北京大学
PEKING UNIVERSITY

表界面物理力学

Mechanics and physics of surfaces and interfaces

Zhaohe Dai (戴兆贺)

College of Engineering, Peking University

11 September 2023

Outline

I. About this course

II. Why I wanted to develop this course

III. Why surfaces and interfaces

- ❑ A few examples in natural systems
- ❑ A few examples in engineering systems

IV. Back to the course

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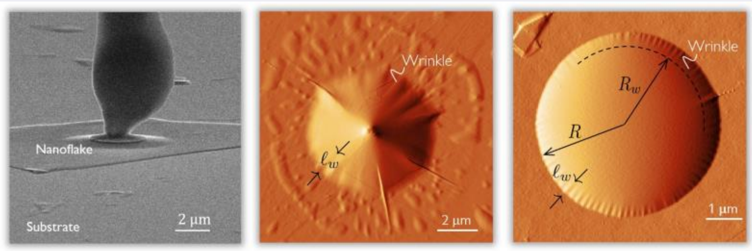
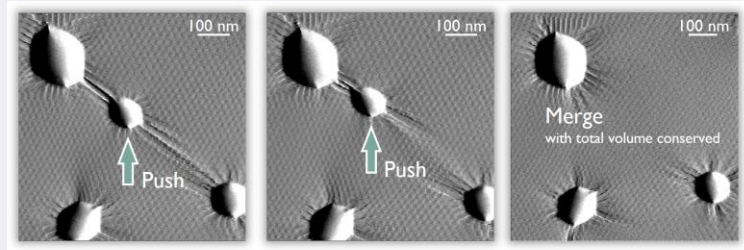
The Lecturer

- ❑ B.S. from USTC
- ❑ M.S. from Institute of Mechanics
- ❑ Ph.D. from University of Texas at Austin
- ❑ Post-doc at Oxford University

Keywords: Thin film mechanics, 2D materials, Adhesion, Friction, Wetting



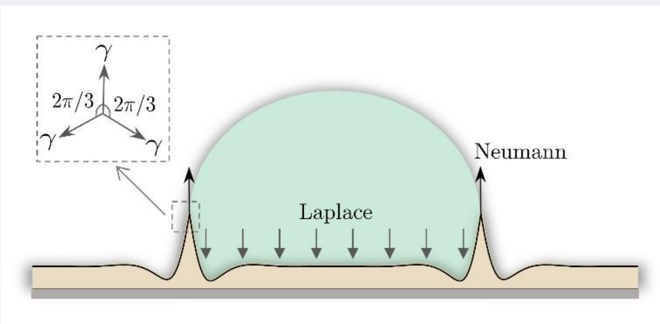


Thin film mechanics
Nonlinear elasticity, wrinkling, FvK

J. Appl. Mech. (2023)
Nano Lett. (2023)
JMPS (2021)
Phys. Rev. Lett. (2019)
Adv. Funct. Mater. (2016)

Surfaces and interfaces (solids)
Adhesion, friction, fracture

JMPS(2023); IJSS (2022)
JMPS (2020)
Curr. Opin. Solid State Mater. Sci. (2020)
Adv. Mater. (2019); Carbon (2019)
Phys. Rev. Lett. (2018); Phys. Rev. Lett. (2017)
Composites Sci. Tech. (2016)



Surfaces and interfaces (liquids)
Wetting, liquid-solid interactions

Sci. Adv. (2023)
Phys. Rev. Fluids (2022)
JMPS (2021)
Nat. Commun. (2021)
PNAS (2018)

Self-Introduction

- Your name & background
- Your department & adviser
- Your research or your adviser's research
- Why study surfaces and interfaces

Introduction of the course

开课教师:	戴兆贺	**邮件:**	daizh@pku.edu.cn	**时间:**	M 18:40 – 21:30
教室:	理教 314	**课程号:**	08611650	**学分:**	3

Course Description: The effects due to the presence of interfaces and surfaces become important at sub-millimeter length scales and smaller, and they often have macroscopic consequences. These surface phenomena have become increasingly important as the size of engineering systems and processes continue to shrink, for example in microelectronics, surface coatings, labs-on-a-chip, nanomanufacturing, and polymer processing. It is also important for many biological systems, such as how geckos stick to walls and cell motion.

This course will focus on phenomena derived from the presence of a surface or interface between two or more phases, particularly those involving surface tension and van der Waals forces. Examples include *contact*, *adhesion*, *friction*, *wetting*, *de-wetting*, *capillarity*, and so on. In this course, we will understand these phenomena by discussing relevant simplified systems that yet contain the most important mechanics and physics ingredients, including thin liquids, thin solids, and slender structures. Besides, a couple of special topics lectures will be given based on input from the class and recent advances in related areas.

Prerequisites: Graduate standing or instructor's permission. Undergraduate-level understanding of calculus, differential equations, and linear algebra.

Course Outline

- ❑ L1: Course introduction & Foreword
- ❑ L2: Van der Waals interactions between surfaces
- ❑ L3: Surface tension/energy/stress?
- ❑ L4: Interfacial stress balance & Droplets
- ❑ L5: Fluid statics: Bubbles, pendant droplets and their stability
- ❑ L6: Lateral capillary forces, condensation, and nucleation
- ❑ L7: Elastocapillarity
- ❑ L8: Literature presentation
- ❑ L9: Modeling and stability of thin liquid films
- ❑ L10: Moving contact lines
- ❑ L11: Coffee stains & Marangoni flows
- ❑ L12: Rayleigh-Plateau instability or/and dynamic instability of elastic rods
- ❑ L13: Fracture
- ❑ L14: Adhesion
- ❑ L15/16: Project presentations

References

References: Unfortunately, there is no single comprehensive text for this course. The skills and information required to complete the problem sets are primarily contained in the lectures. However, additional references and perspectives are always useful for those who want to explore the covered topic further, so below is a list of useful advanced texts on interfacial phenomena, solid mechanics, and fluid mechanics:

- *Lecture Notes: Topics in Fluid Mechanics* by D. Vella & A. Muench
- *Lecture Notes: Interfacial Phenomena* by J. Bush
- *Intermolecular & Surface Forces* by J. N. Israelachvili
- 表界与界面物理力学 by 赵亚溥
- *Contact, adhesion and rupture of elastic solids* by D. Maugis
- *Capillarity and Wetting Phenomena* by D. Quéré, F. Brochard-Wyart, and P.-Gi. de Gennes
- *Contact mechanics* by James Barber

Grades and dates

Evaluation method:

Homework	$10\% \times 6 = 60\%$
Midterm presentation	10%
Project abstract	10%
Project presentation	10%
Project report	10%
TOTAL	100%

Important Dates:

Homework	Every 7–14 days
Two-page Project Abstract	Dec. 4
Final Presentation	Dec. 25, 2023

Policies

Homework Policy: Problem sets will be assigned every 7-14 days. Complete the problem sets in time, because lectures and homework build on previous homework. To discourage lateness, homework will be counted 20% less for each day it is late. Homework may be handed in late without penalty only if prior arrangements have been made with the instructor and there are extenuating circumstances. In addition, homework should be neatly presented and only one side of each paper sheet should be used.

Project Policy: Students will devise and solve an illustrative problem in the mechanics and physics of surface and interface phenomena. The problem should be comparable in scope and difficulty to the more challenging homework problems given in this course. The projects are subject to my approval, which is based on a proposed problem. The milestones are listed on the critical dates above, and the final report should incorporate my comments and our discussions based on the problem proposal and a two-page extended abstract of the project. In addition, each student will give a 10-minute presentation plus a 2-minute Q&A to the class at the end of the semester.

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The philosophy of the course

Generative AI is experimental. Info quality may vary.

A scientist is a professional who conducts research to further knowledge in a particular area.

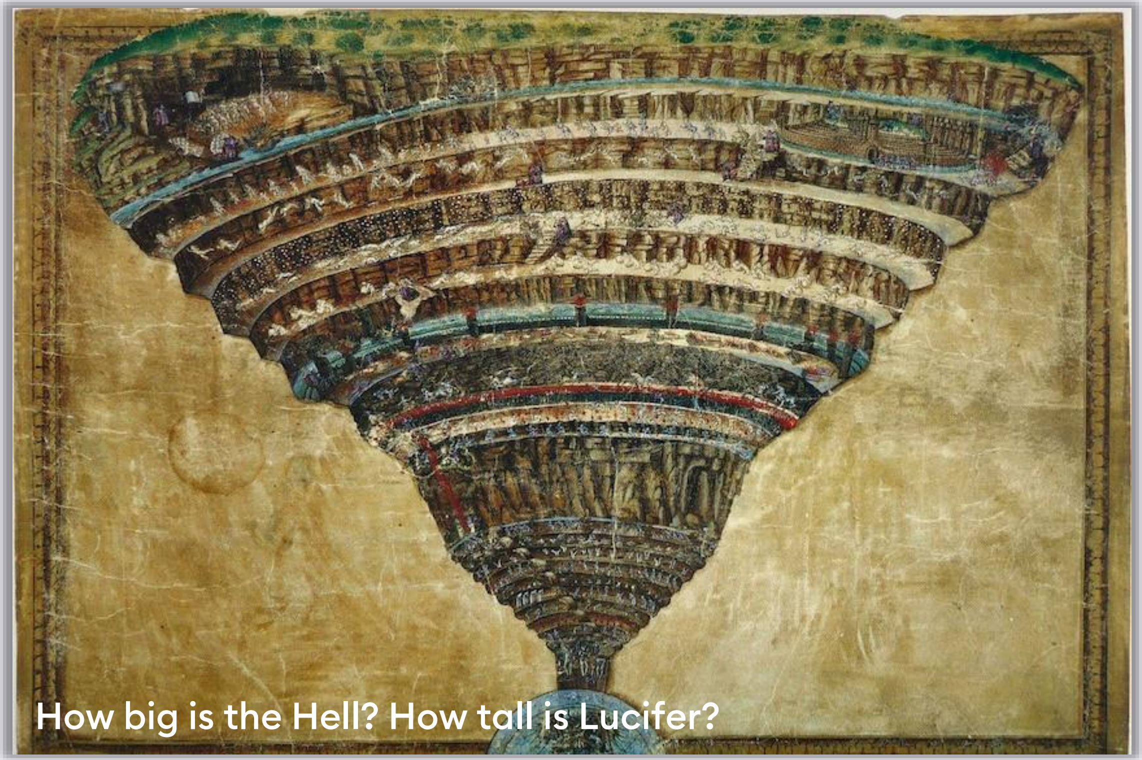
- They make observations in nature and conduct experiments to test their observations.
- They use scientific methods to explain the natural world.
- They believe that there is a natural explanation for most things.


DISCORSI
E
DIMOSTRAZIONI
MATEMATICHE,
intorno à due nuoue ſcienze
Attenenti alla
MECANICA & I MOVIMENTI LOCALI,
del Signor
GALILEO GALILEI LINCEO,
Filoſofo e Matematico primario del Sereniſſimo
Grand Duca di Toſcana.
Con una Appendice del centro di grauità d'alcuni Solidi.
IN LEIDA,
Appreſſo gli Elſevirii. M. D. C. XXXVIII.

Galileo Galilei (1638)

Not only new knowledge but also the process by which it is created!

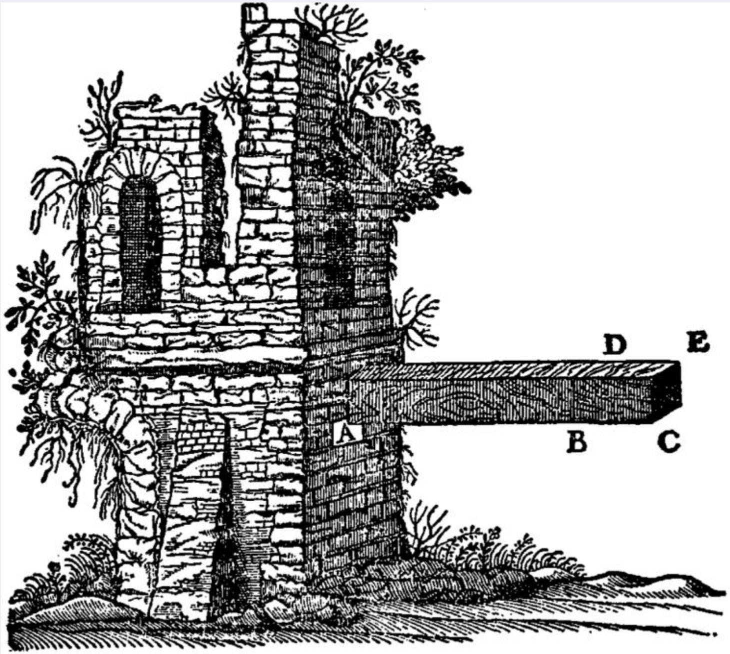
1.1 The project



Dante Alighieri's vision of hell, which Galileo attempted to map.

1.2 The method

1.3 Conclusion



Dome: ~45 meters in diameter and ~3 meters in thickness

Hell: ~ 45 km in radius (from Jerusalem to Marseille) and thus ~6 km in thickness

“On the Shape, Location, and Size of Dante's Inferno”, Galileo Galilei (1588)

2.1 Make observations

Salv. For a while, Simplicio, I used to think, as you do, that the resistances of similar solids were similar; but a certain casual observation showed me that similar solids do not exhibit a strength which is proportional to their size, the larger ones being less fitted to undergo rough usage just as tall men are more apt than small children to be injured by a fall. And, as we remarked at the outset, a large beam or column falling from a
[165]
given height will go to pieces when under the same circumstances a small scantling or small marble cylinder will not break. It was this observation which led me to the investigation of the fact which I am about to demonstrate to you: it is a very remarkable thing that, among the infinite variety of solids which are similar one to another, there are no two of which the forces [*momenti*], and the resistances of these solids are related in the same ratio.

Galileo Galilei (1638): Proposition IV of Day 2

2.2 Use scientific methods

to be devoid of weight. But if the weight of the prism is to be taken account of in conjunction with the weight E, we must add to the weight E one half that of the prism BD: so that if, for example, the latter weighs two pounds and the weight E is ten pounds we must treat the weight E as if it were eleven pounds.

SIMP. Why not twelve?

