAPSULATION

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When a millimetric water drop is gently deposited on a liquid bath, it reaches a quasi-static shape (Charles and Mason, 1960) with the help of a thin lubricating air layer. Upon the drainage of this layer, a triple contact line (between air, water, and oil) forms. Depending on the surface tension coefficients, the contact line may form a stable Neumann triangle (leading to the well-studied case of liquid lenses in equilibrium, (Torza and Mason, 1971)) or results in encapsulation of droplet inside the pool. We focus on the temporal dynamics of the latter process.
We study the problem using experiments and numerical simulations. In experiments, we use high-speed imaging to capture the process of encapsulation and extract information such as the position of the triple line via image processing. In simulations, we first find the initial static shape of the droplet solving the Young-Laplace equation (e.g., Fig 1a). We then solve the Navier-Stokes equations using a Finite Volume Method implemented by Popinet, 2014, where we have modified the Volume of Fluid (VoF) framework to solve for the triple contact line implicitly.

Owing to the motion of this contact line and interaction of the capillary waves (Fig 1(b-c)), the pool engulfs the droplet, which further sinks because of its weight (Fig 1(d-e)). We compare the results of the simulations with the experiments. The present work provides information on the physics of droplet-free surface interaction and presents a new methodology for modeling triple contact lines to be used in a wide range of applications involving three immiscible liquids.

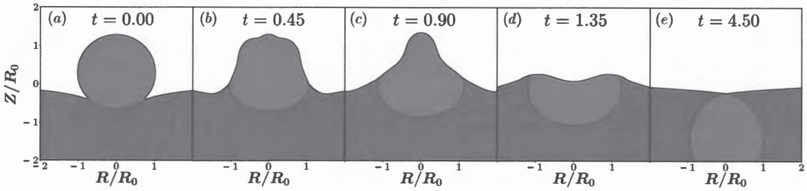

Figure 1: Temporal evolution of the interface during the droplet encapsulation. Time is non-dimensonalized with the capillary time scale.

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Wetting transitions of a binary liquid on a nanosculptured surface

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Abstract

Using nonlocal classical density functional theory, two different types of wetting transitions have been studied for a symmetric binary liquid mixture of two species of particles A and B in contact with a wall endowed with nano pits.

Intrusion of a mixed liquid into vapor filled pits is studied as a function of various system parameters such as the composition of the binary liquid, the strengths of the A-A and A-B interactions, the strength of the wall-A and the wall-B interactions, and the geometric parameters of the pit. Different from the macroscopic theory, it is found that intrusion of the liquid into the pits, i.e. the Cassie–Wenzel transition, cannot be predicted based on the knowledge of a single parameter, like the contact angle within the macroscopic theory.

In order to model the stability of lubricant infused surfaces, a partially miscible binary liquid has been studied in the phase separated regime. In this case a pore might be filled with the liquid rich in the constituent prefered by the walls of the pore whereas the space above is occupied by the other liquid. The conditions for replacement of the pore-liquid by the liquid filling the space above have been explored.

Dynamics of Aqueous Drops on Lubricating Fluid Coated Slippery Surfaces: Sinking or Slipping

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Static and dynamic behavior of aqueous drops on thin lubricating fluid coated solid surfaces is presented here. The experimental system consists of four phases, namely solid substrate, lubricating fluid, test liquid, and surrounding air. Individual characteristics of each phase play an important role in determining the final slippery behavior. Wettability of the underneath solid surface is one of the most important parameters which determines the stability of aqueous drops on such slippery surfaces. Aqueous drops on lubricating oil coated hydrophilic substrates are found unstable as they sink into the lubricating oil layer. This is because, under water, a thin oil film coated on a hydrophilic surface becomes unstable due to attractive van der Waals interaction and ruptures which result in the conversion of the oil film into multiple oil drops. Apart from substrate wettability, the sink dynamics also depend on the viscosity of the lubricating oil. Sinking behavior of aqueous drops can be analyzed in terms of change in the apparent contact angle with time. Sink time of aqueous drops depends on both, the wettability of the substrate as well as the viscosity of the lubricating layer, while the final apparent contact angle depends only on the surface wettability.

