Lab on a Chip and Microfluidics

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Part X. Capillarity and Wetting

Capillarity and Wetting

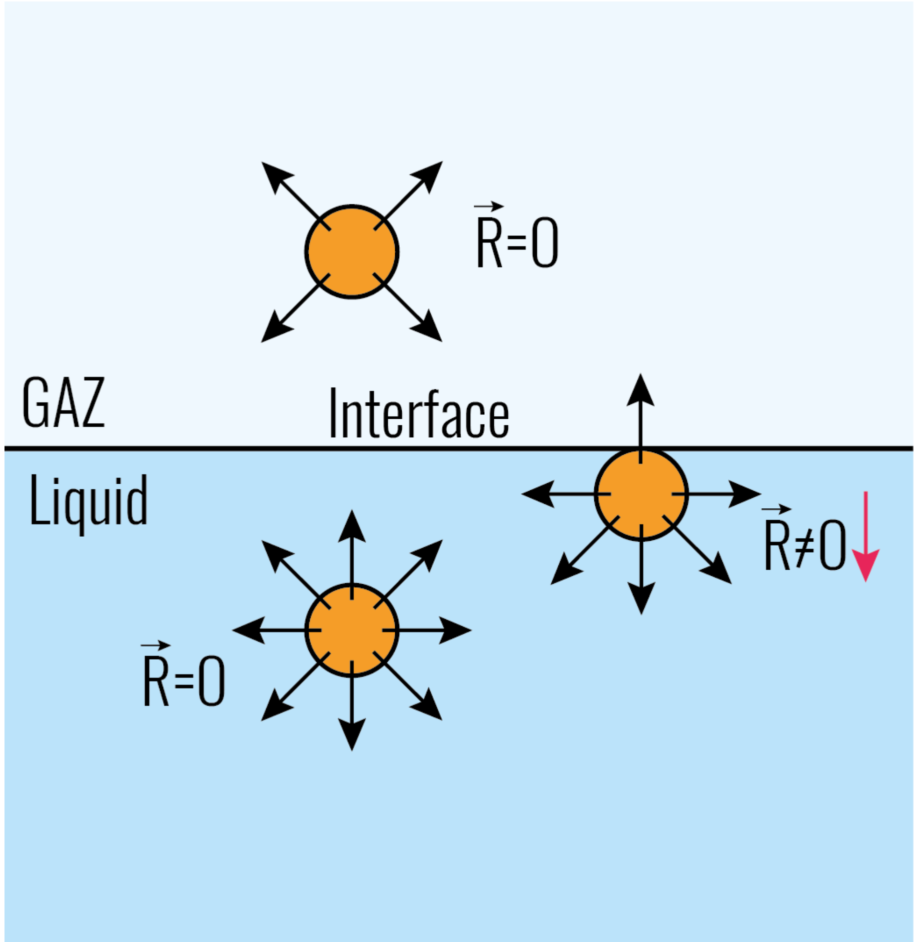
Surface Tension

The superficial layer of a liquid is submitted to a force that tends to lower this surface : it is the Surface Tension

Greater attraction of liquid molecules to each other than to the molecules in the air

$$E_s = \gamma S$$

$$[\gamma] = J/m^2 = N/m$$

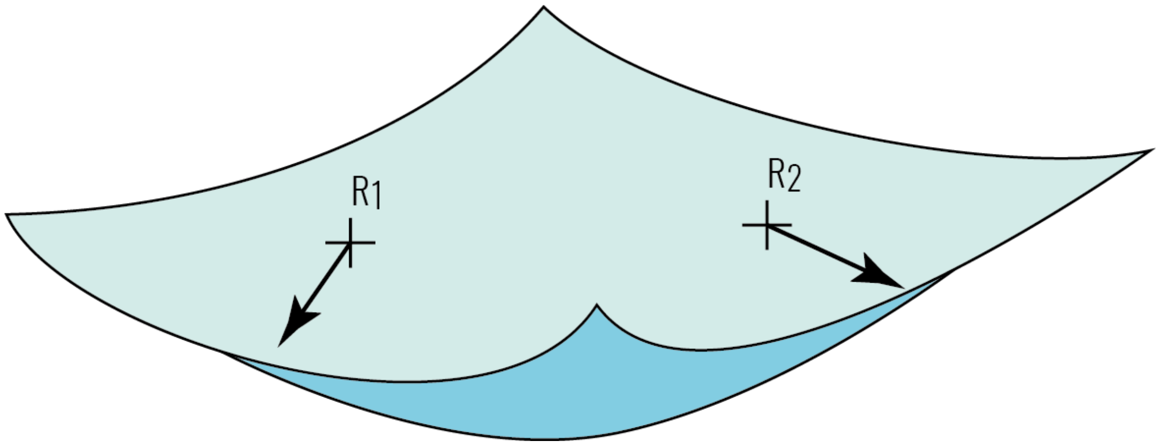


Water	72,8	10^{-3} N.m^{-1}
Ethanol	22,2	
Acetone	23	
Blood	60	
Liquid Nitrogen	8,8	
Mercury	**486**	

Surface Tension : Young Laplace

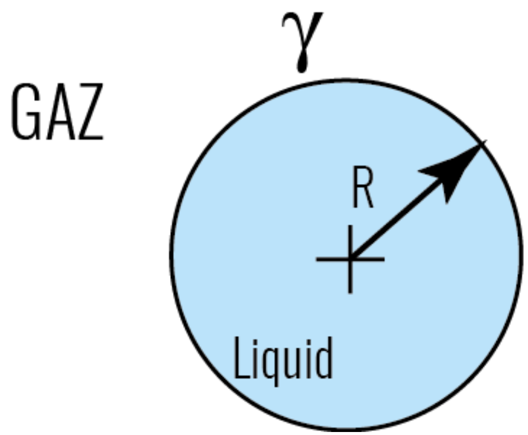
The bending of a liquid/gaz interface produces a pressure difference between each sides of the interface such as :

$$\Delta P = \gamma . div(\vec{n}) = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$



For a sphere (one curvature radius) :

$$\Delta P = \frac{2\gamma}{R}$$



Surface Tension : Young Laplace

Droplet of water in the air

$$\Delta P = \frac{2\gamma}{R}$$

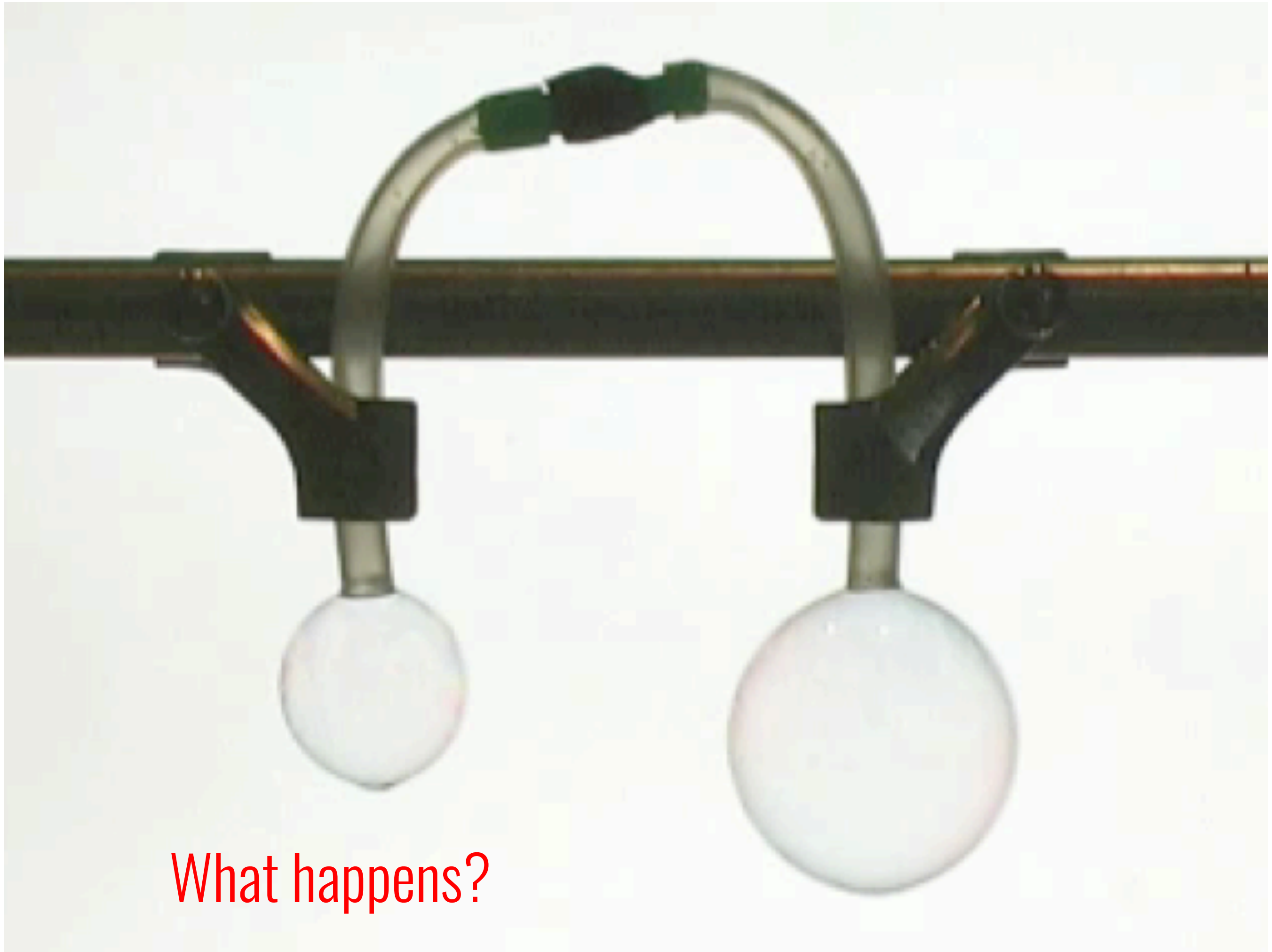
Soap bubble

$$\Delta P = \frac{4\gamma}{R}$$

Why 4?