SALV. The weight E, my dear Simplicio, hanging at the extreme end C acts upon the lever BC with its full moment of ten pounds: so also would the solid BD if sus-

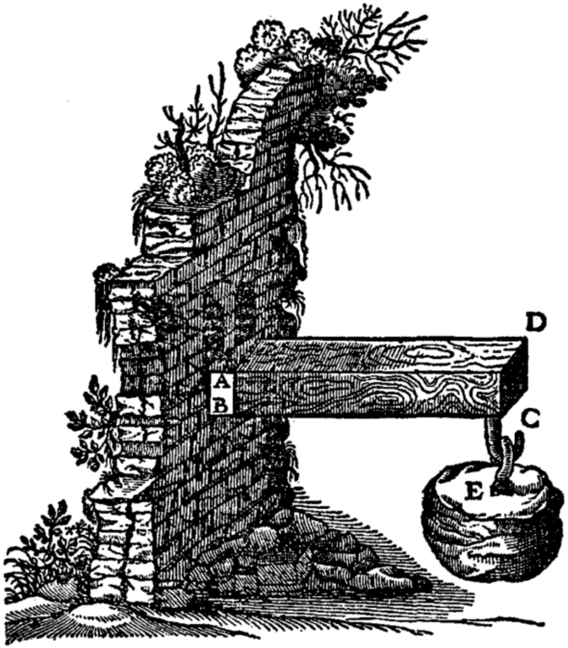


Fig. 17

Galileo Galilei (1638): Proposition IV-VIII of Day 2

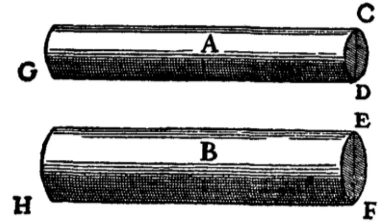


Fig. 20

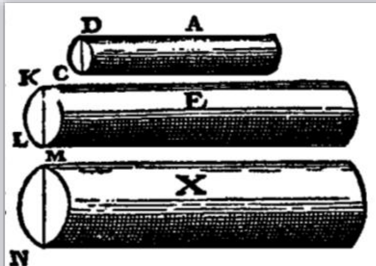


Fig. 26

- ❑ Galileo’s square-cube Law
- ❑ CD:KL=KL:MN

3.3 Draw new knowledges

Dome: ~45 meters in diameter and ~3 meters in thickness

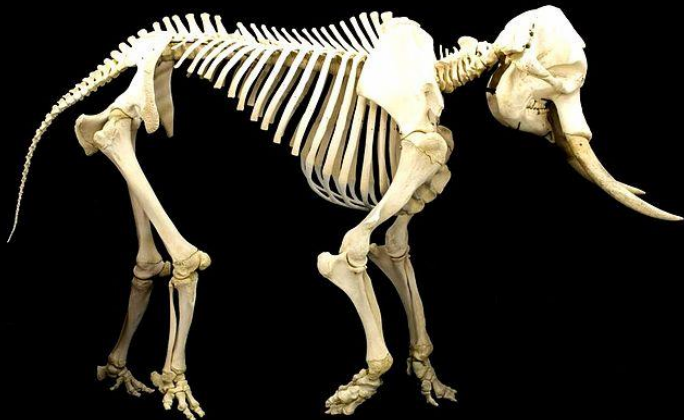
Hell: ~ 45 km in radius (from Jerusalem to Marseille) and thus ~6km***2000** in thickness

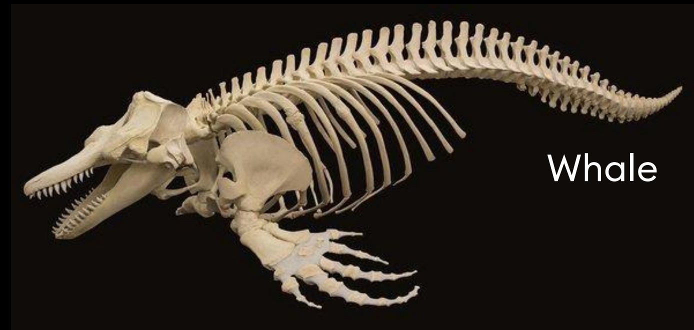
From what has already been demonstrated, you can plainly see the impossibility of increasing the size of structures to vast dimensions either in art or in nature; likewise the impossibility of building ships, palaces, or temples of enormous size in such a way that their oars, yards, beams, iron-bolts, and, in short, all their other parts will hold together; nor can nature produce trees of extraordinary size because the branches would break down under their own weight; so also it would be impossible to build up the bony structures of men, horses, or other animals so as to hold together and perform their normal functions if these animals were to be increased enormously in height; for this increase in height can be accomplished only by employing a material which is harder and stronger than usual, or by enlarging the size of the bones, thus changing their shape until the form and appearance of the animals suggest a monstrosity. This is

"The roof would have to be so thick that there would hardly be any room underneath to accommodate all those dead souls."

Scaling

Elephant



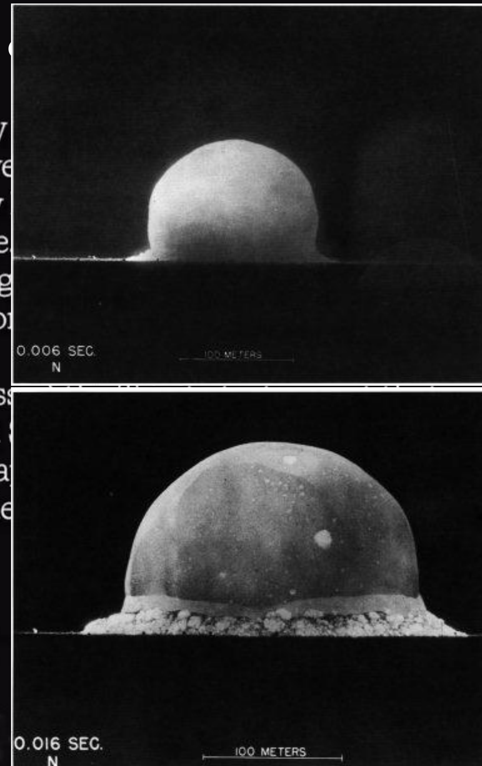


Rat

The Trinity explosion

“What mechanical effect might be expected if such an

G. I. Taylor: $R_f \sim (Et^2/\rho_0)^{1/5}$ with r_0, p_0 not important



The methodology of this course

- ❑ **Calculus must become a pump and not a filter for the STEM pipeline.**
  Robert White, president of the National Academy of Engineering
  - ❑ From lecture-based practices in which students are passive learners to problem-driven in which students are active thinkers (two presentations).
  - ❑ The observation-method-new knowledge process.
  - ❑ Not a theocratist or experimentalist but problem/goal-classified.

- ❑ **A combination of mathematical foundations and physical pictures.**
  - ❑ From NC and NS equations to reduced theories.
  - ❑ Analytical or asymptotic solutions rather than numerics.
  - ❑ Geared more toward engineering than mathematicians.

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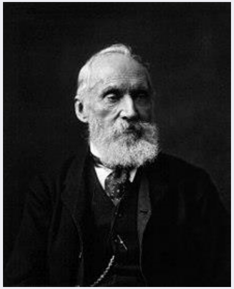
Surfaces and interfaces

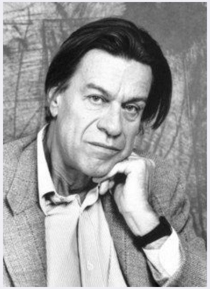
Surface/interface science is the study of physical and chemical phenomena that occur at the interface of two phases, including solid–liquid interfaces, solid–gas interfaces, solid–vacuum interfaces, and liquid–gas interfaces. Many fields have a branch or branches concerned with surfaces and interfaces, including chemistry, physics, mathematics, mechanics, materials sciences, biology, energy…


Thomas Young (1773 –1829)


William Thomson, "The Lord Kelvin" (1824 – 1907)


F. Wilhelm Ostwald (1853 – 1932)


Irving Langmuir (1881 – 1957)


Pierre-Gilles de Gennes (1932 – 2007)

Wolfgang Pauli: "God made the bulk; the surface was invented by the devil."

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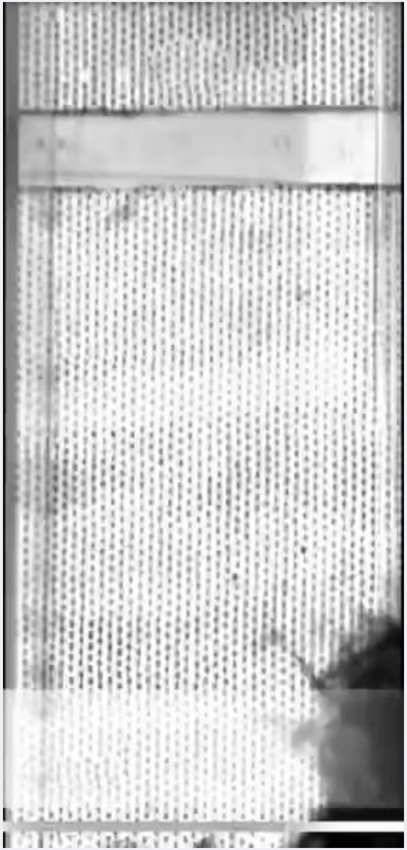
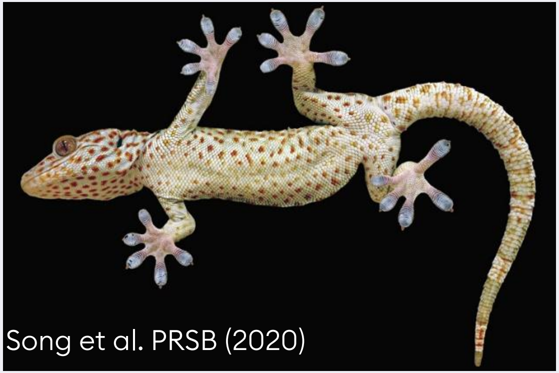
Statics of fluids

Gecko

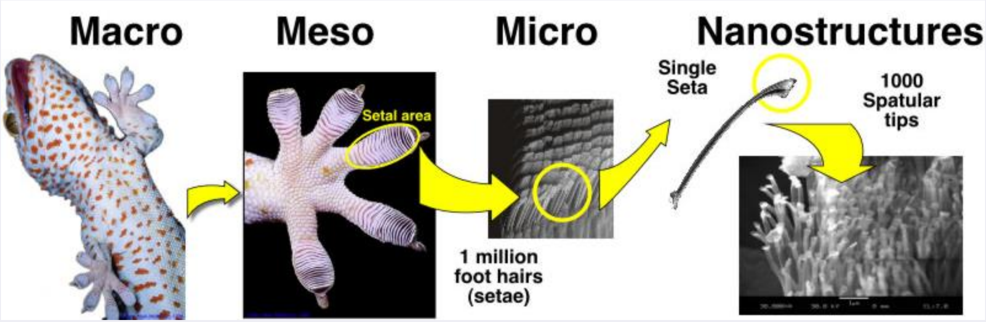


CHROMOS Industrial (YTB)

How gecko's stick to walls: A natural application of van der Waals forces



Song et al. PRSB (2020)

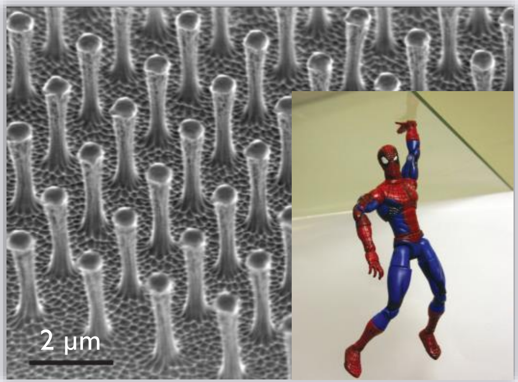


Gecko Project (Berkely)

Related course lecture: van der Waals forces

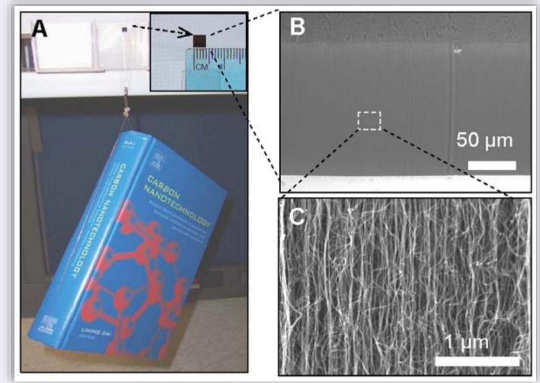
Dry adhesives

Array of polyimide hairs

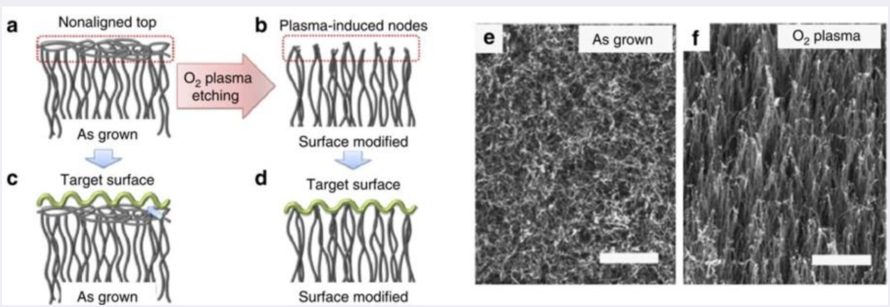


Geim et al. Nat. Mater. (2003)

Carbon nanotube arrays



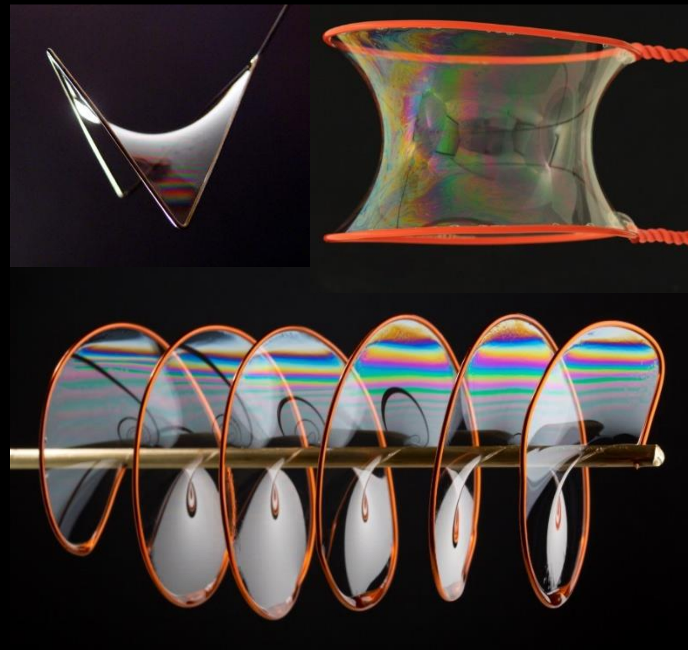
Qu et al. Science (2008)



Xu et al. Nat. Commun. (2016)