However, on a hydrophobic surface coated with lubricating oil, aqueous drops are found stable as they float on the oil coated surface and do not sink. Upon tilting by few degrees only, aqueous drops slip down the surface and the performance of slippery surfaces can be quantified in terms of slip velocity of the drops. Here we also discuss the effect of surface tension of test liquid on the slip velocity. Binary mixture of water and ethanol in different weight ratio is used to tune the surface tension. A theoretical model is also developed to describe the slip behavior of test liquid drops by taking into account all the forces (driving and retarding) acting on a test liquid drop.

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Morphology of liquid- liquid dewetting

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We study the spinodal dewetting of nanometric thin liquid polystyrene (PS) films on liquid polymethyl-methacrylate (PMMA) substrates. The initial stage of dewetting consists of the amplification of thermal fluctuations driven by dispersion forces, eventually leading to the formation of holes with a preferred distance λ. According to theoretical predictions, the PS/air and the PS/PMMA interfaces shall evolve in a coupled way. As the surface tension of the PS/PMMA interface is way smaller then the surface tension of the PS/air interface, the amplitude of the corrugation of the PS/PMMA interface will be much larger than that of the PS/air interface. To determine the morphological evolution of the preferred wavelength λ and of the preferred hole distance, we follow the evolution of the PS/air interface in situ by atomic force microscopy (AFM). The evolution of the PS/PMMA interface is explored ex situ by AFM using a lift up technique. By matching the PS/air and the PS/PMMA interfaces we can decide if the coupled corrugations of both interfaces evolve in phase or anti phase. We also explore the dependence of the preferred wavelength as function of PS film thickness and compare the result with theoretical predictions.

Wetting Adaptation and Charge Separation at the Interface between Polymer Surfaces and Rolling Drops

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Separation of electrical charge in water is a long-observed phenomenon exemplified by the dramatic sparks generated by the famous Kelvin Dropper's water streams. This effect is witnessed, often with some grief, in the charging of aerosols produced by medical nebulizers and in the breakdown of semiconductor chips rinsed with ultra pure water [1]. A number of groups have begun to decipher the reasons behind the charging of water upon contact with substances such as plastic or glass, accrediting hydroxide ions and their affinity for electronegative surfaces [2]. However, the literature is fairly sparse and the topic is highly charged. Much of the literature does not distinguish between charging from drop impact on a surface, and that from continued rolling. Additionally, very little has been written about the timescales involved in electrical surface adaptation to a series of water drops. We have developed a method for studying the individual charge from many thousands of drops rolled successively across a substrate. Our charge measurements are highly sensitive and the drops are grounded after impact to isolate the charge on rolling. On OTS(Octadecyltrichlorosilane)-coated silicon wafers, we observe temporal surface adaptation. Successive drops decrease in charge to a plateau that is dependent on drop rate. These surfaces also show adaptation to an increase in salinity of the water through an increase in drop charge and a decrease in roll speed. With the obvious prevalence and importance of water droplets in science and in society, a more thorough understanding of this topic could lead to advances in fields as wide and varied as adaptive wetting, tribocharging, electrochemistry, and renewable energy.

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Contact angle hysteresis induced by multiple nanodefects

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The wetting of realistic, nano-corrugated surfaces is a topic of vivid interest for fluid mechanics and interfacial physics [1]. It is indeed widely recognized how the presence of small chemical and topographic defects on a surface is able to drastically change its wetting properties. In a seminal paper Joanny and De Gennes [3] explained the macroscopic phenomenon of contact angle hysteresis in terms of the effect of a dilute distribution of such surface defects.

Contrary to early predictions, simulations have then shown how even defects of nanometric size are capable of inducing hysteretical behavior of the motion of the liquid-vapor-solid triple line [2]. This mechanism is supposed to be important in a number of nanoscale phenomena including the debated long-term stability of surface nanobubbles.

The present work aims at a further understanding the effect of such imperfections on contact angle hysteresis by looking at the combined effect of multiple defects arranged in various patterns. In order to do this we use microscopic Density Functional Theory (in the form of the Fundamental Measure Theory), in combination with rare events sampling [4]. This approach allows us to compute the microscopic pinning force associated with a non-trivial arrangement of nanodefects.