Surface Tension : Young Laplace

Two connected balloons experiment



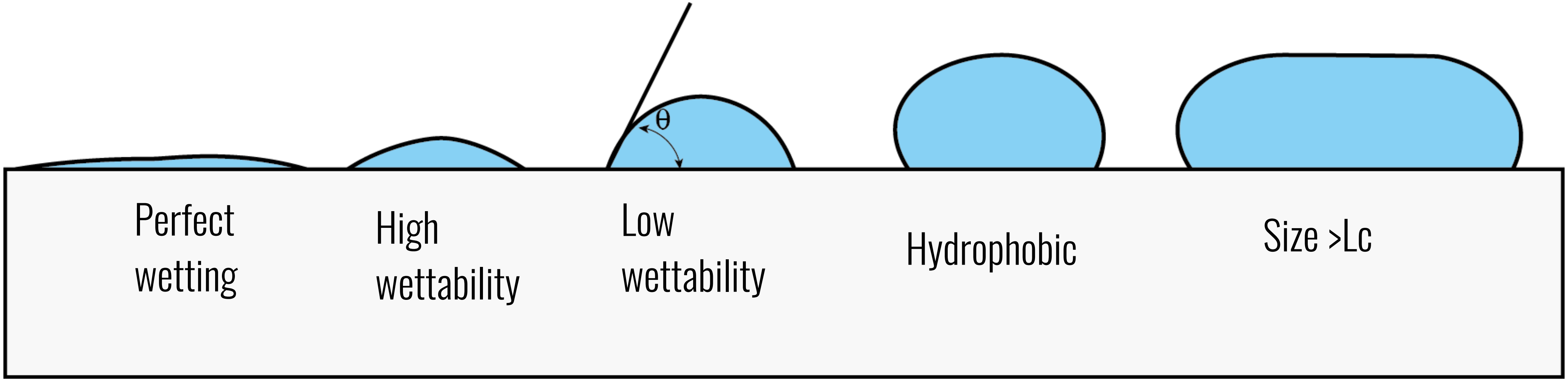
Surface Tension : liquid metal

Liquid Gallium droplet coalescence

Wetting

Now, Three phases :
Solid / Liquid / Gaz

Wetting is the balance between cohesive and adhesive forces



Capillary length

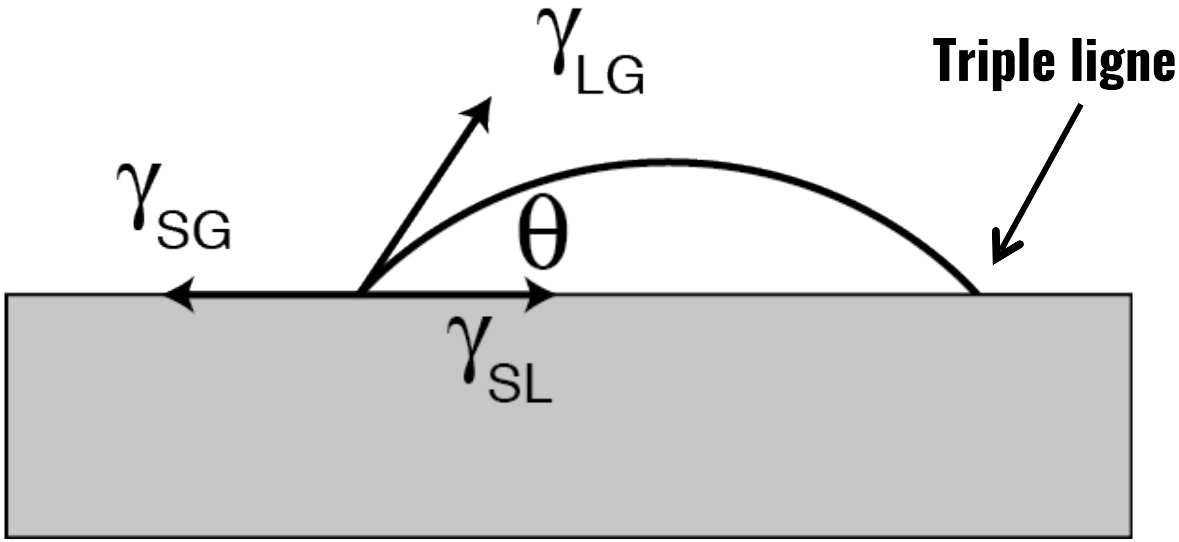
$$L_c = \frac{\gamma}{\rho g}$$

γ Is the surface tension
ρ is the density of the liquid
g is the gravitational acceleration

Wetting : Young Dupré

Young-Dupré law

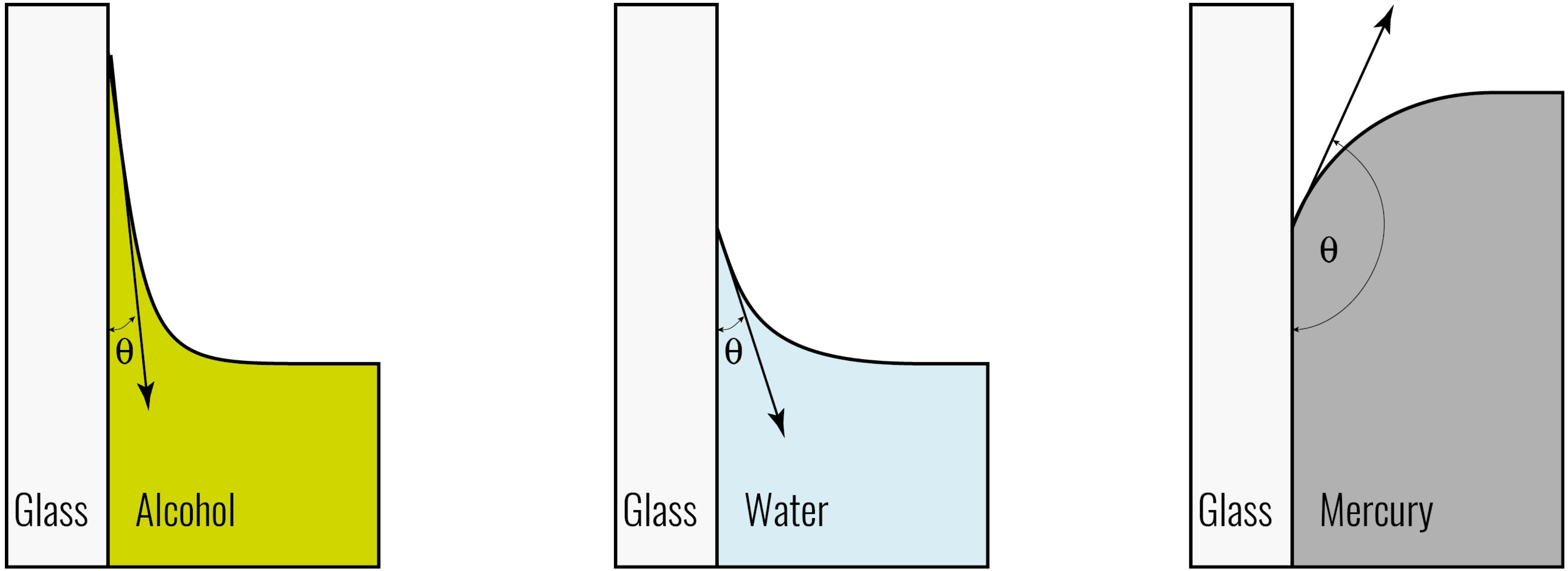
$$\cos\theta = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma_{LG}}$$



Wetting angles

Water on SiO_2	52,3°
Water on Glass	25°
Water on Gold	0°
Water on Platinum	40°
Water on PMMA	73,7°
Water on PDMS	100°
Mercury on Glass	140°

Wetting : Meniscus



Wetting : Larmes du vin

Marangoni effect

mass transfer along an interface between two fluids due to surface tension gradient.

A liquid with a high surface tension pulls more strongly on the surrounding liquid than one with a low surface tension