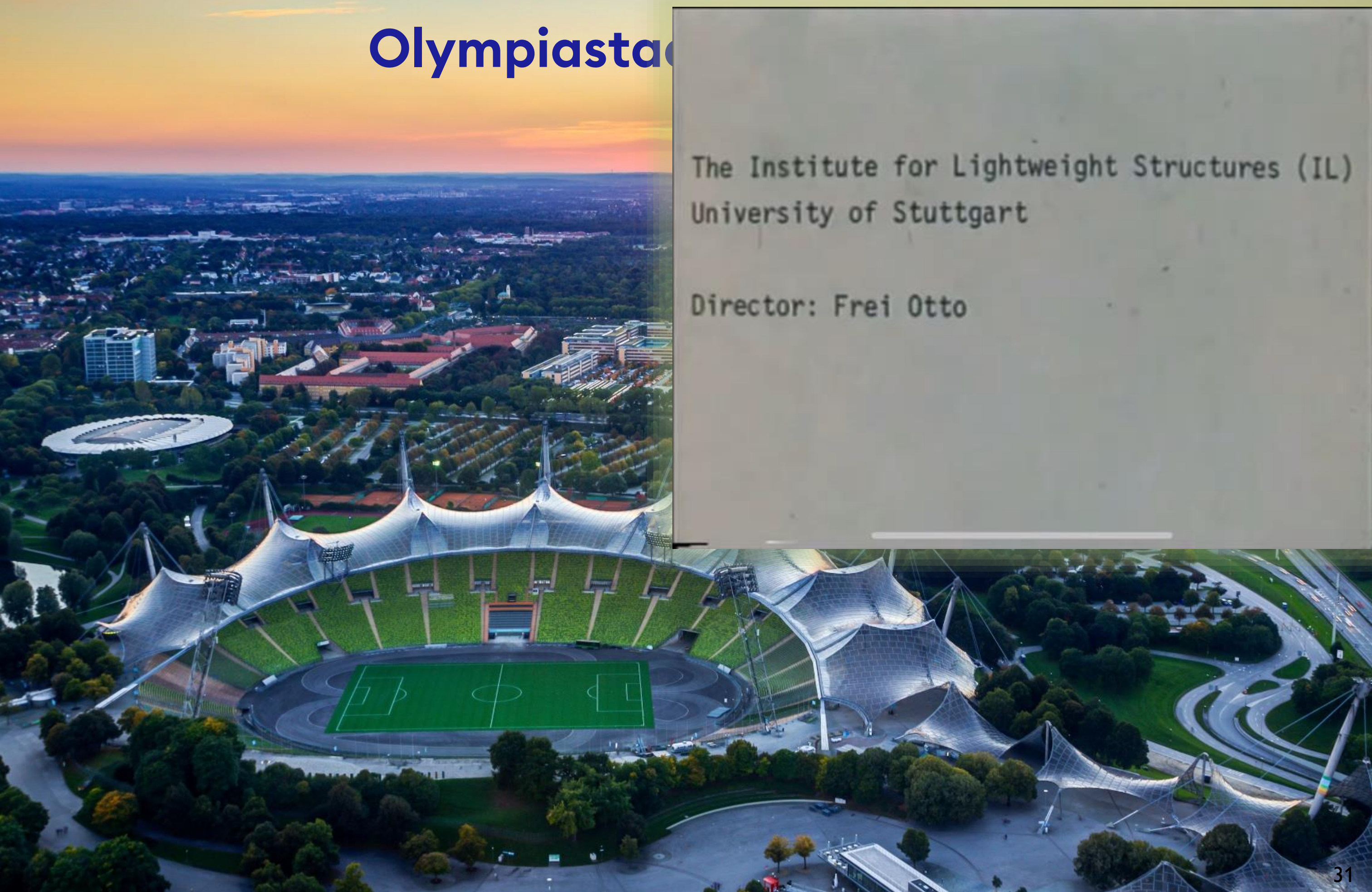
Soap bubbles

Jean Siméon Chardin (French) ca. 1733–34



Related course lecture: Interfacial stress balance

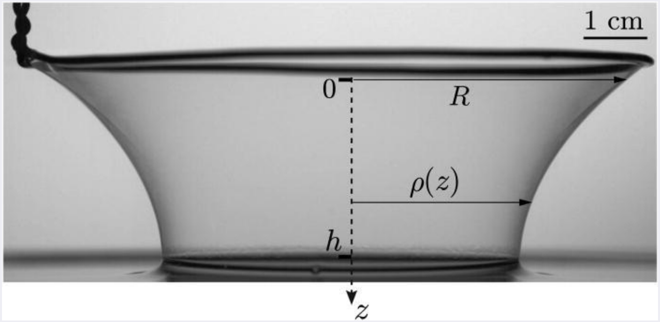
Olympiasta



The Institute for Lightweight Structures (IL)
University of Stuttgart

Director: Frei Otto

Catenary and catenoid

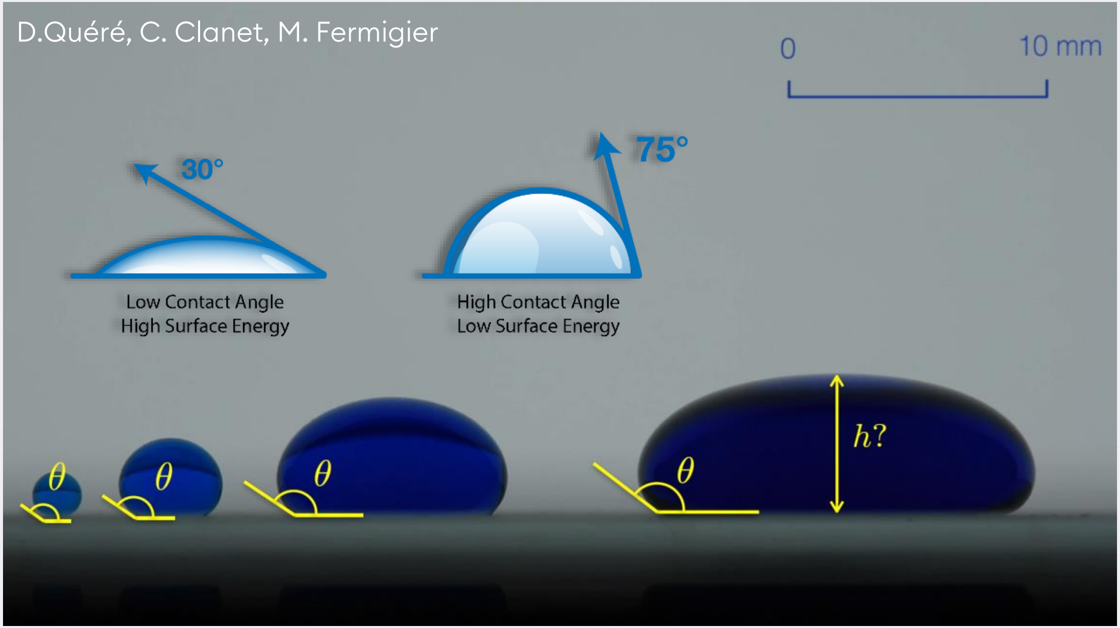


Catenary: From Galileo, Hooke, to Leibniz, Huygens and Johann Bernoulli

Related course lecture: Interfacial stress balance and variational analysis

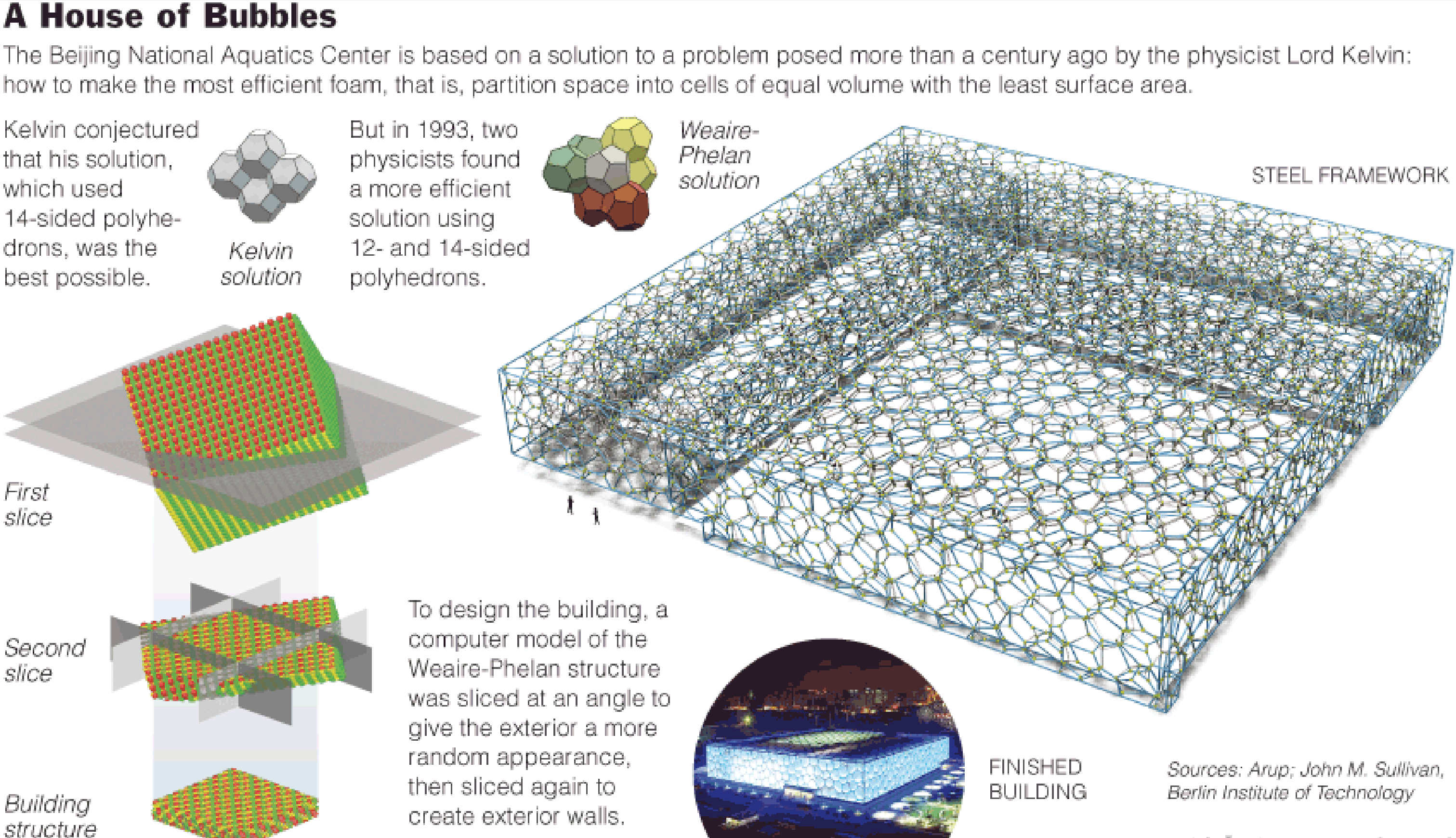
From Brachistochrone to droplets

Brachistochrone: From Galileo, Johann Bernoulli, to Newton, Jakob Bernoulli, Leibniz, to Euler and Lagrange

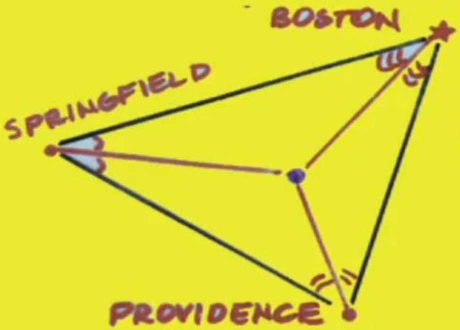


Related course lecture: Contact angle, adhesion, elastocapillarity

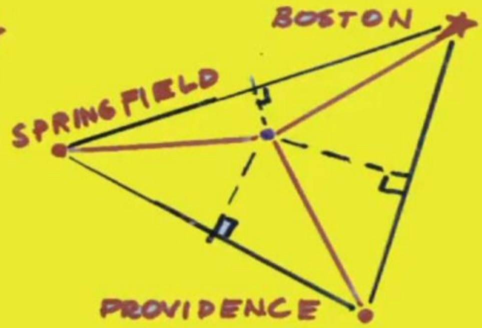
Bubble foams



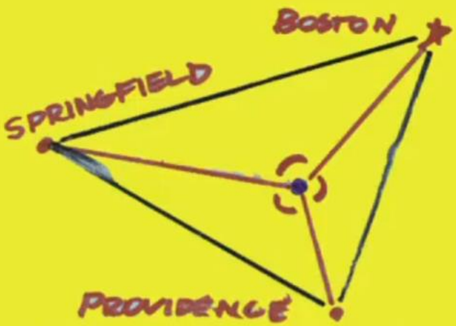
Q2. FERMAT PROBLEM. FIND THE SHORTEST ROAD SYSTEM CONNECTING 3 CITIES.



A. ANGLE BISECTORS



B. PERPENDICULAR BISECTORS



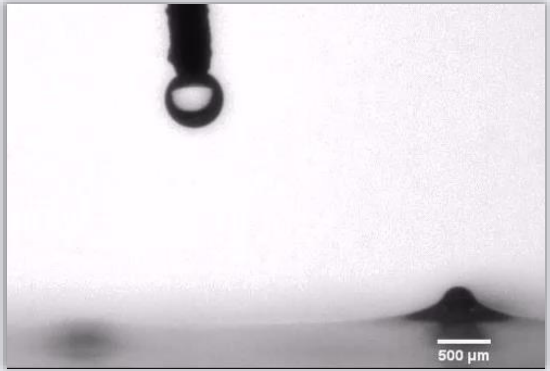
C. EQUAL ANGLES

Loss of symmetry

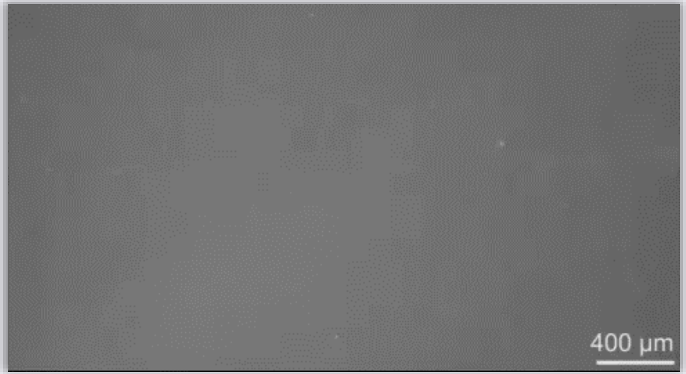
"There's some pretty cool physics at work when those last few Cheerios clump together in the bowl."