The goal of this work is to be able to model the wetting of actual surfaces on which defects can be randomly distributed and densely packed. This is a step beyond the dilute approximation adopted in the aforemetioned studies of the wetting of single defects [2,3].

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Droplets on switchable substrates: a simulation study

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In this work the wetting of switchable surfaces is analyzed. These surfaces can change their hydrophobicity due to an external stimulus like for example light of a defined wave length. To complement current experiments, it is desirable to study these systems also from a theoretical perspective.

To evaluate the nonequilibrium effects resulting from the switching process, we performed Molecular Dynamic simulations where we modelled a droplet consisting of Lennard-Jones particles on a switchable surface. Here we present the impact of different switching frequencies on the droplet. In particular the (time-dependent) shape and the size of the resulting droplets are analyzed.

Laser micro-/nano-structuring of surfaces for icephobic applications

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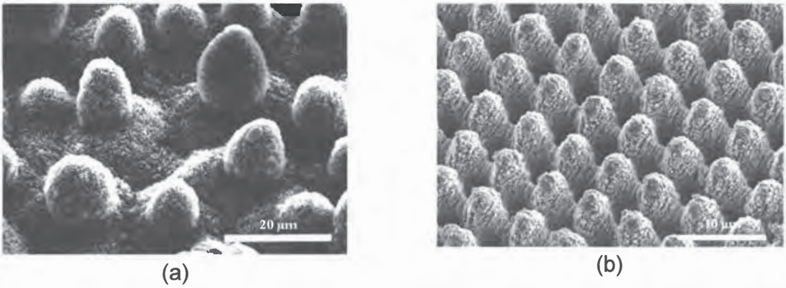
Ice accretion on aerodynamic surfaces impacts safety and performances of an aircraft. Surface modification is a promising strategy for producing icephobic surfaces, which can delay ice accretion and/or reduce ice adhesion. Among the several approaches to manufacture icephobic surfaces, superhydrophobic surfaces represent a promising solution to obtain icephobicity and contrast icing, due to the strong water repellent properties of such surfaces.

In this work we propose short and ultra-short pulsed laser treatments as a technique to enhance the functional properties of alloys commonly used in the aviation industry. The investigated laser technologies can tune the wetting properties of the materials producing Lotus-like superhydrophobic surfaces (Figure 1), due to the micro/nanostructures generated on them.



(a) (b)

Figure 1. (a) Lotus leaf surface [1]; (b) Direct Laser Interference Pattern produced on Stainless Steel [2]

Acknowledgements

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Impact and spreading dynamics of ferrofluid droplet

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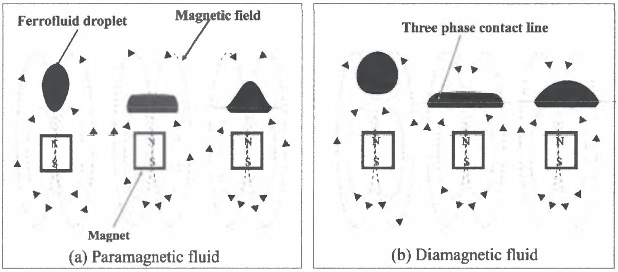
Owing to the spectacular, unique and non-intuitive shape evolution ability, ferrofluid is leveraged as an alternative for many applications ranging from sealing of bearing to droplet based microfluidics. Despite the abundance of literatures in the field of droplet spreading and impact[1],[2], the spreading dynamics of a ferrofluid droplet under the influence of magnetic field remain unanswered. In this study, several aspects of impact and spreading dynamics of ferrofluid droplet have been studied both theoretically and experimentally. Based on the energy balance approach, a theoretical model has been developed to predict the the maximal deformation upon impact influenced by magnetic field for both diamagnetic water based ferrofluid and paramagnetic oil based ferrofluid. From the theoretical analysis, it has been proposed that the maximum spreading is a function of numerous nondimensional parameters dictating the inertia, viscous, capillary and magnetic effects that are represented in the form of Weber, Reynolds and magnetic Bond number. The theoretical formulation presented here is also validated with the experimental observations. The transient variation in the morphology of an impinging droplet before and after the impact is also studied with the presence of magnetic field of various strengths. Through extensive experimental investigation a new phenomenological evidence was observed, where ratio of drop shape parameters before the impact and after the impact with minimal impacting energy remain constant regardless of magnetic field strength and magnetic field direction.