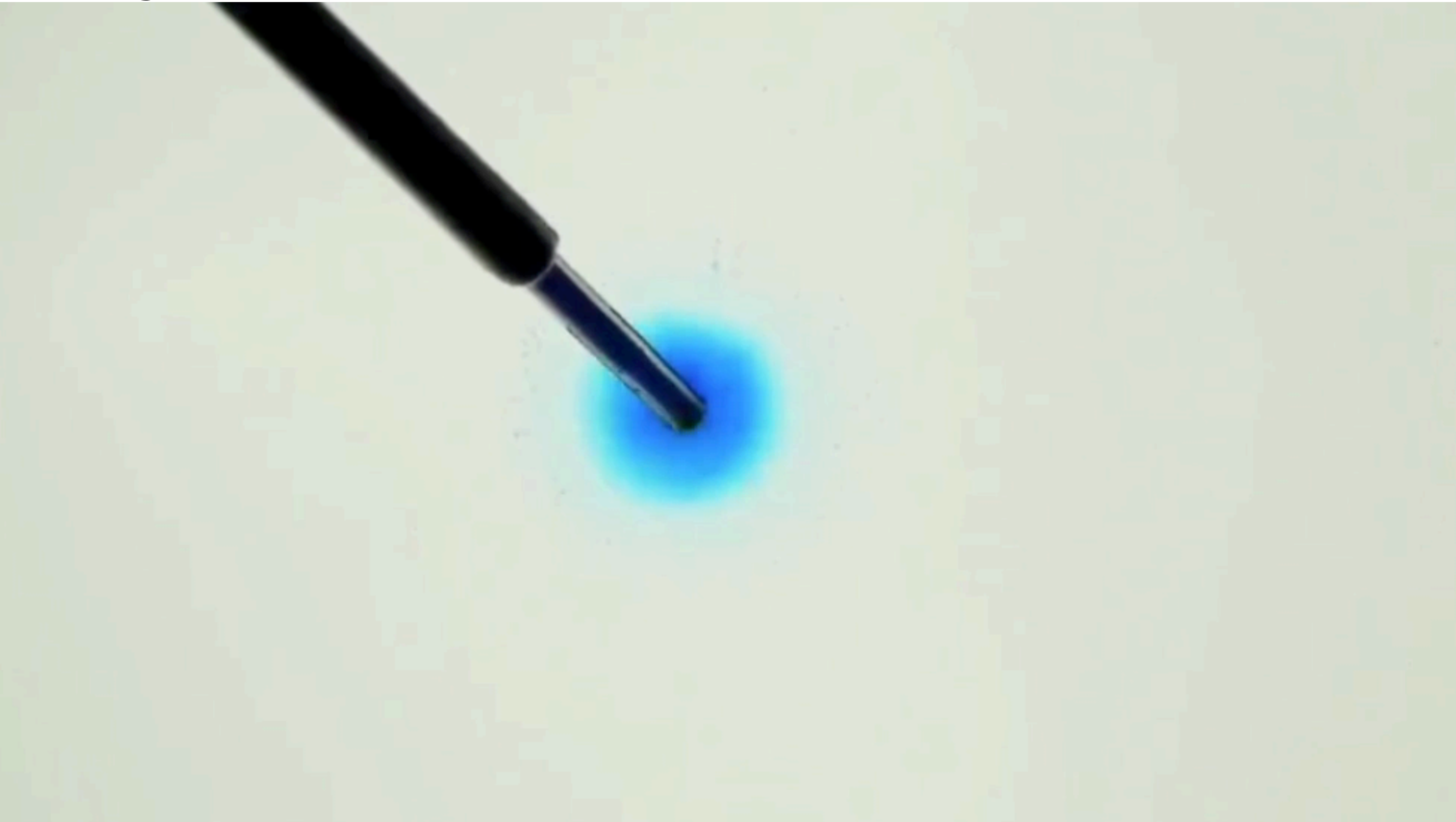
Marangoni number

$$\mathrm{Ma} = -(\partial\gamma/\partial T).\,\frac{L.\,\Delta T}{\eta.\,\alpha}$$

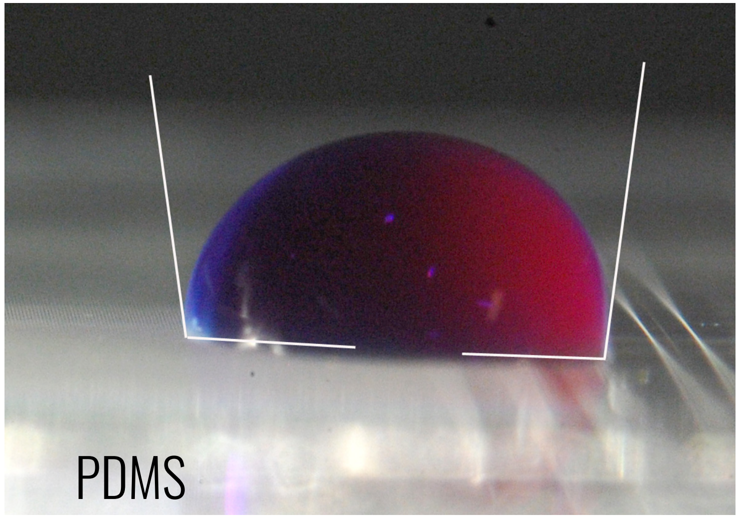
Par Epop — Travail personnel, Domaine public, https://commons.wikimedia.org/w/index.php?curid=4528610

Wetting

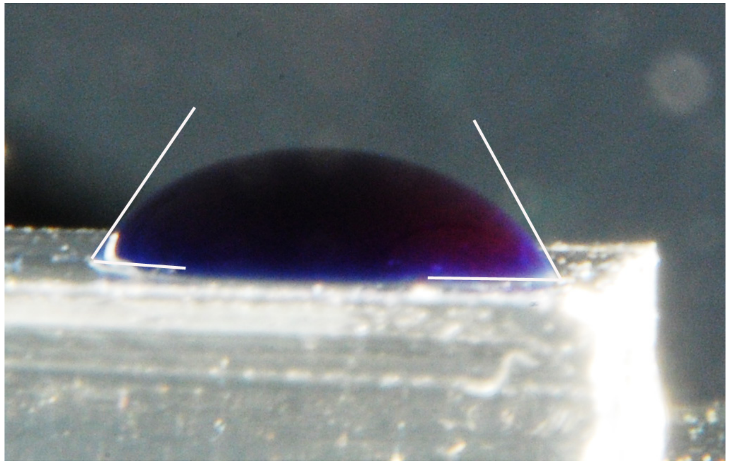
Marangoni effect



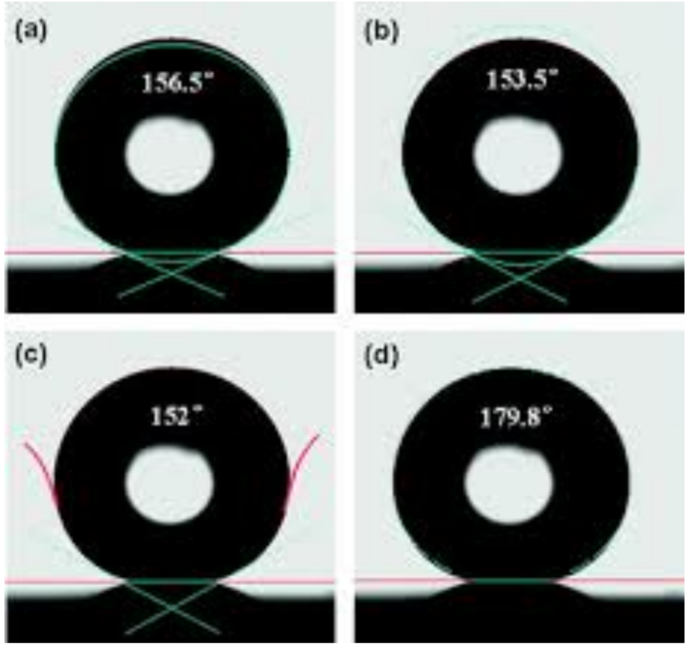
Hydrophobicity



PDMS

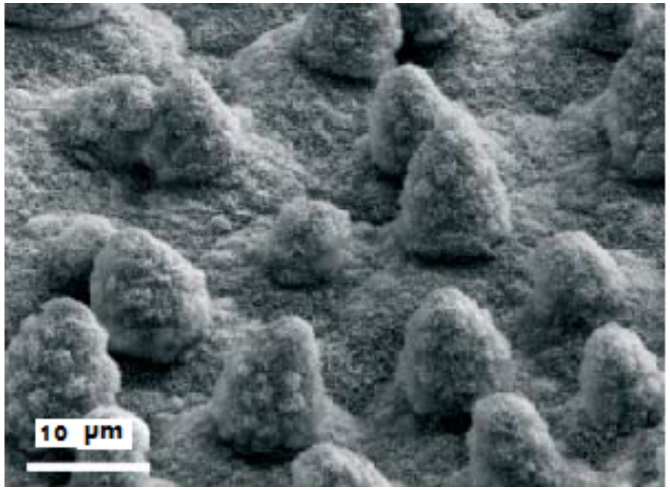


PDMS + triton X 0,01%
(surfactant)

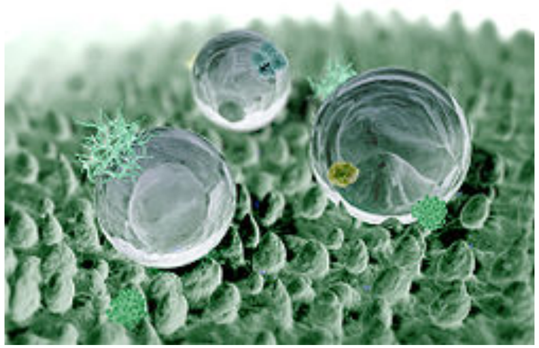


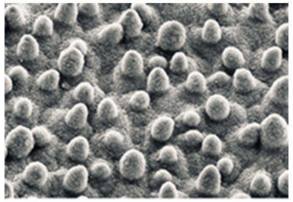
Mercury

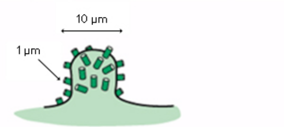
Super Hydrophobicity



Lotus

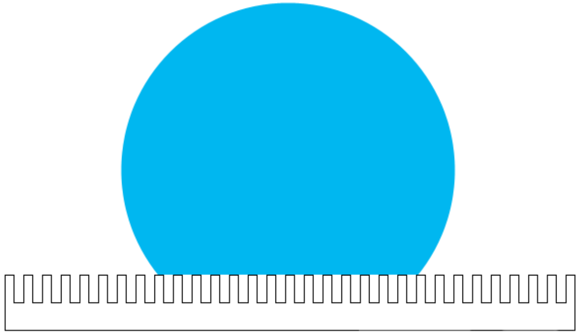




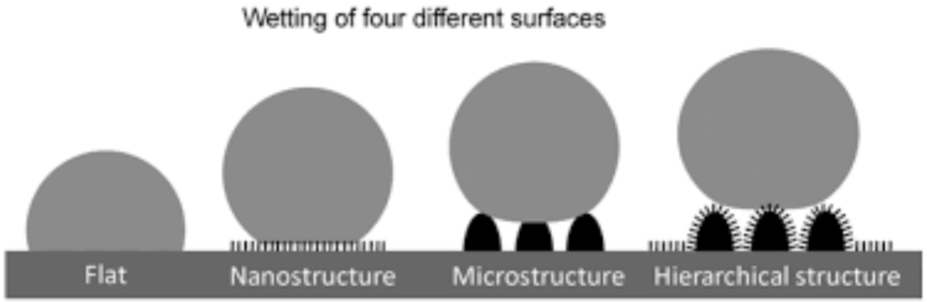


Wenzel and Cassie-Baxter models

Wenzel : état « empalé »