Related course lecture: Surface tension forces/Lateral capillary forces

“Cheerios” effect



Jiang et al. PNAS (2019)



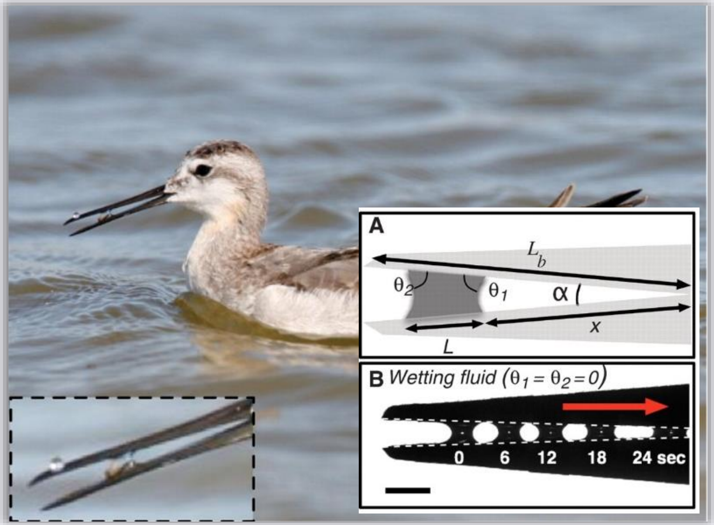
Guo et al. Cell Rep. Phys. Sci. (2021)

Zhang et al. Nat. Commun. (2021)

Asymmetry from geometry

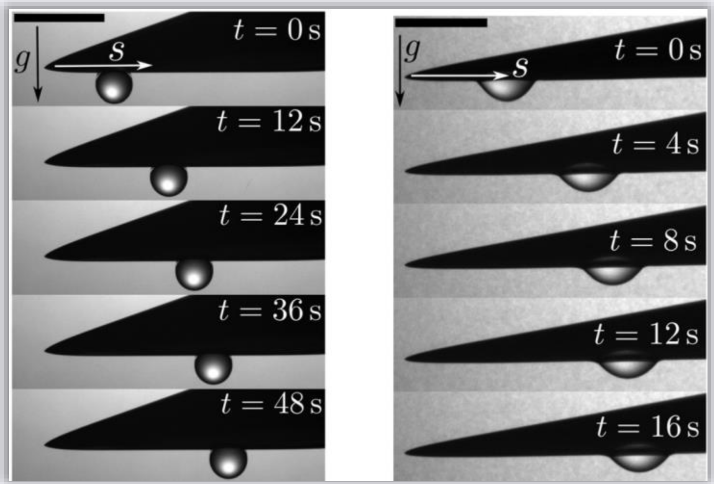
Related course lecture: General theory for sessile and pendant droplets

A juvenile Wilson's phalarope feeding



Prakash et al. Science (2008)

Spontaneous motion of water droplets moving on conical surfaces

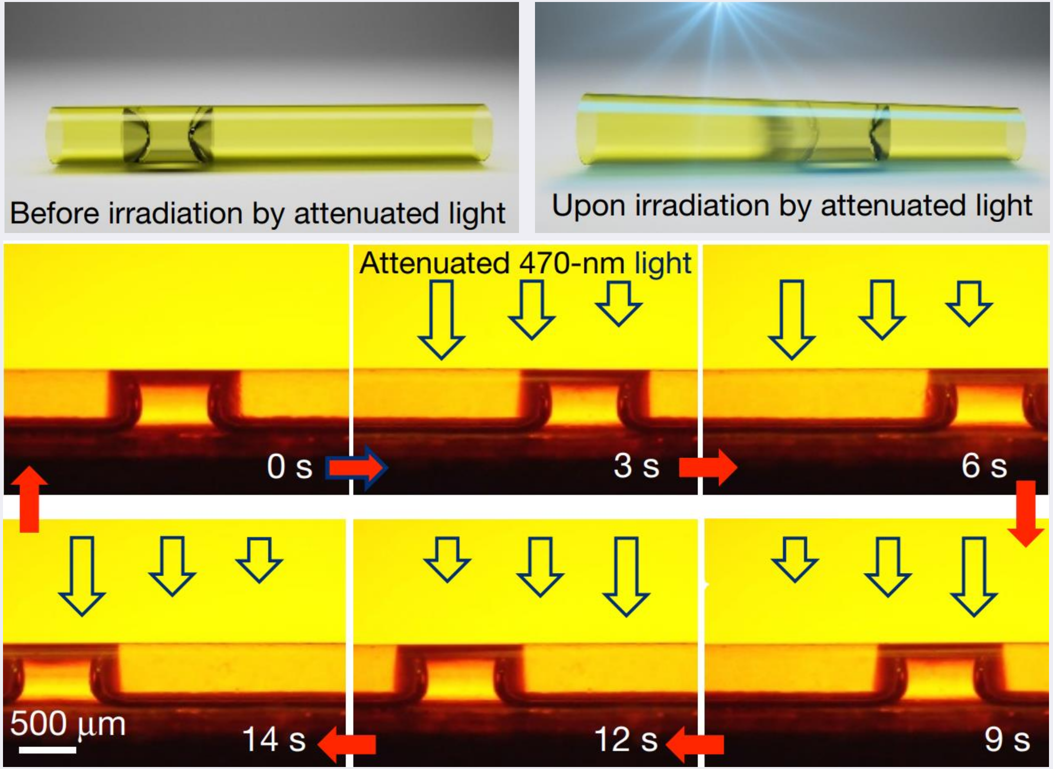


McCarthy et al. Soft Matter (2019)

It is all about to reduce the area of the surface/interface! But how to derive the driving force?

The use of asymmetry

Photo-induced asymmetric deformation of tubular, liquid crystal polymer actuators.



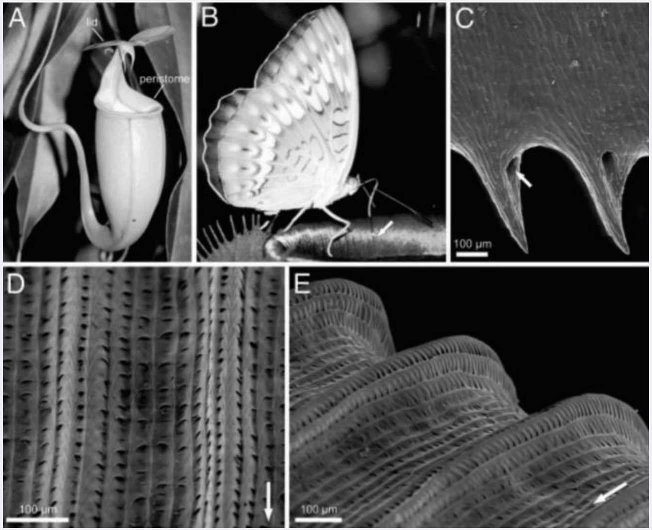
Lv et al. Nature (2016)

Slippery liquid films

Nepenthes pitcher plants 猪笼草

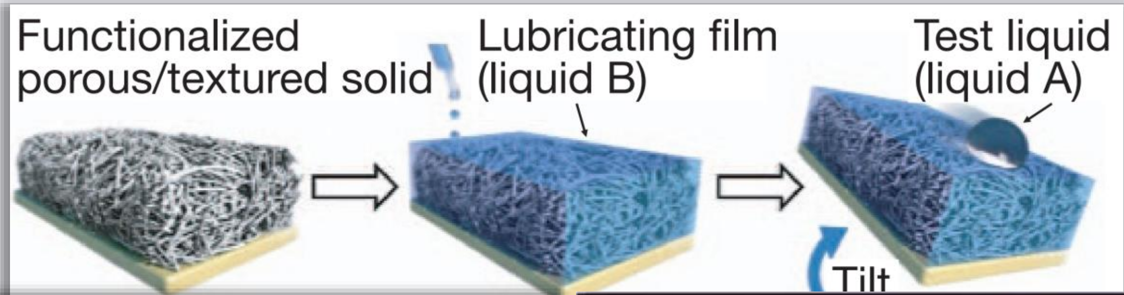
Bohn & Federle PNAS (2004)

Peristome surface with 1st and 2nd radial ridges. Arrows indicate direction toward the inside of the pitcher



Related course lecture: Spreading number/vdW forces/modeling of thin films

Slippery surfaces



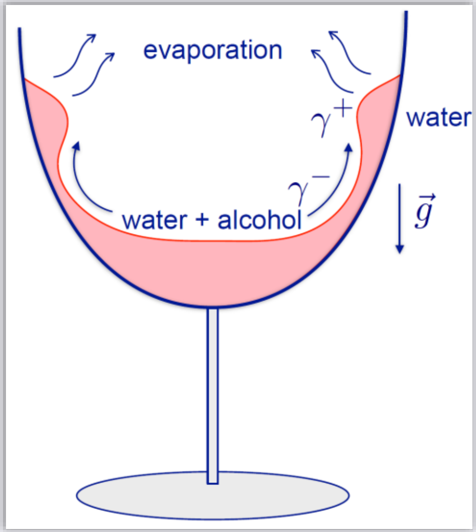
Wong et al. Nature (2011)

Dynamics of fluids

Tear of wine

The Marangoni effect (also called the Gibbs–Marangoni effect) is the mass transfer along an interface between two fluids due to a gradient of the surface tension.

Dan Quinn, “Why does wine cry?”



Tears of wine (J. Bico)

Related course lecture: Surface-tension driven flow

When Maotai meets coffee

Keiser et a. Phys. Rev. Lett. (2017)

Entry #V0020

Marangoni Bursting: Evaporation-Induced Emulsification of a Two-Component Droplet

Guillaume Durey[1], Hoon Kwon[1], Julien Mazet[2], Quentin Magdelaine[1], Mathias Kasiulis[1], Ludovic Keiser[3], Hadrien Bense[3], Pierre Colinet[4], José Bico[3], Étienne Reyssat[3]

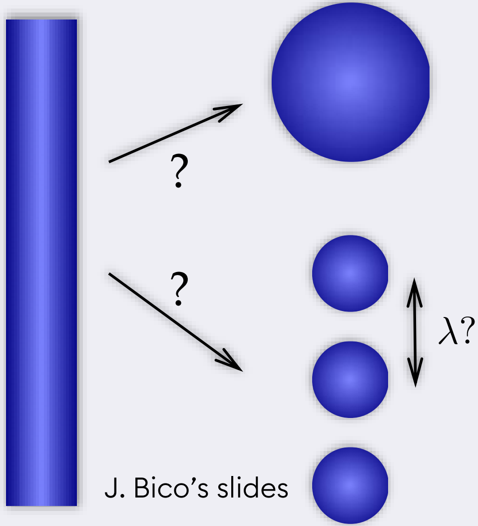
1 The Lutetium Project, ESPCI Paris, PSL Research University, youtube.com/thelutetiumproject
2 Conservatoire National Supérieur de Musique et de Danse de Paris, PSL Research University
3 Laboratoire PMMH, CNRS, ESPCI Paris, PSL Research University, Sorbonne Université, Université Paris Diderot
4 Transferts, Interfaces et Procédés, Université Libre de Bruxelles

Beyond Bernoulli's principle

Dripping, beading or jetting?

Gopi Krishnan (YTB)

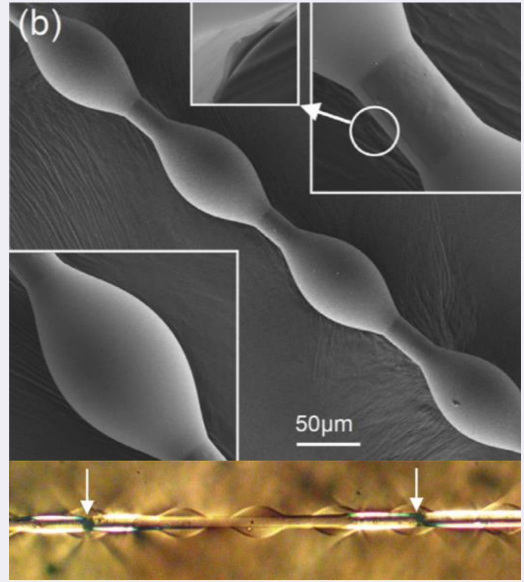
Min. area but slow



J. Bico's slides

Not min. area but faster

HW: Dip-coating and equilibrium

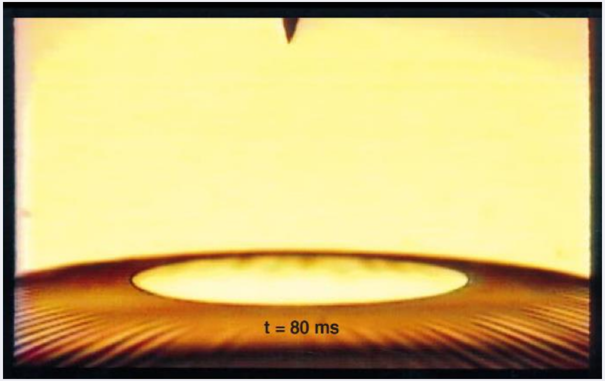


Greenfeld et al. JMPS (2019)

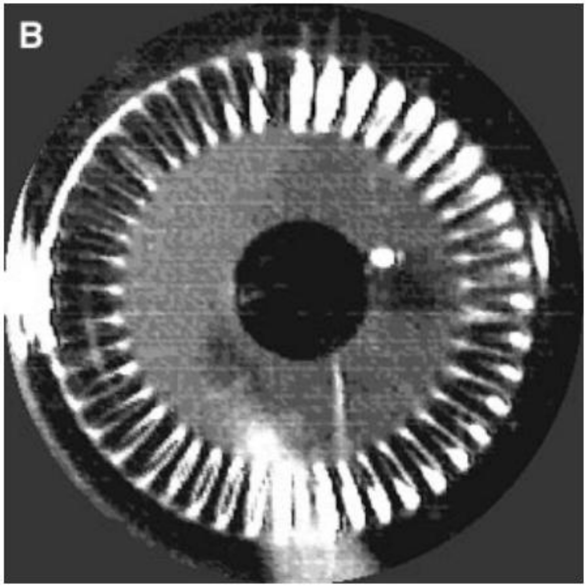
Related course lecture: Rayleigh-Plateau instability and stability analysis of thin films

Break a soap film

Collapse and wrinkling driven by gravity and resisted by viscosity?

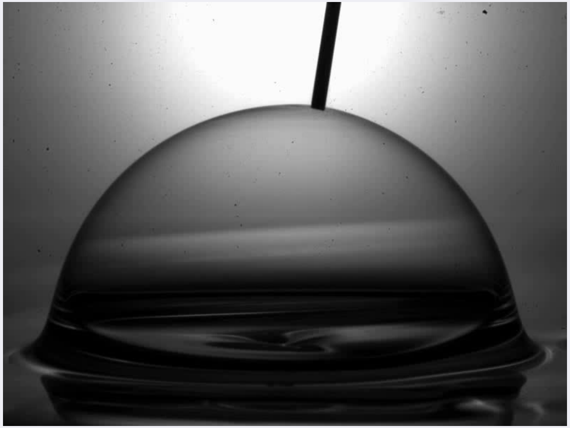


Debregeas, De Gennes and Brochard-Wyart
Science (1998)

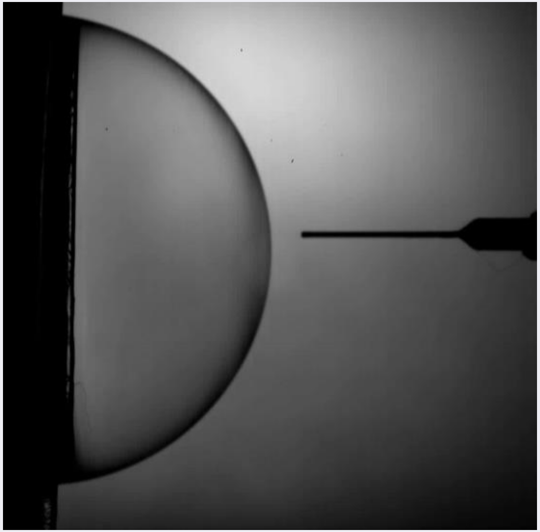


Da Silveira, Chaieb and Mahadevan
Science (2000)

Related course lecture: Dynamic wrinkling of thin sheets



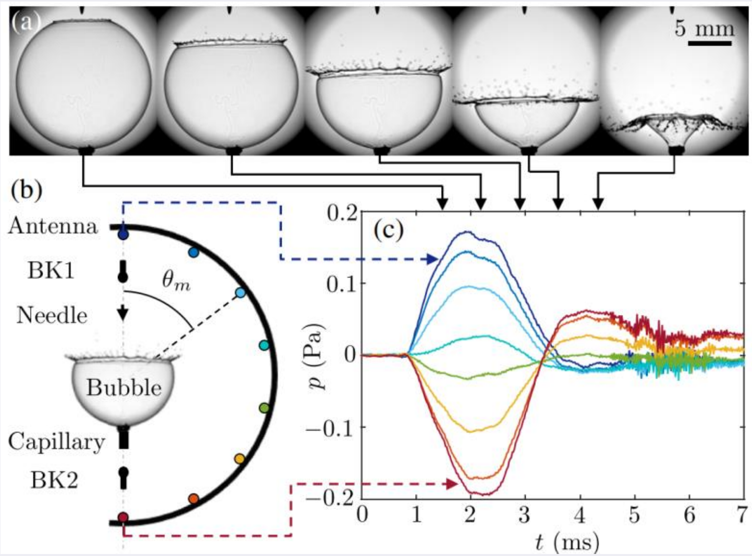
- Gravity not important
- Surface tension drives the collapse
- Resisted by viscosity