(a) Paramagnetic fluid

(b) Diamagnetic fluid

Figure 1. *Morphology of (a) Paramagnetic oil based and (b) Diamagnetic water based ferrofluid : droplet before and after the impact under the effect of vertical magnetic field.*

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Replacing the solid needle by a liquid one when measuring static and advancing contact angles

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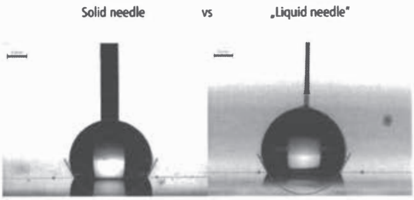
Generally, the optical determination of static and advancing contact angle (CA) is made on drops applied or extended, respectively, onto a substrate through the use of solid needles. Although this method is used extensively, this way of dosing can be time consuming, cumbersome and - if not performed meticulously - leads to erroneous results. Essential parameters, such as drop volume, needle movement speed and deposition distance, are typically not reported, and can contribute to poor reproducibility especially if CA measurements are performed by different experimentalists. Recently, we established a novel "liquid needle" dosing as a promising and advantageous alternative (compare figure and reference). Herein, we will review the main concepts of the liquid needle and illustrate using novel data why the liquid needle can provide the most precise, i.e. reproducible CA. For this, we studied the capillary waves of the deposited droplets captured through high speed recordings. These waves are generated during both the solid needle and the liquid needle dosing process. Interestingly, those caused by the drop pinch-off from a solid needle are considerably larger than in liquid needle dosing. Moreover, we found that those waves triggered by the solid needle dosing can cause deviations in CA as large as 20°. These observations will be further supported by calculations based on fluid dynamics.



Next to this scientifically fundamental advantages, we will demonstrate that optical (static and advancing) CA measurements using the liquid needle are two orders of magnitude faster, facilitates drop deposition on super hydrophobic surfaces, and automatic CA mappings impossible with a traditional solid needle dosing so far. Therefore, we believe that our contribution will be relevant and beneficial for everyone who uses optical CA measurements to assess surface properties.

Reference: Ming Jin, Raymond Sanedrin, Daniel Frese, Carsten Scheithauer, Thomas Willers; Colloid Polym. Sci. (2016), DOI 10.1007/s00396-015-3823-1

Revising the Pendant Drop Model: Contactless Method for Analyzing Contact Angle Hysteresis

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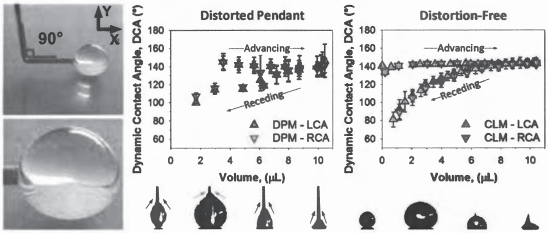
Despite the rapid advent of superomniphobic materials, methods capable of accurately investigating low energy liquid-surface interactions are lacking.[1] For instance, universally employed models such as the pendant drop often fail to provide representative information when wetting superomniphobic surfaces. Delicate balance between the miniscule forces acting at the drop-surface and drop-needle interfaces easily result in heavily distorted drop profiles. Here, we introduce a contact-free method capable of overcoming limitations of the needle-distorted pendant drop. This technique enabled a distortion-free assessment of interactions between superomniphobic materials and low surface tension liquids (i.e. hexadecane, 27 mN/m). Distortions in experimentally determined profiles were compared to computationally predicted drop shapes during dynamic drop expansion and contraction cycles. Notably, pendant drops resulted in up to 50% distortion while the contact-free method was limited at 10%. We believe that this revised method bears ample potential for the accurate characterization of the rapidly emerging family of superomniphobic materials, setting the basis for their future engineering in numerous emerging applications.[2]



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Direct Observation of Dewetting Process on Soft Substrates