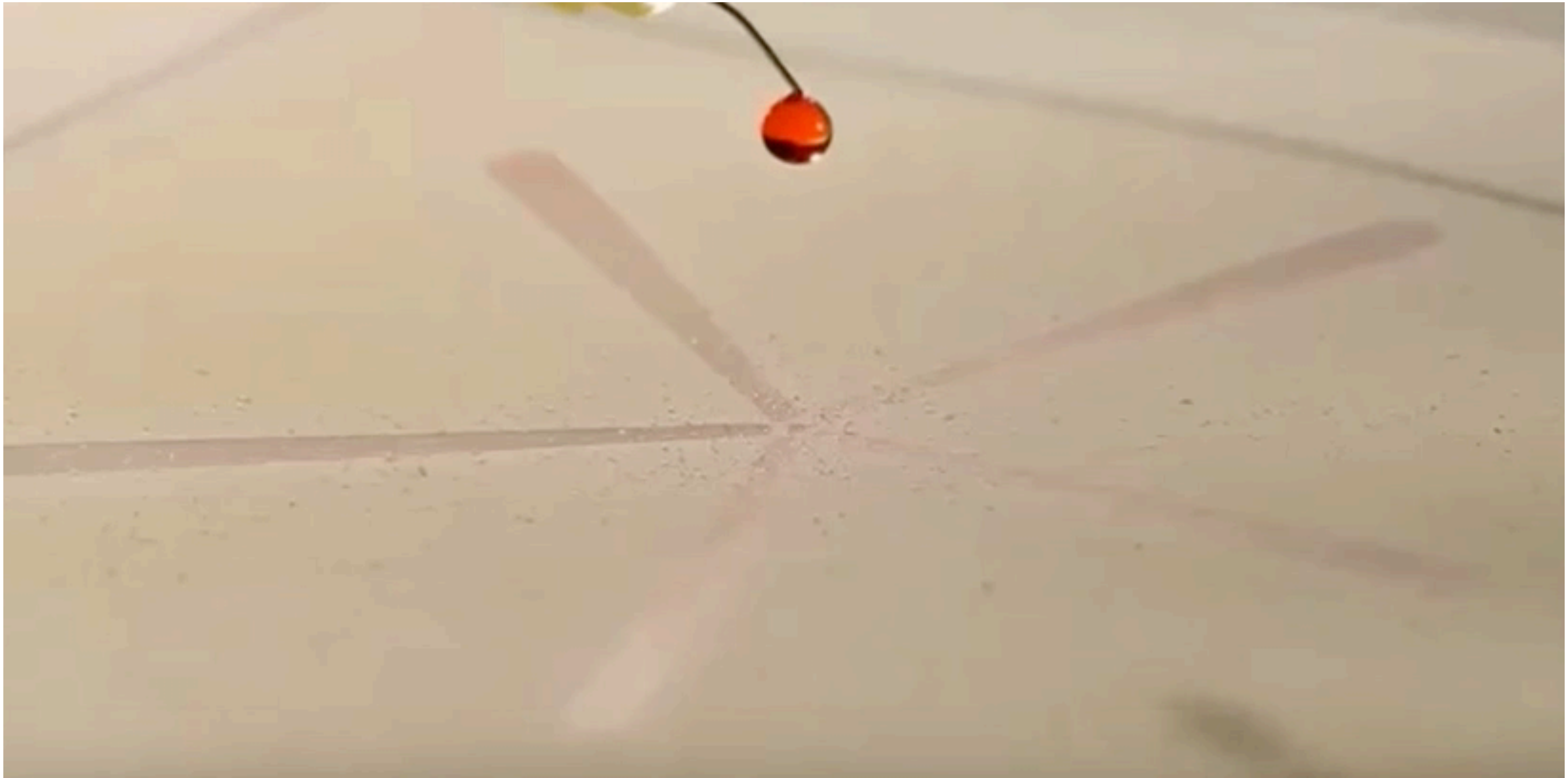
Cassie-Baxter: état « fakir »



Super Hydrophobicity

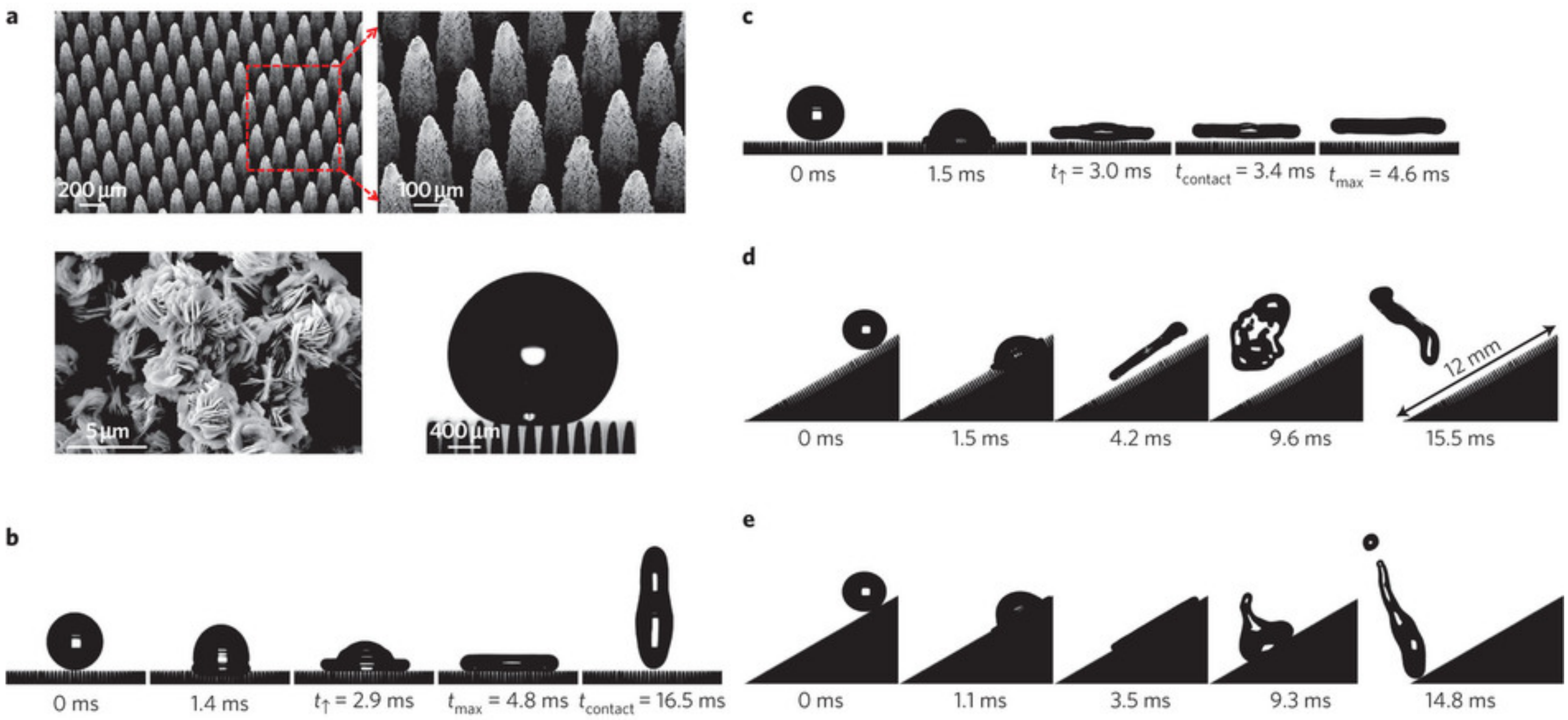
Hydrophilic patterns on a hydrophobic surface

Constantine M. Megaridis, Aritra Ghosh, Ranjan Ganguly, Mechanical and Industrial Engineering, University of Illinois at Chicago



Super Hydrophobicity

Dynamique des gouttes, rebonds



Capillary number

$$C_a = \frac{v\mu}{\gamma}$$

γ est la tension superficielle du liquide ;
v est la vitesse du liquide
μ est la viscosité dynamique;

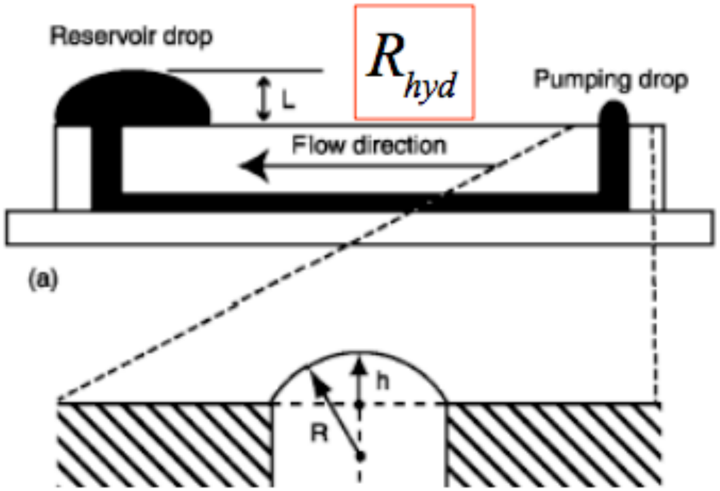
Capillary length

$$L_c = \frac{\gamma}{\rho g}$$

γ est la tension superficielle du liquide ;
p est la masse volumique du liquide
g est l'accéleration gravitationnelle