Oratis et al. Science (2020)

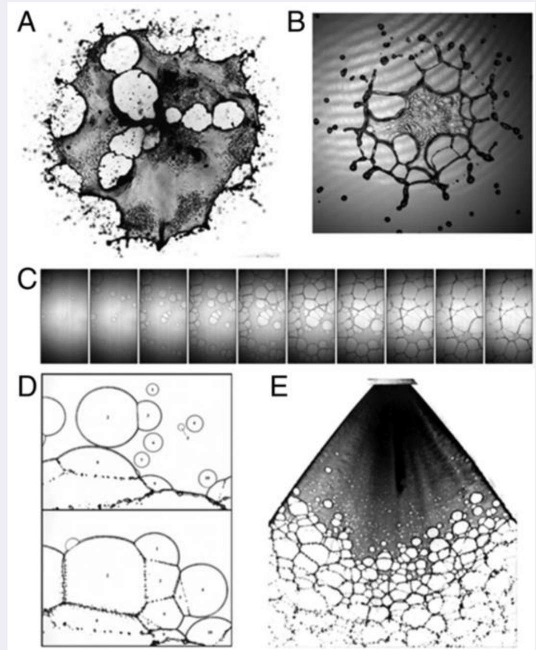
Rupture of a soap film

Bussonnière et al. Phys. Rev. Lett. (2020)



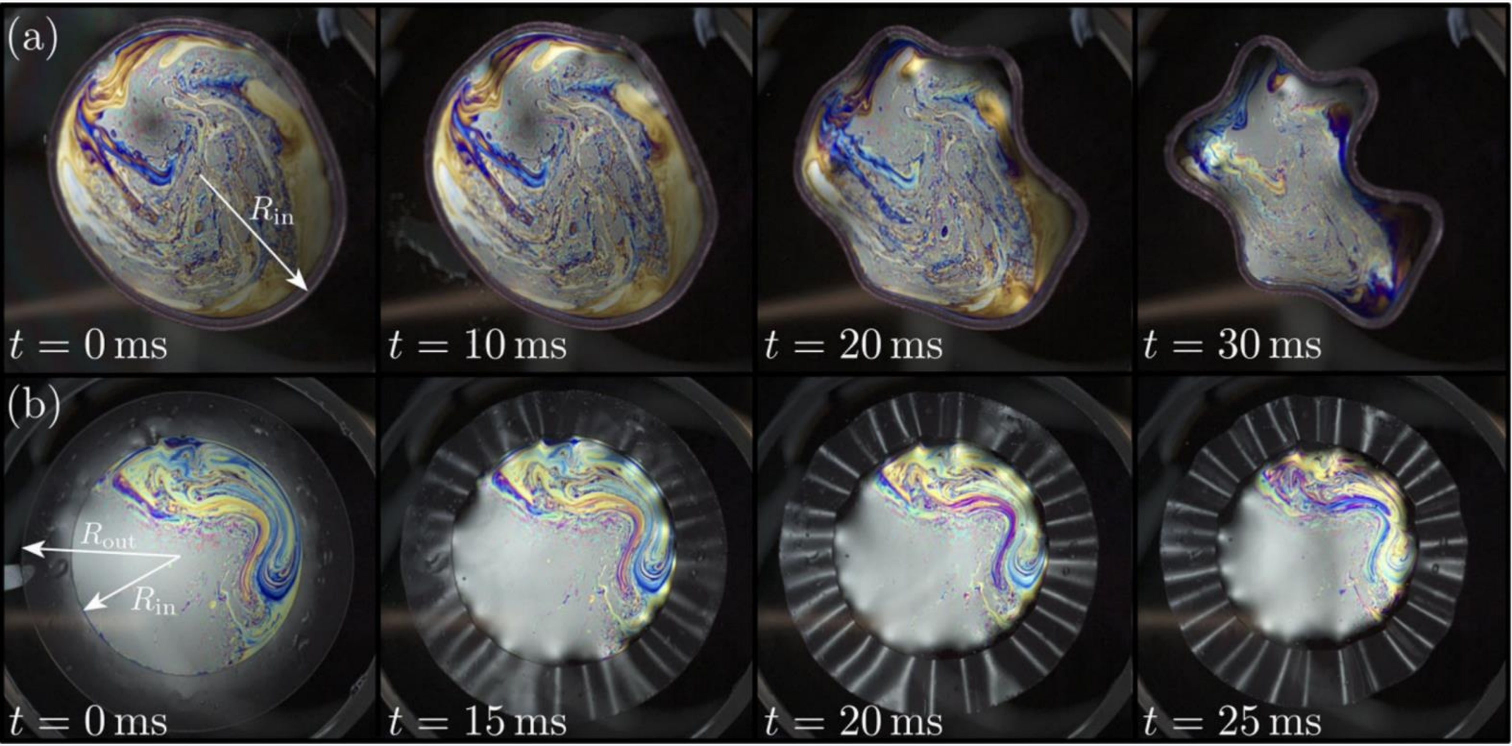
The popping sound of a bursting soap bubble

Lohse and Villermaux PNAS (2020)



Nucleation of holes on various liquid sheets (large We)

Soap film and rubber band

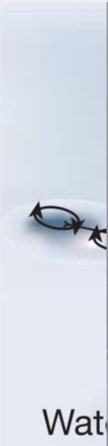


Related course lecture: Dynamic wrinkling of elastic sheets

Statics and dynamics of solids

Is flexibility a help or a hindrance?

David Hu, Brian Chan, John Bush
Nature (2003)



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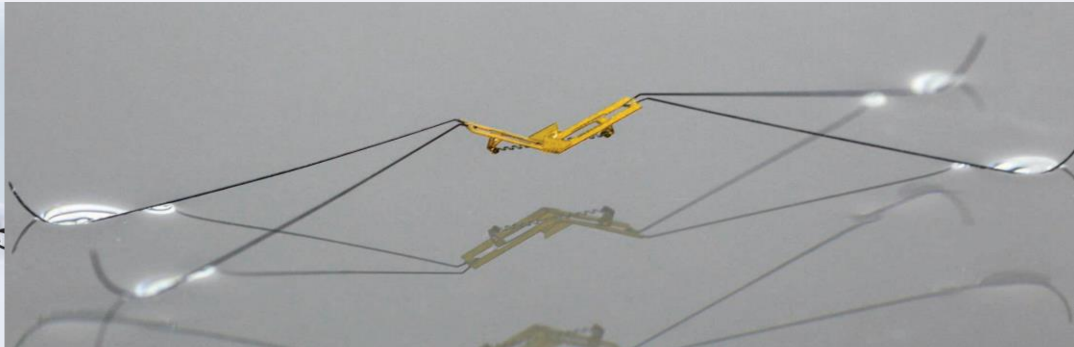
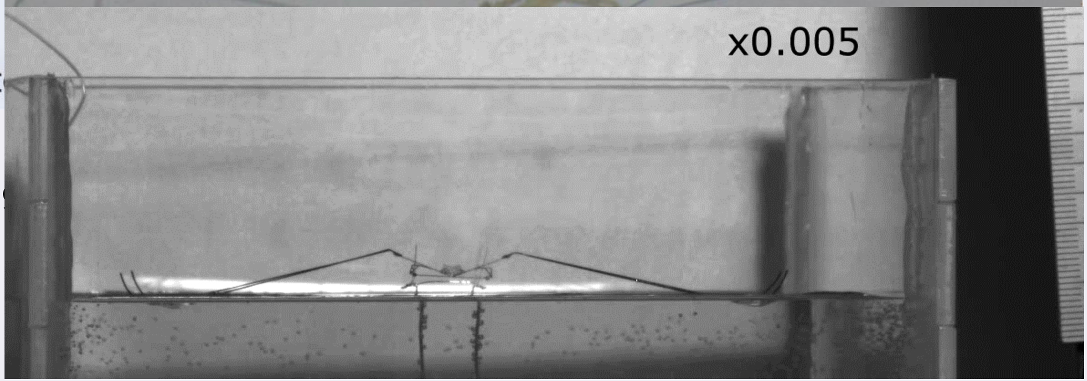
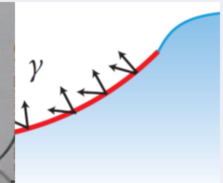




Koh et al. Science (2015)



-to-radius
etical)~130

l. Mech. (2015)

Self-cleaning?

Prakash et al. Science (2008)

nature

Nature 567, 9 (2019)

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RESEARCH HIGHLIGHT | 27 February 2019

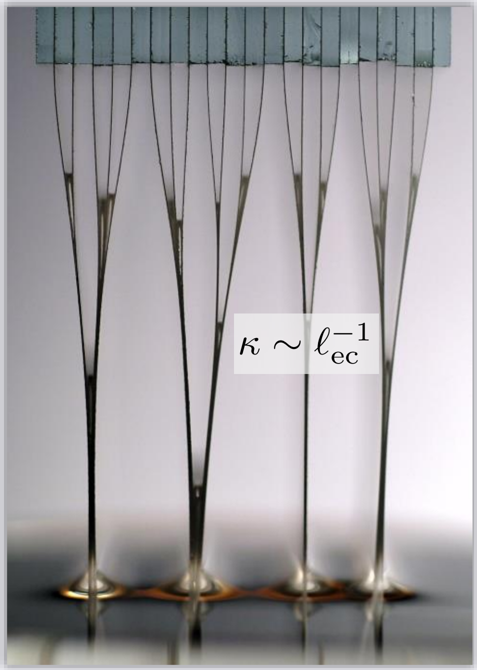
Micro-droplets in minuscule channels need no help to get ahead

Channel design allows fluid droplets to self-propel in a controlled manner.

Bradley et al. Phys. Rev. Lett. (2019)

Duprat et al. Nature (2012)

1D rods and beams



- Smaller, "stronger"

$$\frac{\gamma \times \mathrm{area}}{U_{\mathrm{e}} \times \mathrm{volume}} \sim \frac{\gamma}{U_{\mathrm{e}}} \times \frac{1}{t}$$

- What is meant by "strong"?

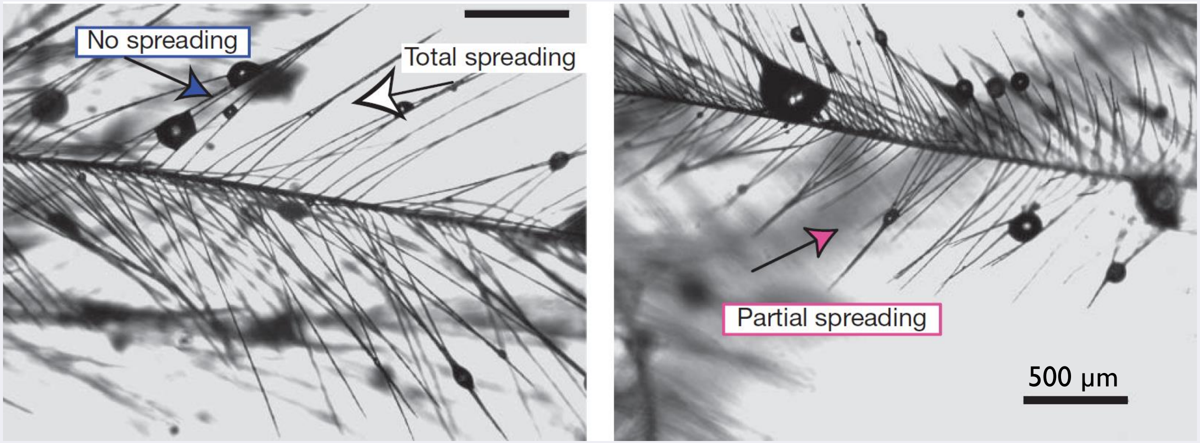
$$\ell_{\mathrm{ec}} \sim \left(\frac{B}{\gamma}\right)^{1/2}$$

An elastocapillary length-scale

Bico et al. Nature (2004)

Related course lecture: Elastocapillarity

Feather and oil



Duprat et al. Nature (2012)

One of reasons for why most heave losses of birds due to oil pollution happen in winter.

Hartung, R. J. Wild. Mgmt (1967)

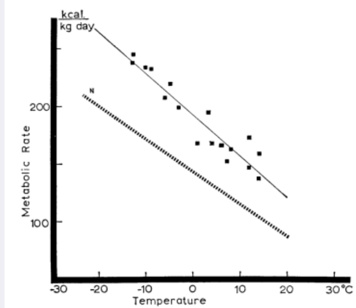


Fig. 8. Metabolic rates of a mallard oiled in a small spot; (N) normal mallards.

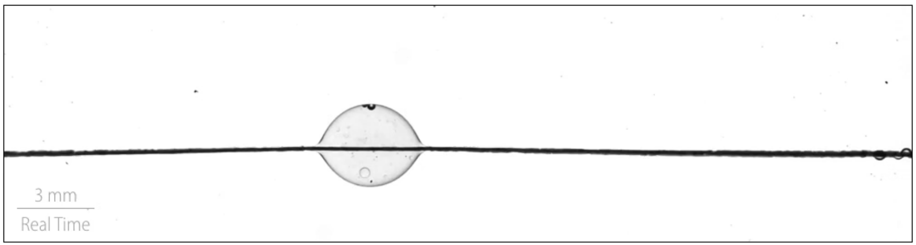
Capillary coil

The capillary forces exerted by a liquid drop can be strong enough to make a thin elastic fiber buckle and coil within it. When the ends of the fiber are brought together, it therefore spontaneously starts spooling inside the drop.