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Wetting of liquid droplets on soft gels (E ~ KPa) deforms gel interface significantly: a wetting ridge grows under the balance between liquid surface tension and solid surface stress near contact line [1,2]. Using interference microscopy and fast camera imaging, we directly observe the recovery of gel surface from this wetting-induced deformation after removing liquid droplet. We show experimentally that surface relaxation of soft gels cannot be simply modelled by their viscoelastic rheology. Instead, the relaxation behaviour is a consequence of interplay between different restoring stresses near the interface, including solid capillarity and elasticity, and resisting stresses from the bulk, such as osmotic pressure across the network and local viscous stresses. By measuring scaling of wetting shapes under relaxation, we can determine which stress dominates the dissipation. Our results further extend the current understanding of elastocapillarity with the effect of bulk porosity, and bring new insight into the study of wetting dynamics on soft materials.

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Three-dimensional morphology and size-dependent stiffness of nanomenisci on porous alumina

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The entrapped air cavities in microscopic structures of superhydrophobic surfaces are well-known. Still lacking is, however, a detailed microscopic study of the three-dimensional morphology and mechanical properties of the liquid-air menisci confined by these nonwetting structures in relation to the surface wetting behavior. In this study, we imaged the three-dimensional morphology of the menisci confined by nanopores (pore diameter ranging from ~50nm to ~600nm) on a series of hydrophobized porous alumina surfaces beneath a water drop using a high-resolution atomic force microscopy. It was found that water invades partly into the nanopores and the invasion depth is determined by the surface structures. The water-air nanomenisci are stable during imaging, though they could be deformed under increasing forces. We show that this deformation is reversible under decreasing forces. Furthermore, we determined the stiffness of the nanomenisci from the force-distance curves and found its size-dependence, which can be correlated to the transition from bouncing to sticking of impinging macroscopic droplets on the nanoporous surfaces. The present work quantitatively resolves the three-dimensional morphology and size-dependent mechanical properties of microscopic liquid-air interfaces, which are correlated to the macroscopic static and dynamic wetting phenomena of micro-/nano-structured surfaces.

Deposited hygroscopic aerosols affect the wetting and water movement on leaf surfaces

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Many leaf surfaces are hydrophobic, which can be an adaptation to avoid wetting and contamination by particulate matter from the atmosphere. However, electrical conductance measurements detect continuous thin water films on hydrophobic leaf surfaces even under dry atmospheric conditions [1]. These films are initiated by hygroscopic, deposited aerosols and water vapor from foliar transpiration.

Environmental scanning electron microscopy (ESEM) shows the deliquescence of deposited aerosols on leaf surfaces [Figure 1]. Humidity fluctuations cause the extension of these concentrated solutions by “salt creep”. Salt solutions may also enter into the stomata of leaves [2; Figure 1]. This process is supported by the presence of chaotropic ions of the Hofmeister series, as they reduce water surface tension. Important consequences for plant/atmosphere interaction may result, e.g. drought stress as a direct effect of air pollution [3; Figure 2].

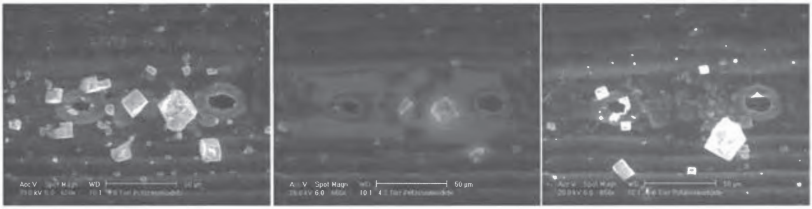

Figure 1: ESEM series of KI crystals on a pine needle surface, undergoing a humidity cycle. Note crystal formation inside the stomatal pores.

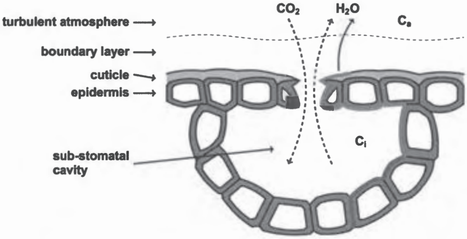

Figure 2: “Hydraulic activation of stomata”: Deliquescent salt particles creep into the stomatal pore (blue line) and connect with water coming from the roots (green line). This can cause additional transpiration (solid H_2O arrow) and reduce stomatal control.

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