Capillary Pumps

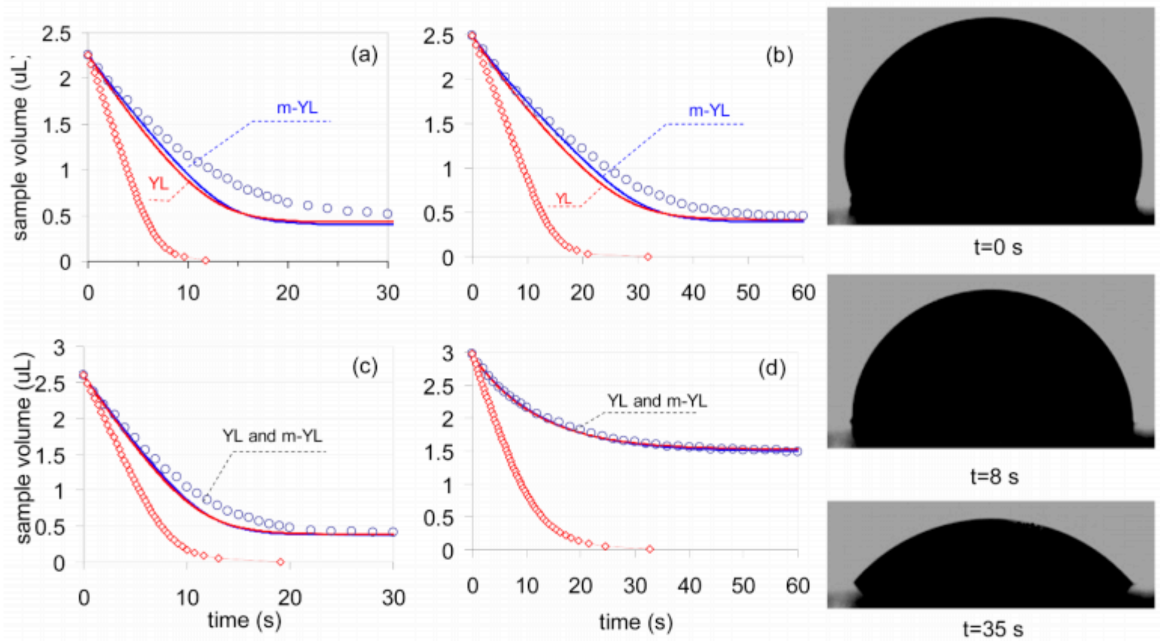
Application : Pumping without mechanics



$$\Delta p = \frac{2\gamma}{R}$$

$$Q = \frac{\Delta p}{R_{hydro}} = \frac{dVol}{dt}$$

$$t_{disparition} \approx \frac{R_{hydro} R_0^4}{\gamma}$$

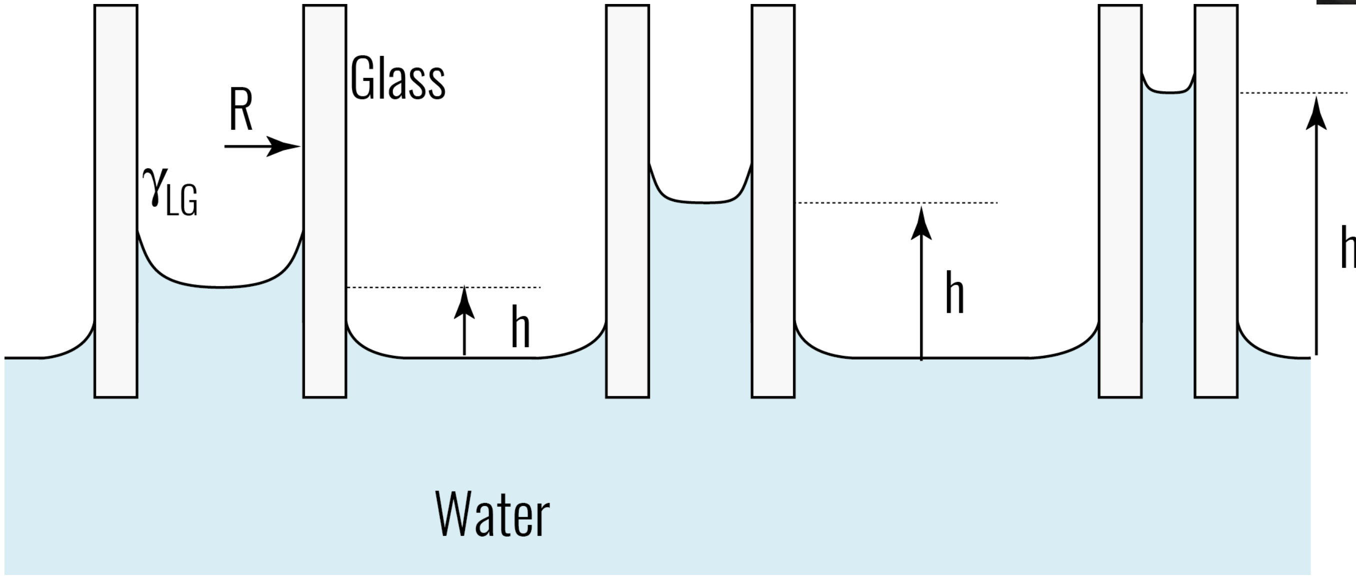


Jurin's law

James Jurin (baptisé le 15 décembre 1684 – 29 mars 1750) est un médecin et physicien anglais passé à la postérité pour ses travaux pionniers relatifs à l'action capillaire et à l'épidémiologie (variolisation). Il fut l'un des plus chauds partisans des travaux d'Isaac Newton et mit tout son talent de satiriste au service de ses idées.

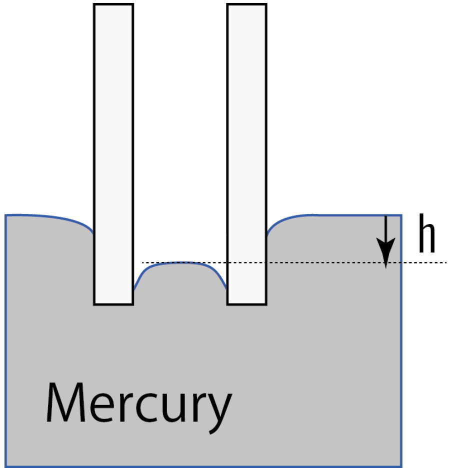
Jurin's law describes the rise and fall of a liquid within a thin capillary tube.

Competition between depression under the meniscus and weight of the water column



$$h = \frac{2\gamma\cos\theta}{\rho g R}$$

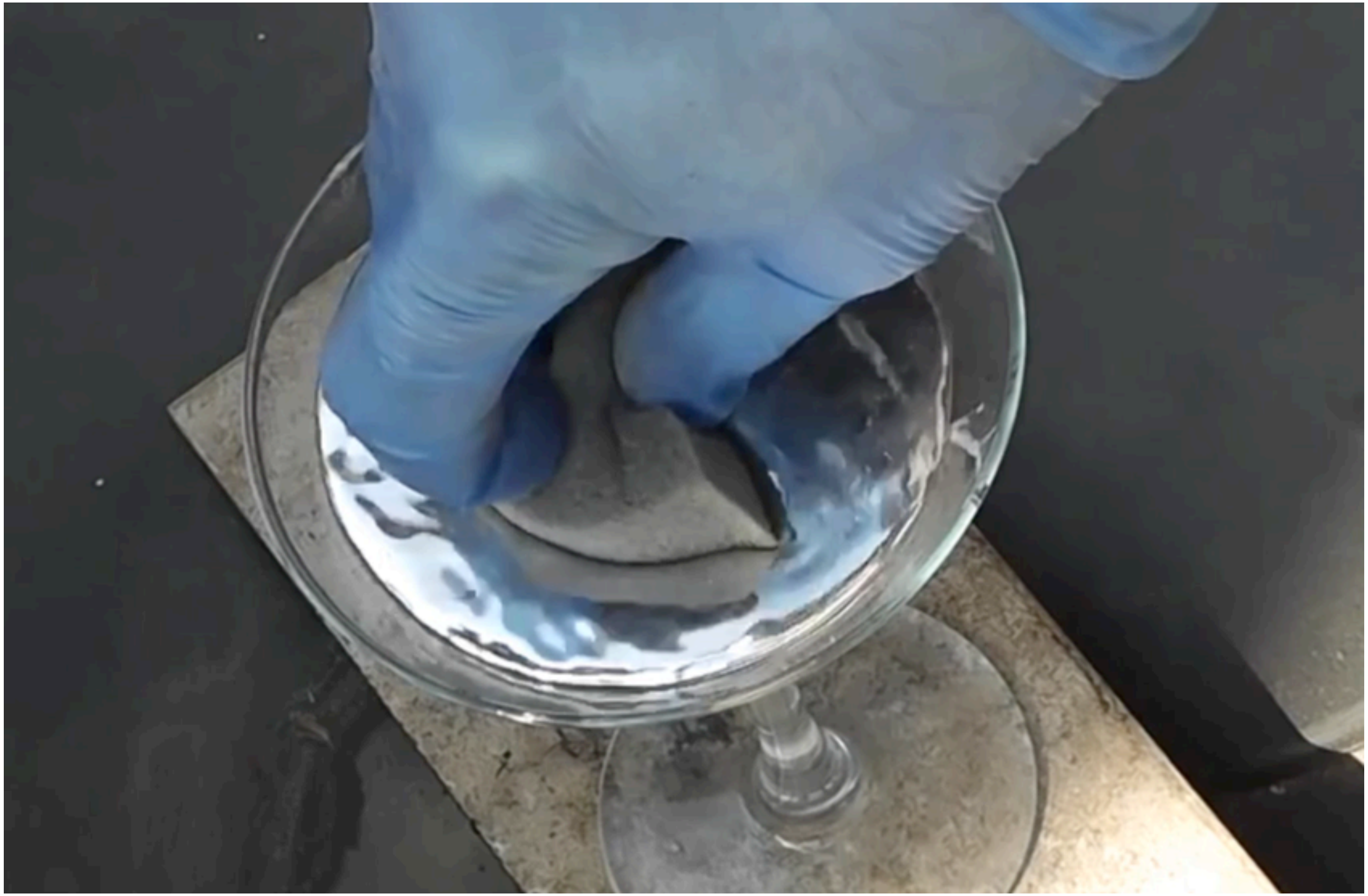
h is the liquid height ;
γ is the liquid surface tension ;
θ is the contact angle of the liquid on the tube wall ;
ρ is the liquid density ;
R is the tube radius ;
g is the gravitational acceleration.