Elasto-capillary coiling

http://paulgrandgeorge.com/

Coiling an elastic fiber inside a liquid drop



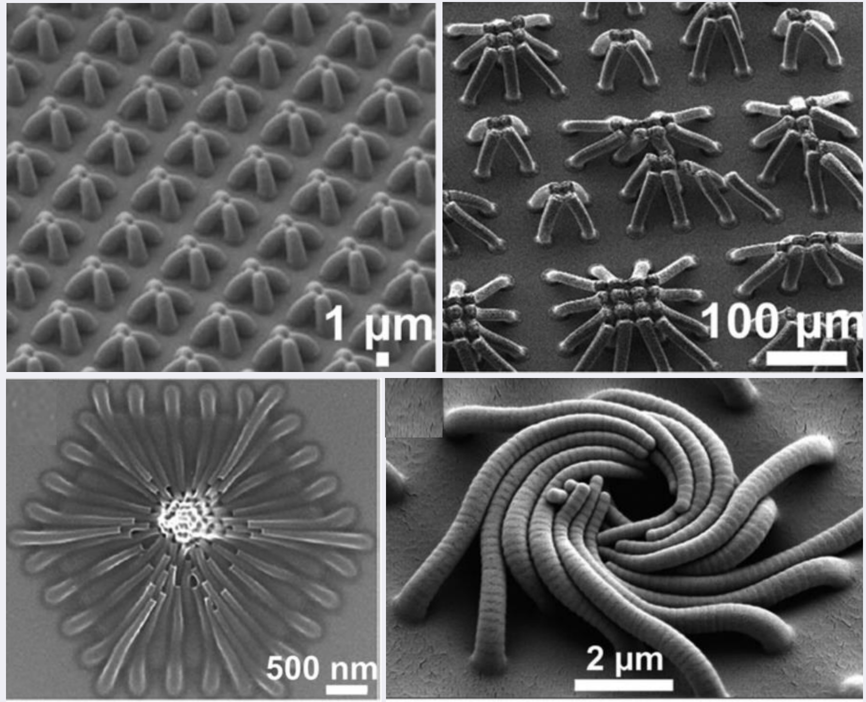
Silicone oil **droplet** on a RTV (silicone polymer) **fiber**.
The system is **immersed** in a water bath to provide buoyancy.
Fiber: radius $a = 35$ µm, Young's modulus $E = 1$ Mpa.
Droplet: radius $R = 1.5$ mm, $\Delta\gamma \approx 40$ mN/m

09/02/2018 - Paul Grandgeorge   Surface-tension induced buckling for the design of stretchable materials | 1

Self-assembly of fibrous structures

Application to self-assembly of carbon nanotubes

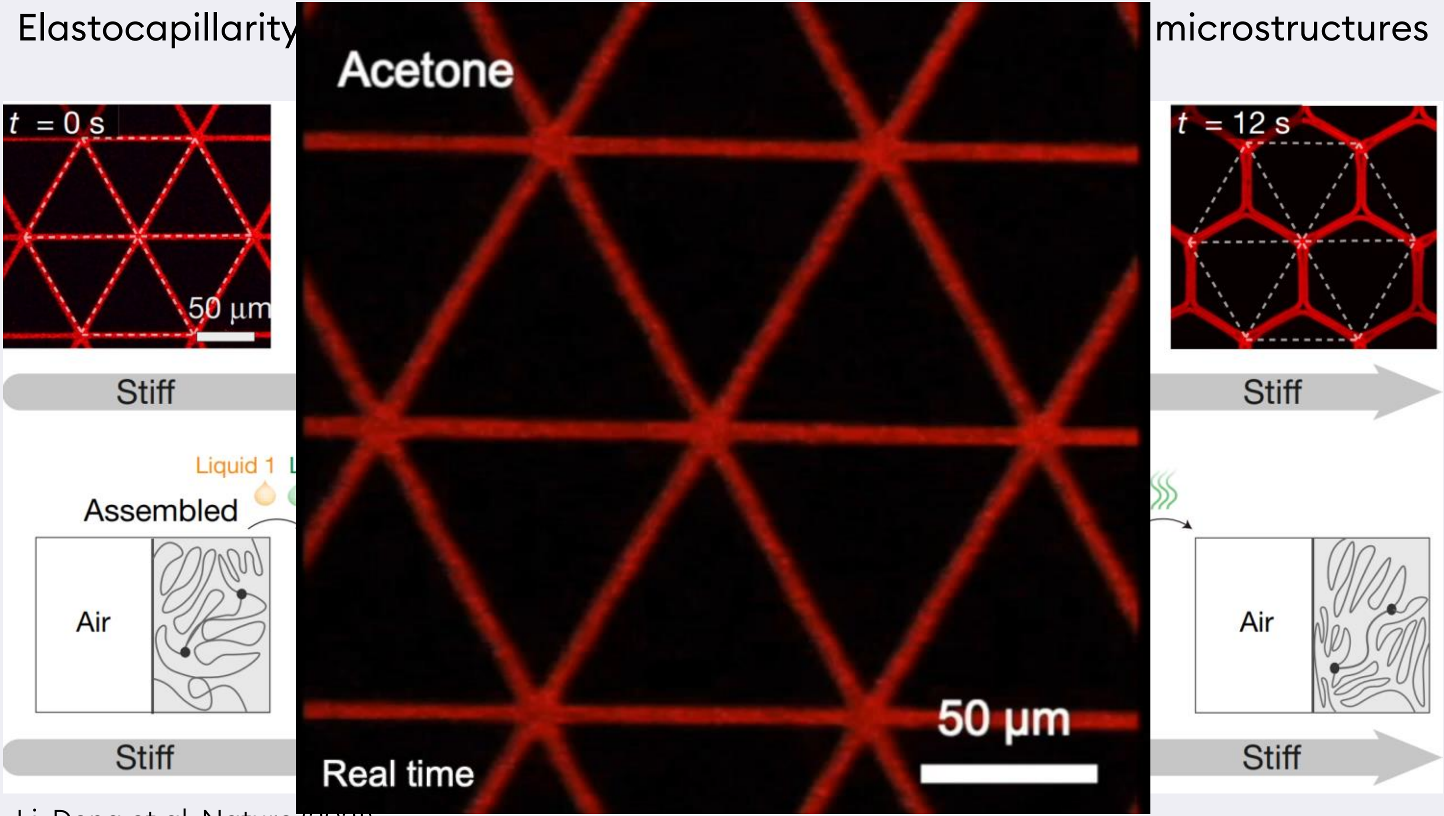
Tokyofashion.com



M. D. Volder and A. J. Hart. Angew. Chem. (2013)

Topological transformations in cellular structures

Elastocapillarity ... microstructures



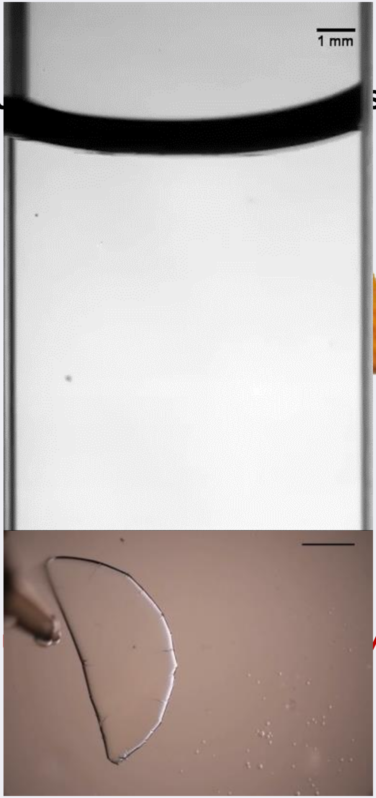
Li, Deng et al. Nature (2021)

2D thin sheets

Maximize the volu sheet of radius W

D. Vella (YTB)

$$\frac{V}{W^3} \sim 0.155$$



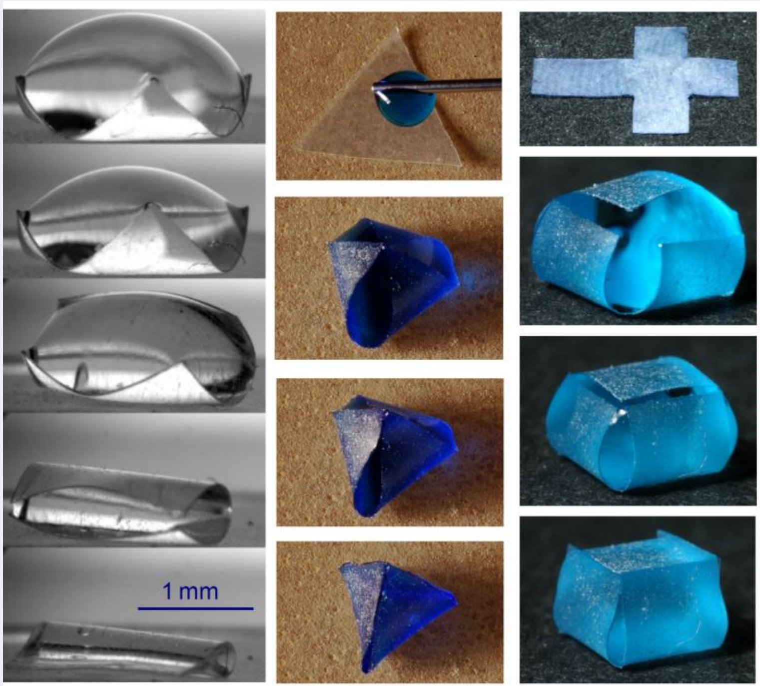
Kumar et al. Science (2018)

$$\frac{V}{W^3} \sim 0.363$$

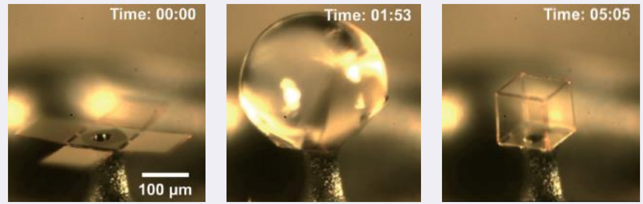
Related course lect /Variational analysis

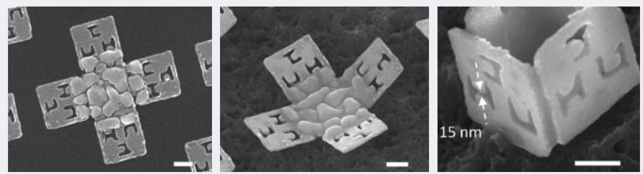
Origami cross various scales

Py et al. Phys. Rev. Lett. (2007)



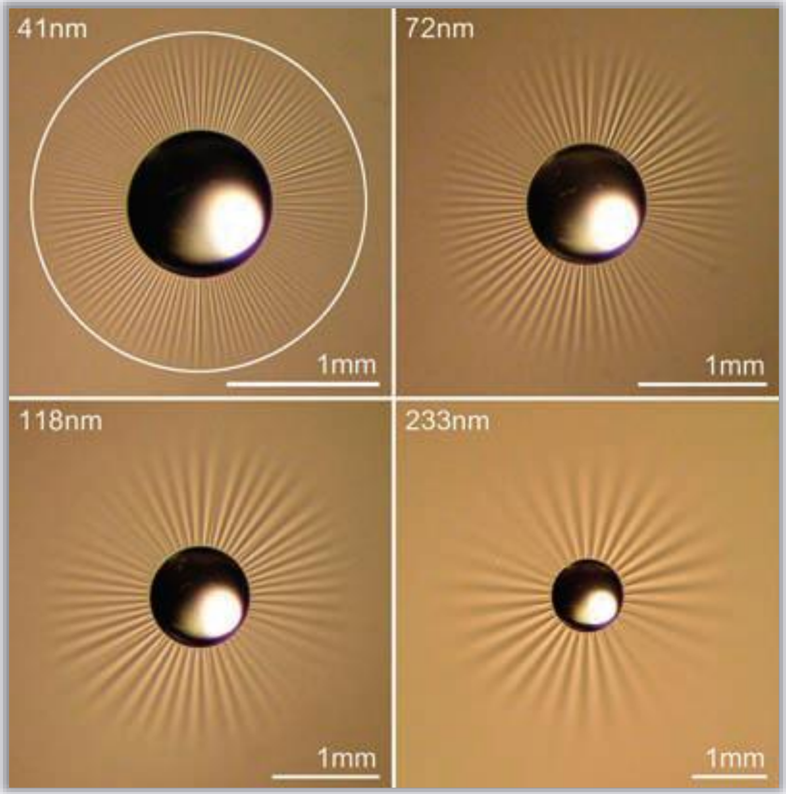
Legrain, Tas et al. (2013)



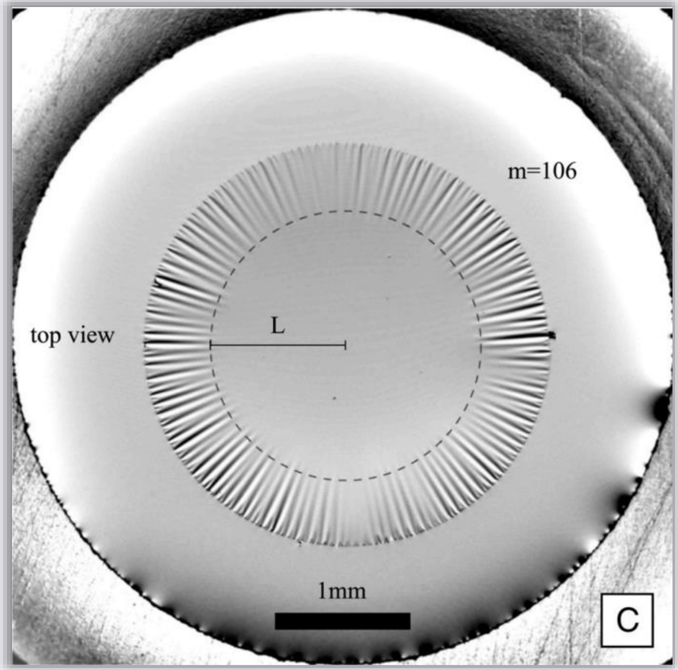


Cho & Gracias Nano Lett. (2009)

The intrinsic difference of 2D from 1D



Huang et al. Science (2007)

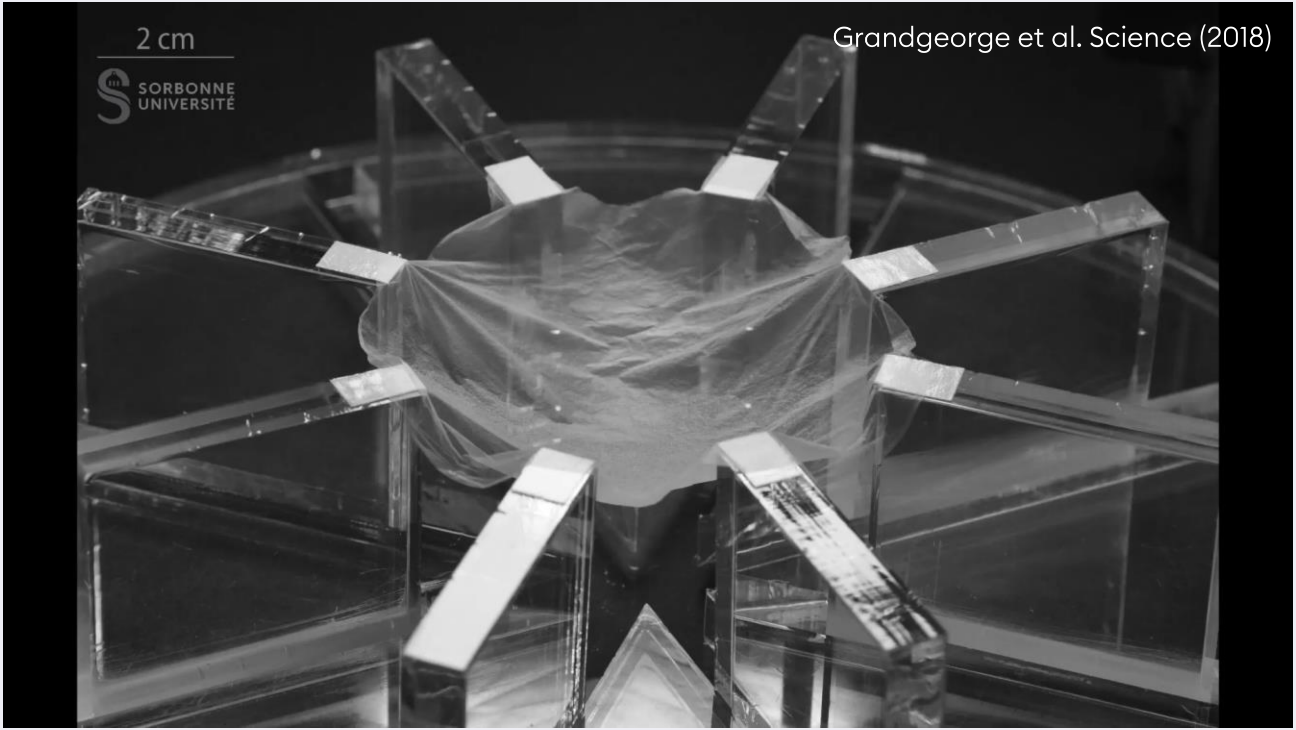


King et al. PNAS (2012)

Exploring the novel wrinkling behavior of thin sheets that is controlled by capillary forces.