Valid for R<Lc

Imbibition

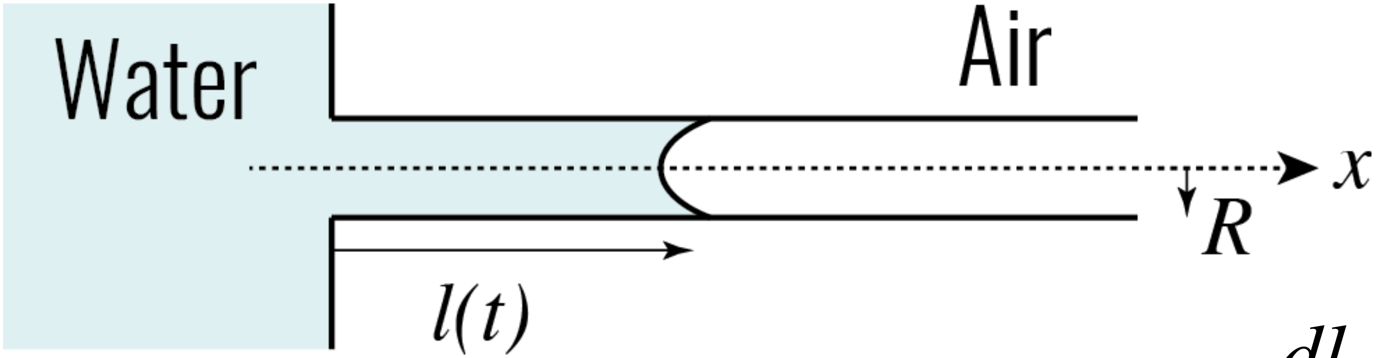
Sponge in mercury : what happens ?



Youtube : TAOFLEDERMAUS

Imbibition

Flow driven by Laplace pressure



$$Q = \pi R^2 v_m = \pi R^2 \frac{dl}{dt}$$

With a Poiseuille flow

$$v_m = \frac{dl}{dt} = \frac{R^2}{8\mu}\frac{dp}{dx} = \frac{R^2}{8\mu}\frac{\Delta p}{l(t)}$$

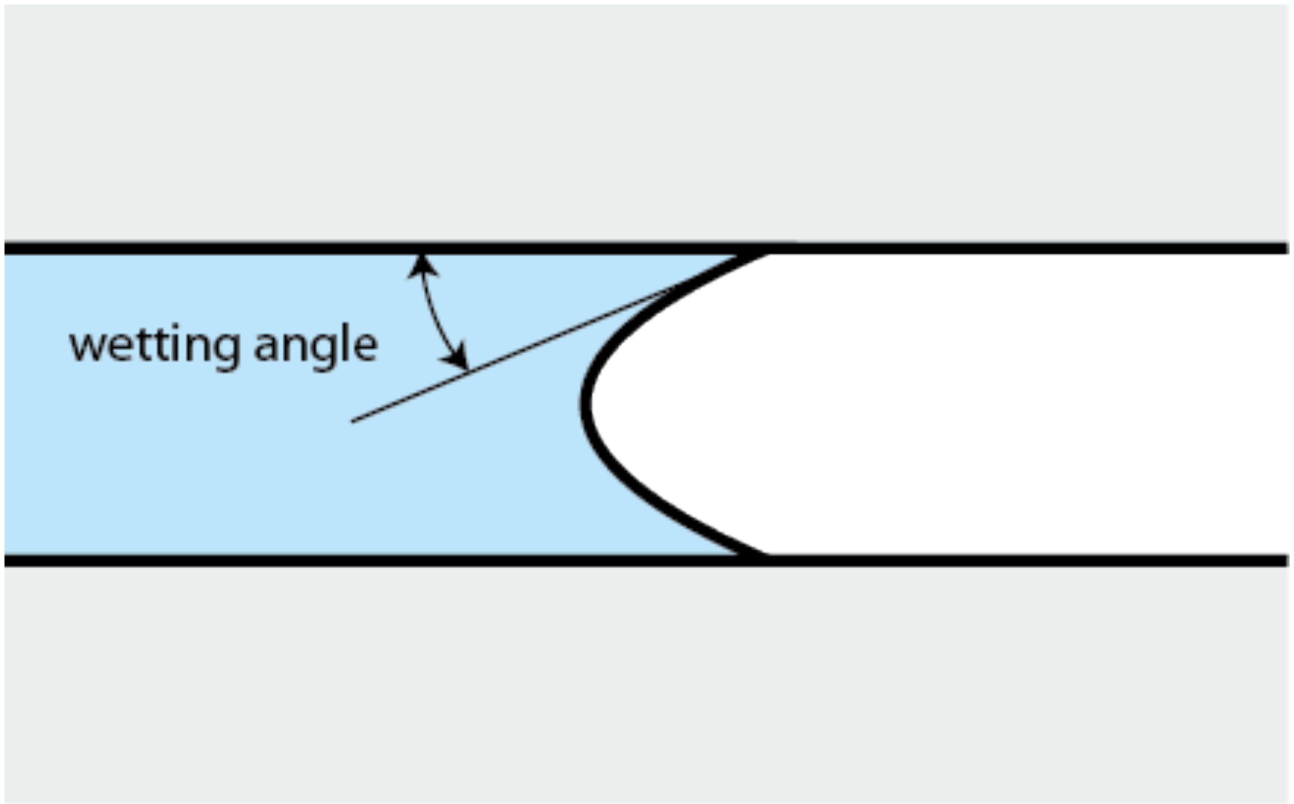
With Young Laplace equation

$$\Delta p = \frac{2\gamma}{R}\cos(\theta)$$

$$l(t) = \sqrt{\frac{R\gamma\cos(\theta)}{2\mu}t}$$

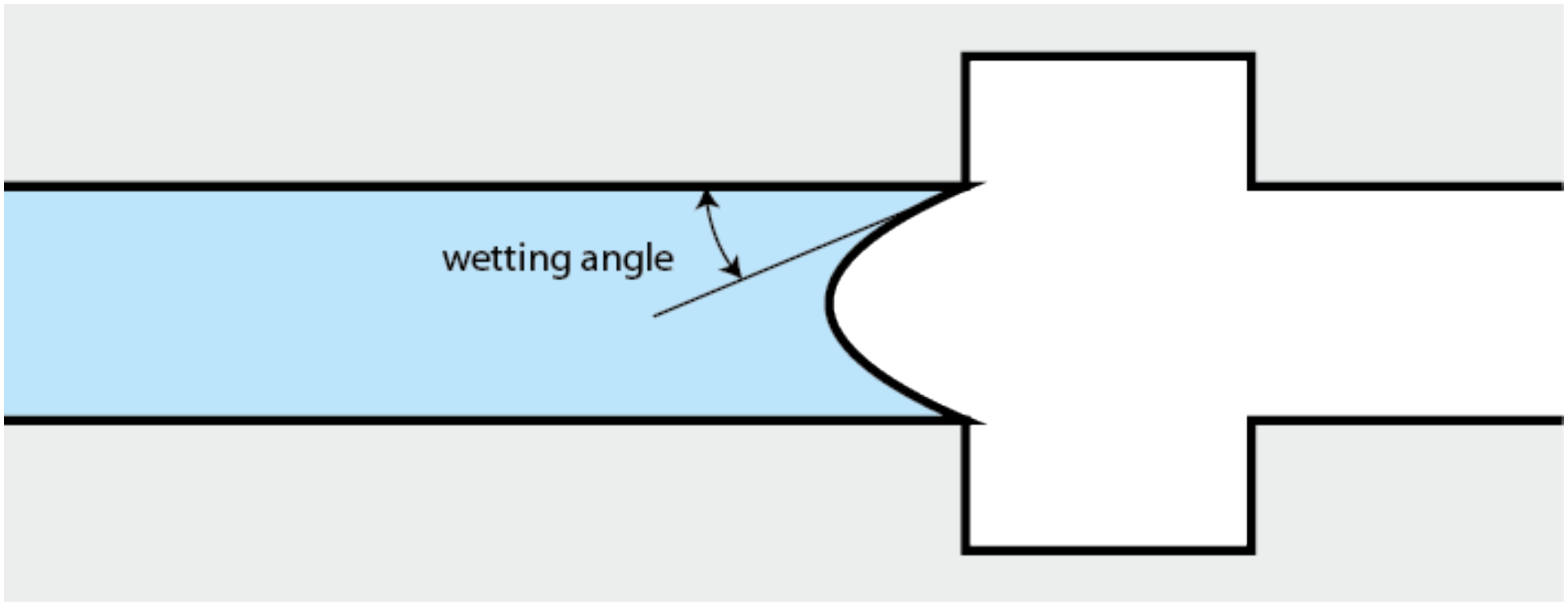
It is the law of Washburn

Capillary driven microfluidics

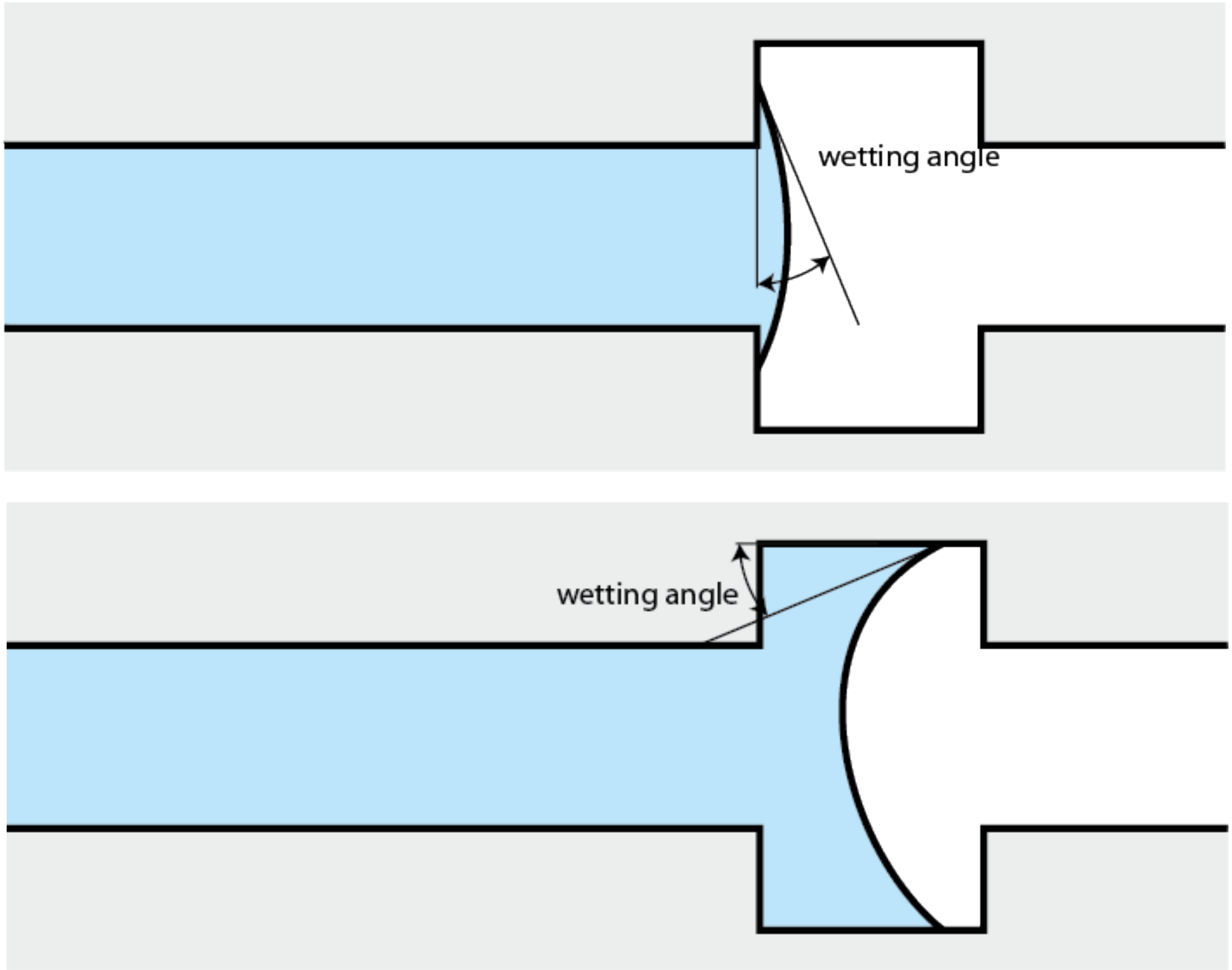


Capillary driven microfluidics

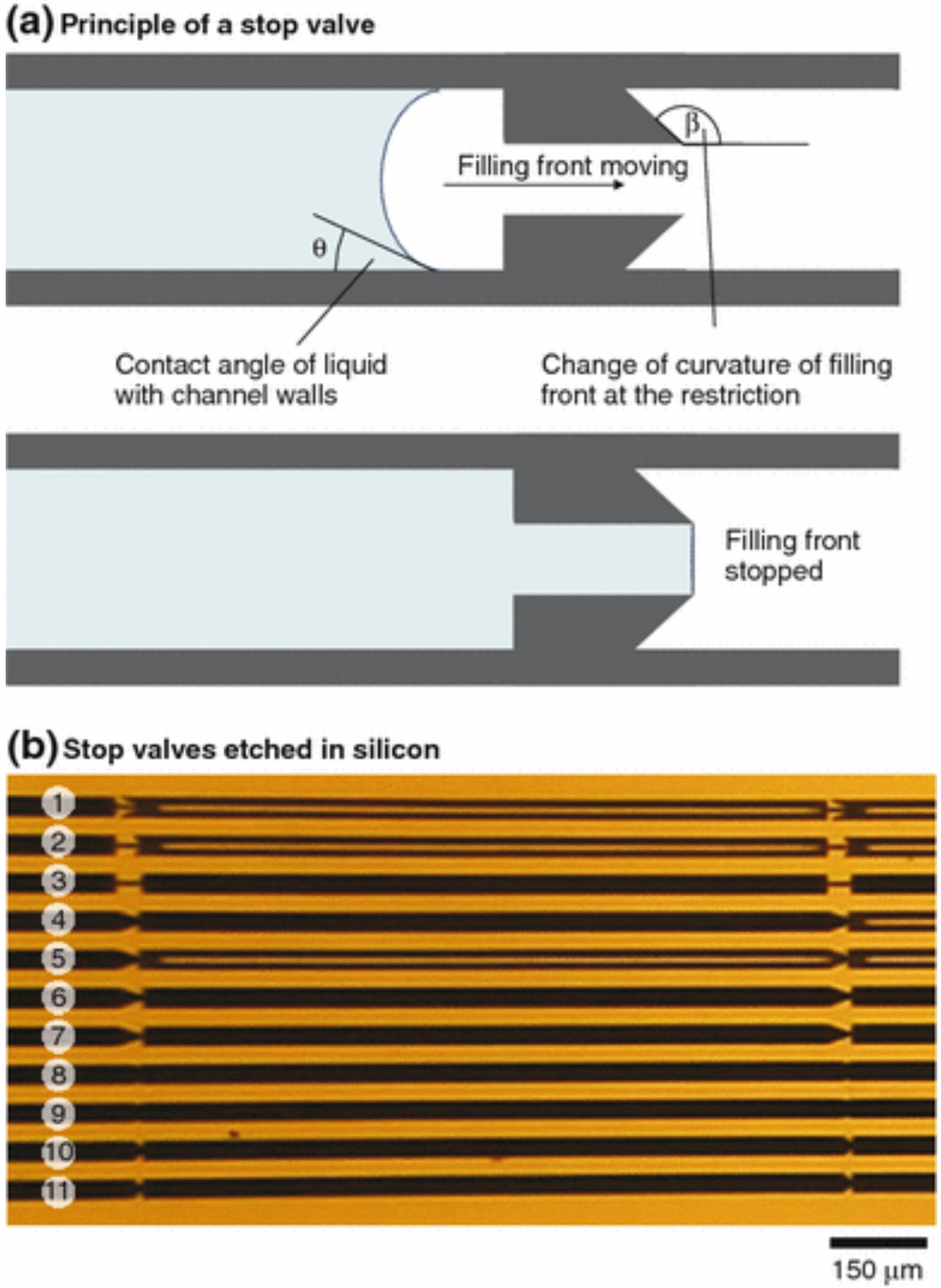
Capillary driven microfluidics



Capillary driven microfluidics

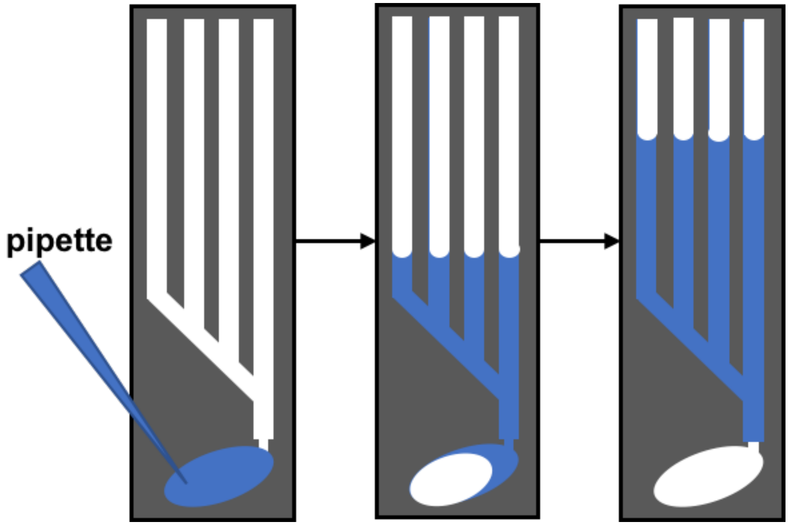


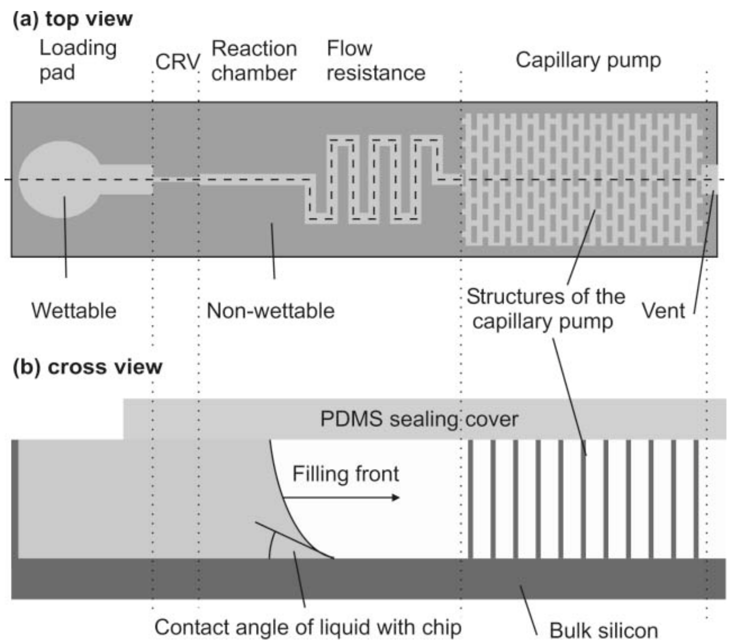
Stop valves

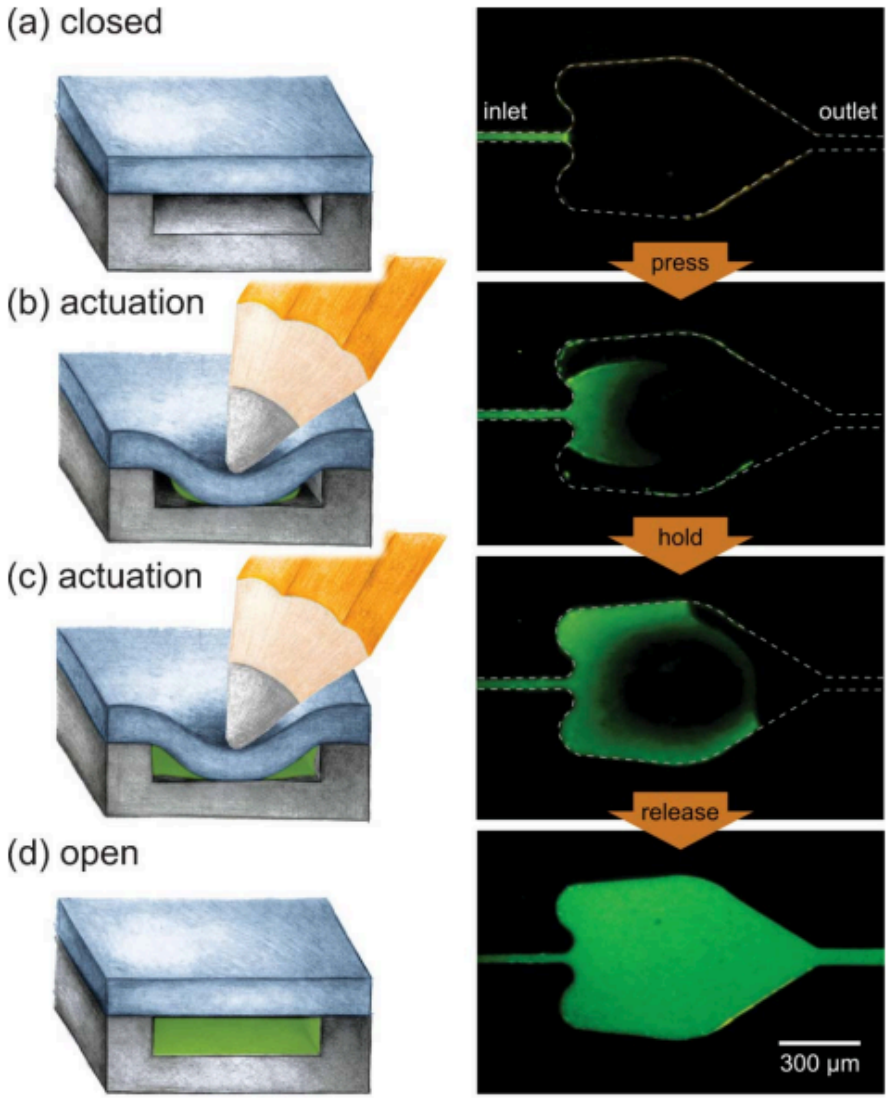


(a) Principle of a stop valve
Filling front moving
θ
β
Contact angle of liquid with channel walls
Change of curvature of filling front at the restriction