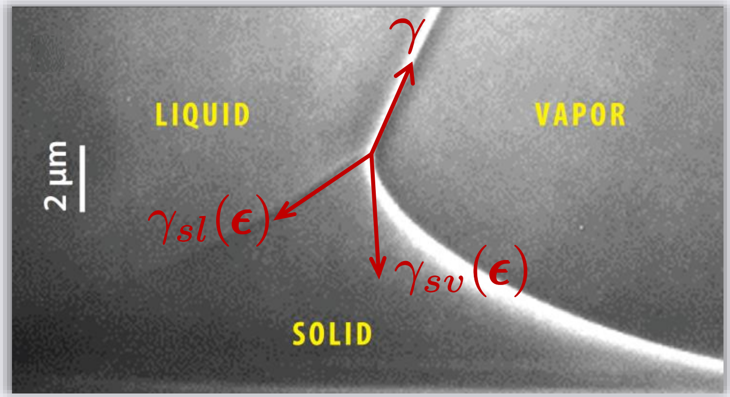
From coil to wrinkle

A thin fibrous membrane is wicked (infused) with a wetting liquid. The membrane is thin enough to buckle and wrinkle inside the liquid film.



3D solids

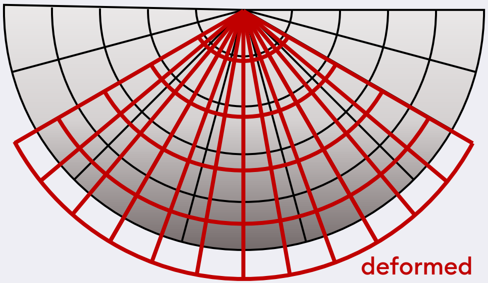
Park et al. (2013)



Neumann's law: $\vec{\gamma} + \overrightarrow{\gamma_{sl}}(\epsilon) + \overrightarrow{\gamma_{sv}}(\epsilon) = 0$

Together with a 2nd BC about (dis)continuity in strain.

Singh & Pipkin (1965)



A logarithmical singularity that can vanish by integration.

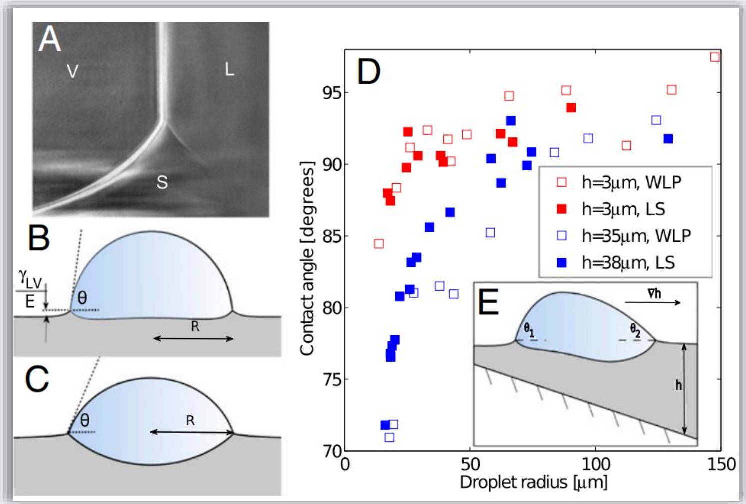
Andreotti & Snoeijer (2019)

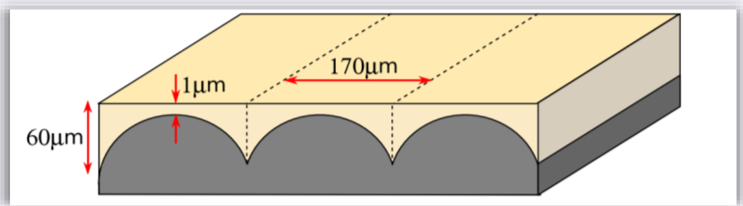
Related course lecture: Surface tension forces/Elastocapillarity (partially covered)

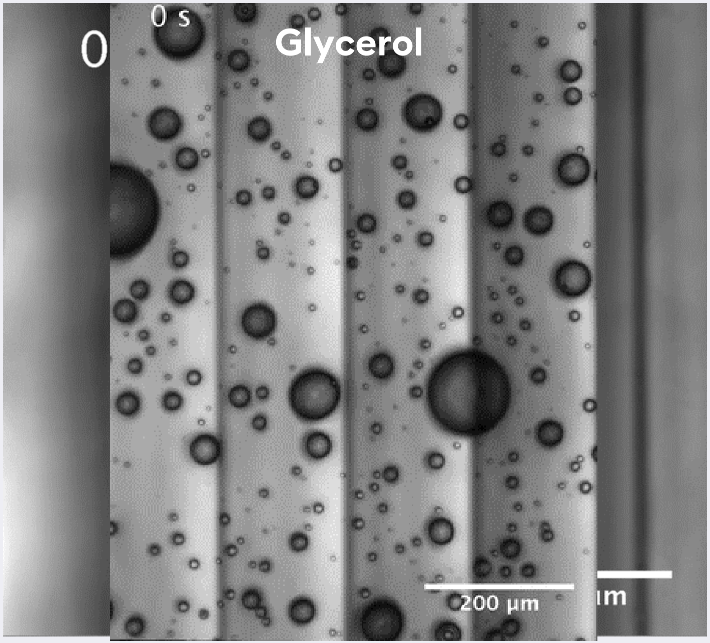
Durotaxis

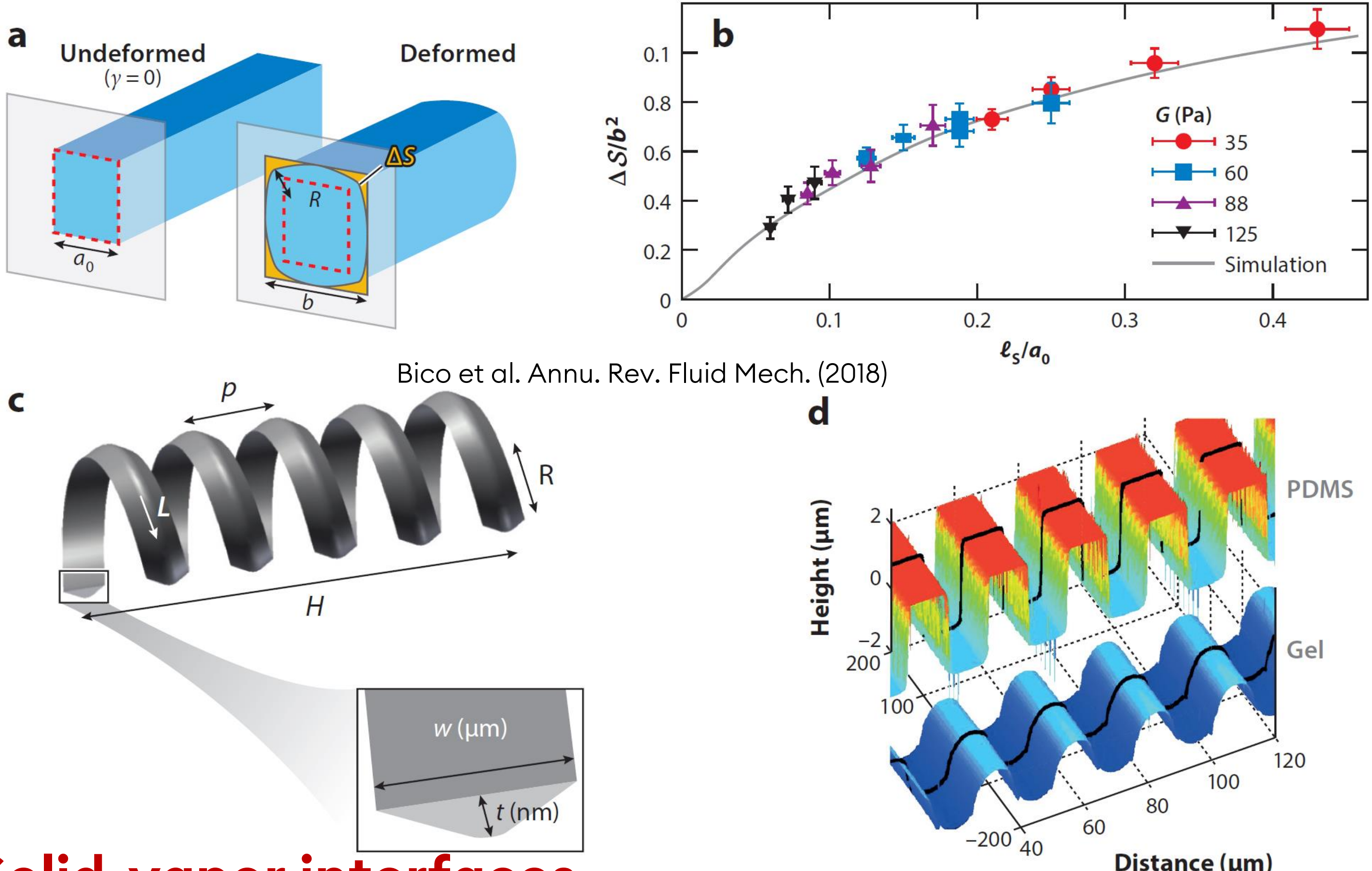
Durotaxis is a form of cell migration in which cells are guided by rigidity gradients, which arise from differential structural properties of the extracellular matrix.

Style et al. PNAS (2013)







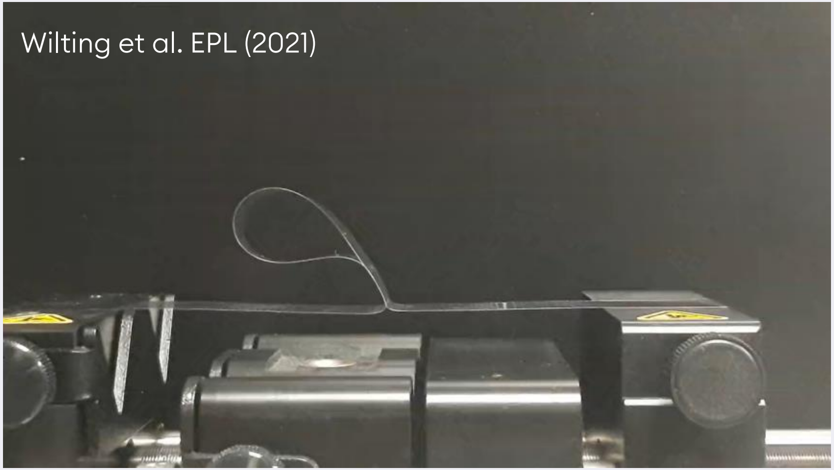


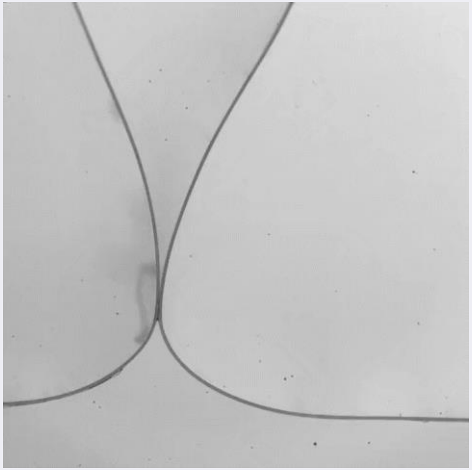
Bico et al. Annu. Rev. Fluid Mech. (2018)

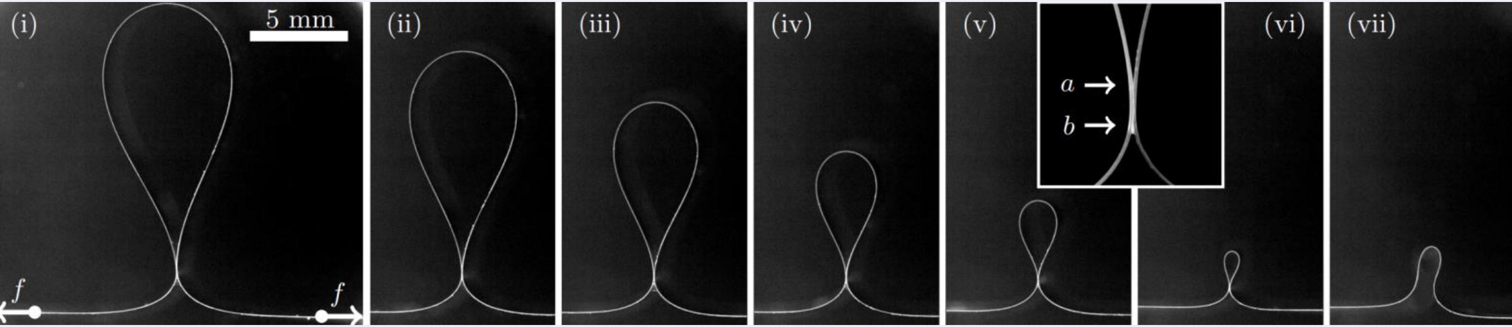
Solid-vapor interfaces

Solid-solid interfaces: Peeling a sticky tape

Related course lecture: Adhesion

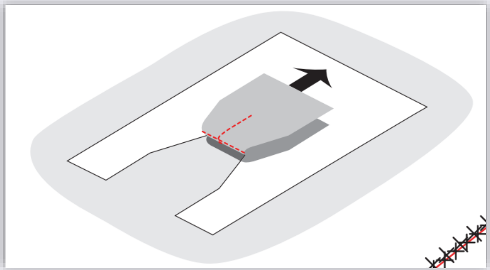


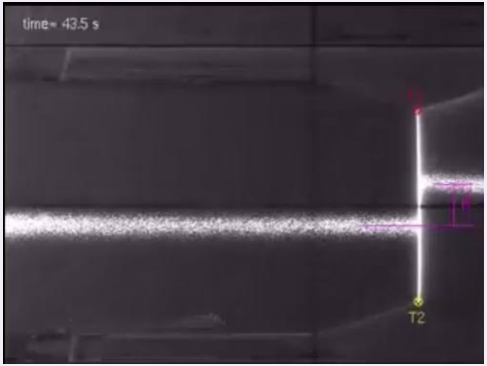




Peeling and tearing a sticky tape

Tearing as a test for mechanical characterization of thin adhesive films

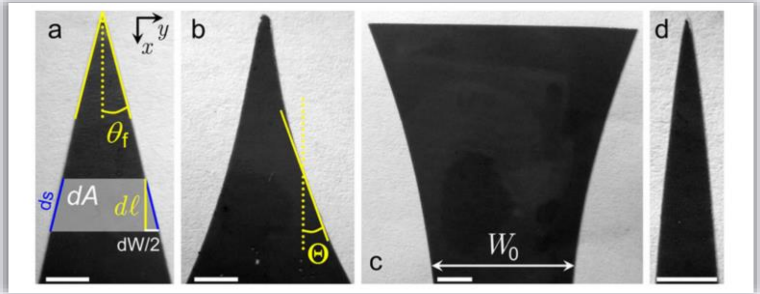




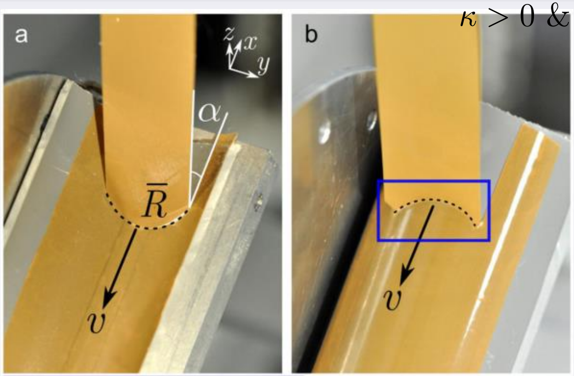
Hamm et al. Nat. Mater. (2008)

Related course lecture: Fracture

$\kappa = 0$ $\kappa < 0$ $\kappa > 0$ & $W_0 > W_c$



$\kappa > 0$ & $W_0 < W_c$

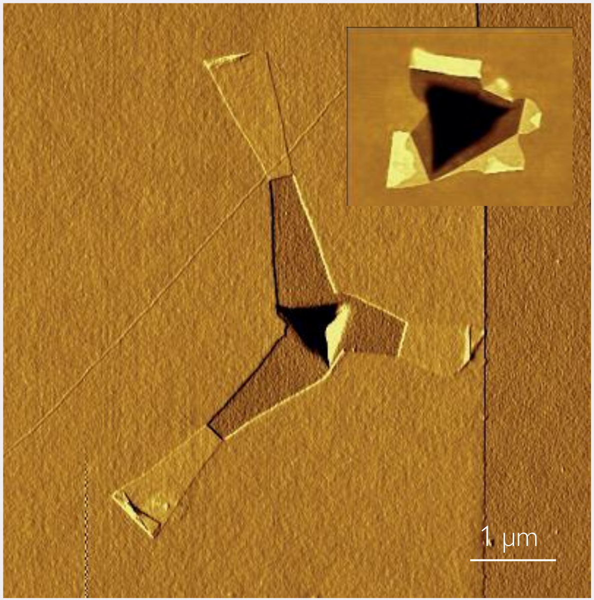


$\kappa > 0$ $\kappa < 0$

Kruglova et al. Phys. Rev. Lett. (2011)

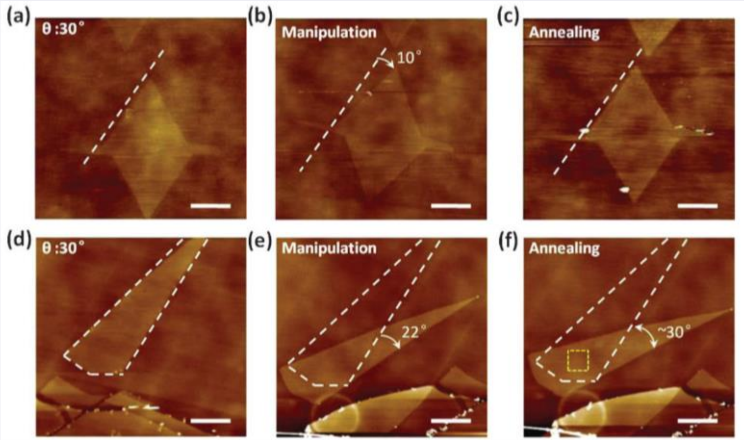
Self-tearing/peeling & Self-rotating of 2D materials

Self-assembly of graphene ribbons by self-tearing/peeling from a substrate



Annett and Cross Nature (2016)

After the rotation, two thermally stable configurations of graphene on h-BN with a relative lattice twisting angle of 0° (most stable) and 30° (metastable), respectively, were found.

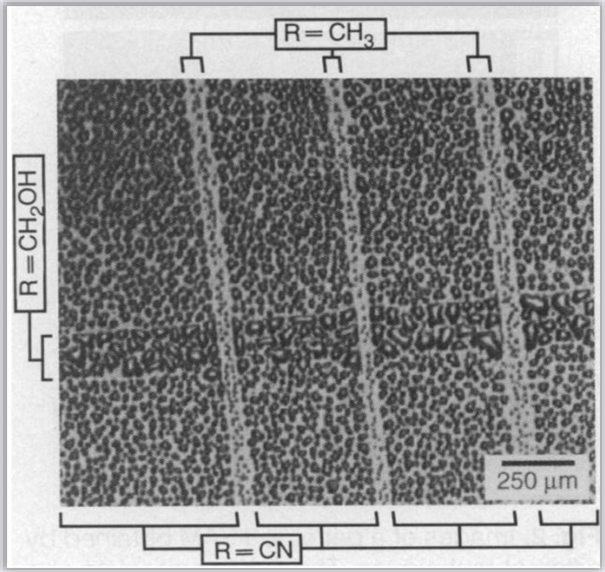


Wang et al. Phys. Rev. Lett. (2016)

Condensation on surfaces

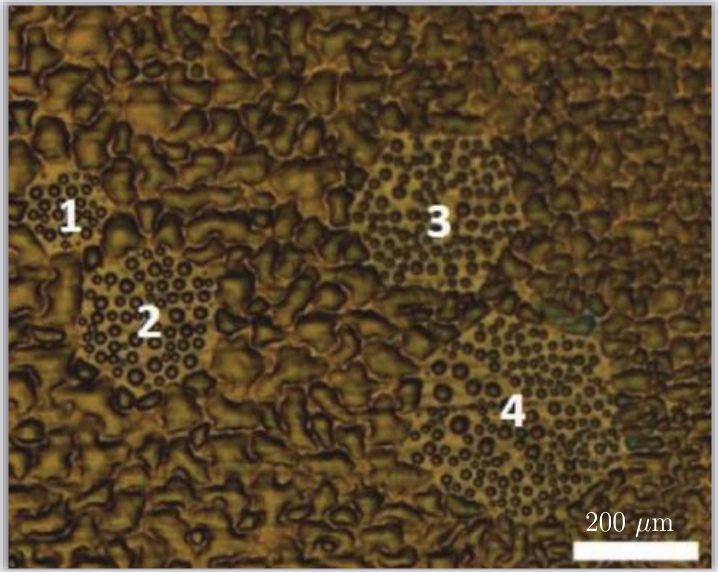
Condensation figures, historically called "breath figures“, are arrays of liquid drops that form upon condensation of vapor onto a solid surface.

A surface patterned with different chemical components



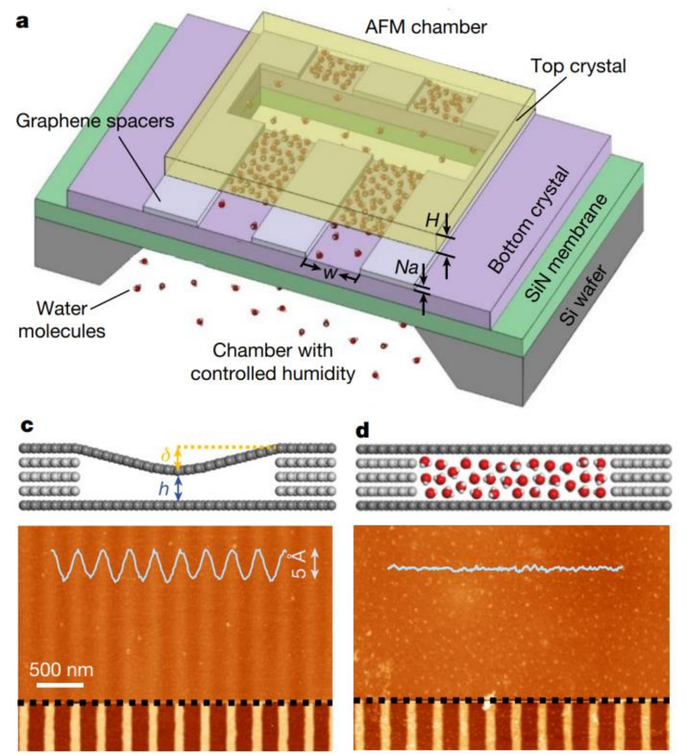
Lopez et al. Science (1993)

Cu surfaces with several graphene nanoflakes

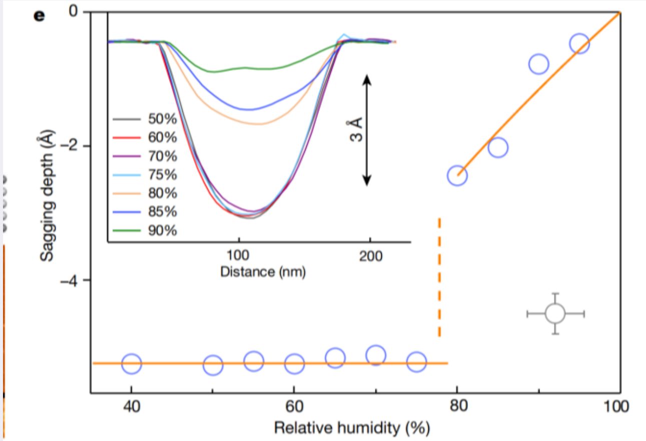


Xia et al. Adv. Mater. Interfaces (2016)

Condensation at nanoscale

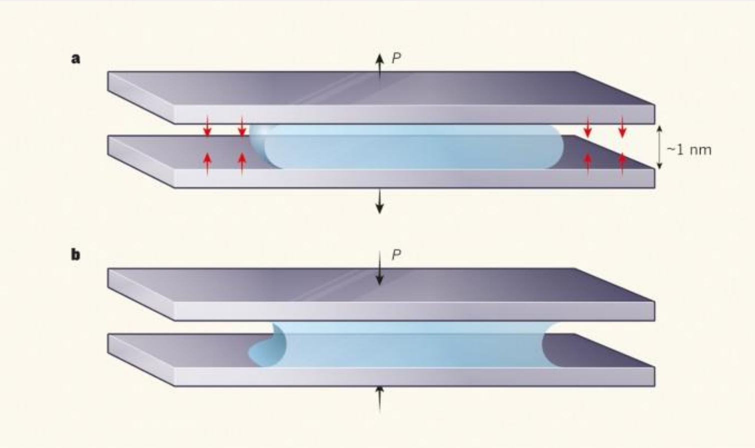


Condensation transition in weakly hydrophilic (graphite) capillaries

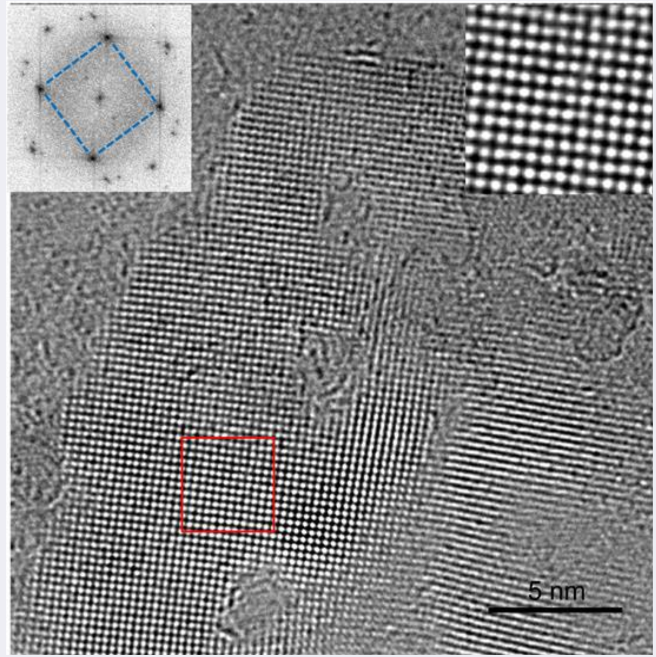


Yang et al. Nature (2020)

Water under confinement



Confined water is found to form square ice at room temperature – a phase with symmetry principally different from the conventional tetrahedral geometry of hydrogen bonding.



Algara-Siller et al. Nature (2015)

Outline

I. About this course

II. Why I wanted to develop this course

III. Why surfaces and interfaces

- ❑ A few examples in natural systems
- ❑ A few examples in engineering systems

IV. Back to the course

Goals

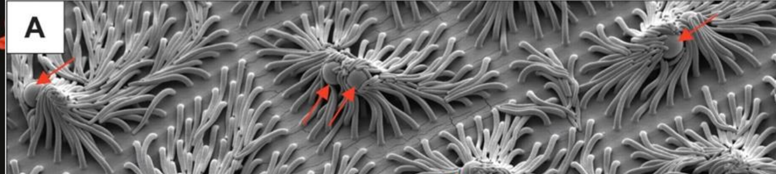
Goals: By means of course lectures, homework problem sets, and an advised project, I hope to achieve the following specific goals:

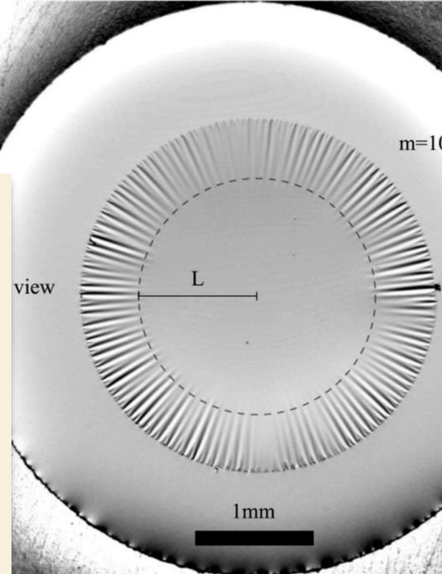
- Understanding of van der Waals interactions and their consequences
- Understanding of the concept of surface energy/tension and its applications
- Being capable of analyzing the static & dynamic consequences of these forces in model systems
- Developing some analytical/numerical skills at modeling such interfacial processes

Topics

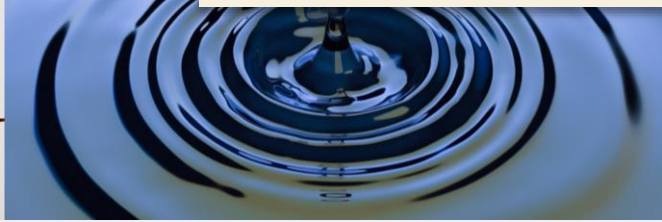
- ❑ L1: Course introduction & Foreword
- ❑ L2: Van der Waals interactions between surfaces
- ❑ L3: Surface tension/energy/stress?
- ❑ L4: Interfacial stress balance & droplets
- ❑ L5: Fluid statics: Bubbles, pendant droplets and their stability
- ❑ L6: Lateral capillary forces, condensation, and nucleation
- ❑ L7: Elastocapillarity
- ❑ L8: Modeling and stability of thin liquid films
- ❑ L9: Literature presentation
- ❑ L10: Moving contact lines
- ❑ L11: Coffee stains & Marangoni flows
- ❑ L12: Rayleigh-Plateau instability or/and dynamic instability of elastic rods
- ❑ L13: Fracture
- ❑ L14: Adhesion
- ❑ L15: Project presentations

Questions?





- ❑ Your name & background
- ❑ Your department & adviser
- ❑ Your (proposed) research area for M.S. or Ph.D.
- ❑ Which part do you feel particularly interesting (What do you want to learn)?



Thanks!