Filling front stopped
(b) Stop valves etched in silicon
1
2
3
4
5
6
7
8
9
10
11
150 μm

Capillary driven microfluidics



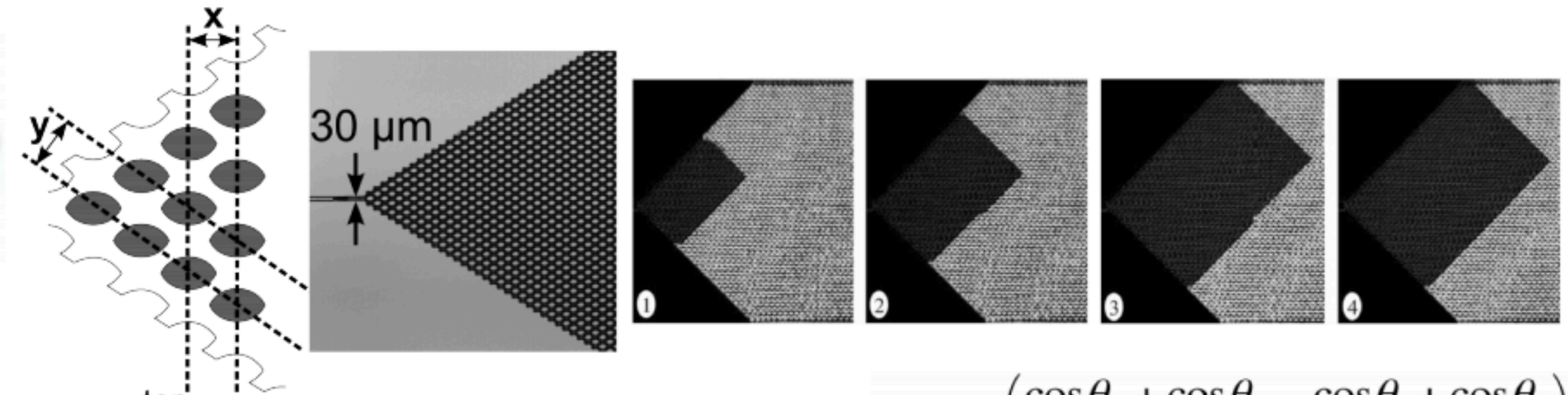


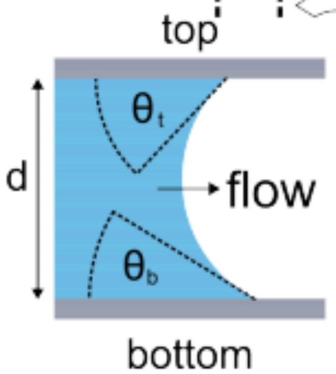


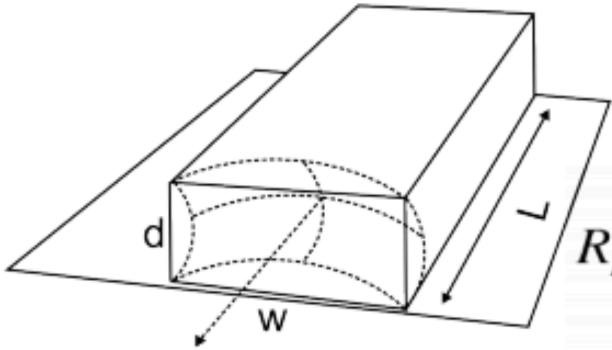
E.Delamarche, Lab Chip, 2012, 12, 1972–1978

Capillary driven microfluidics

(f) capillary pump







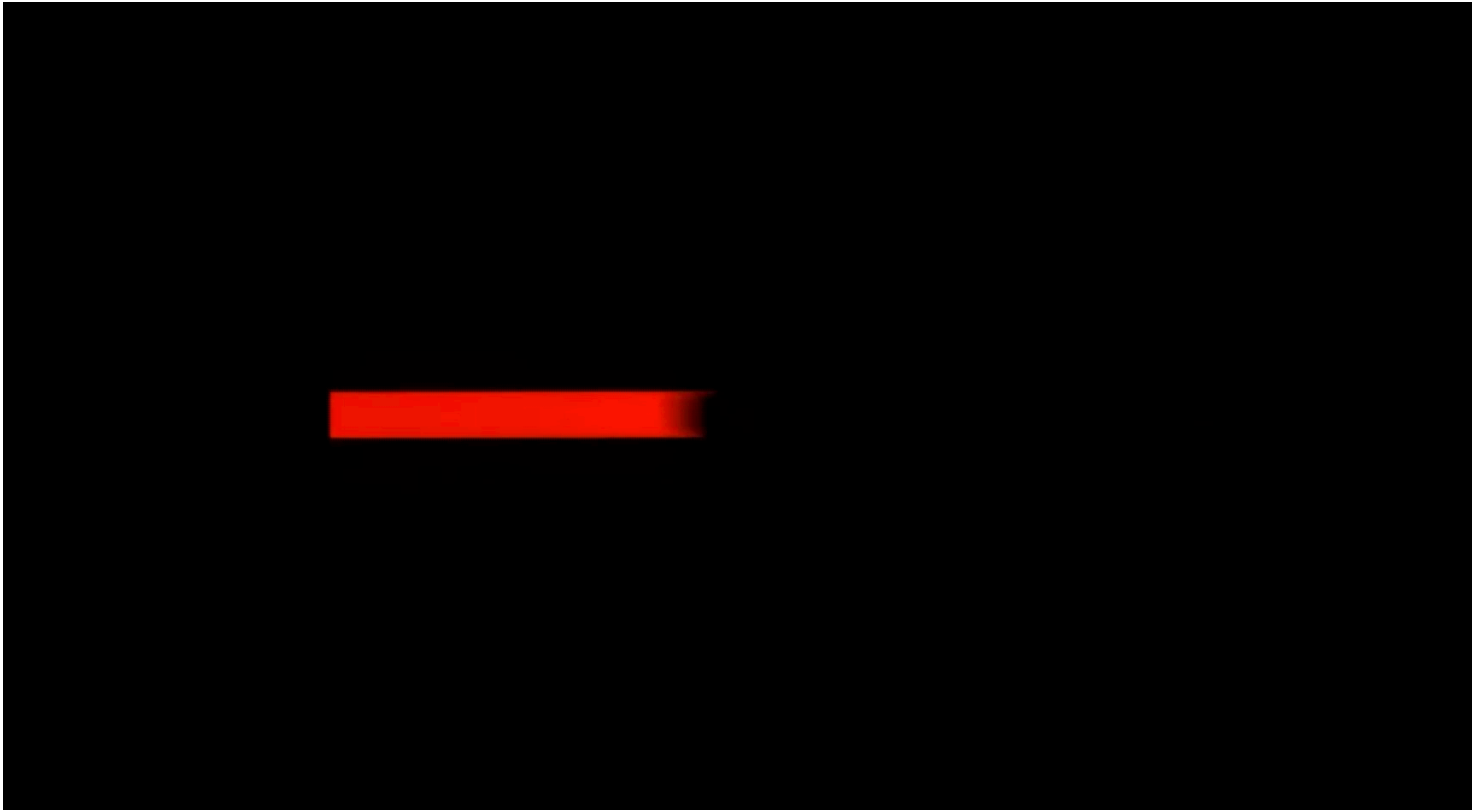
$$P_c = -\gamma\left(\frac{\cos\theta_b + \cos\theta_t}{d} + \frac{\cos\theta_l + \cos\theta_r}{w}\right)$$

$$R_{FR} = \left[\frac{1}{12}\left(1 + \frac{5a}{6b}\right)\frac{AR_H^2}{L}\right]^{-1} \quad R_H = \frac{2A}{P} \quad D = \frac{1}{\eta}\frac{\Delta P}{R_{FR}}$$

a and b: width or depth, $b > a$

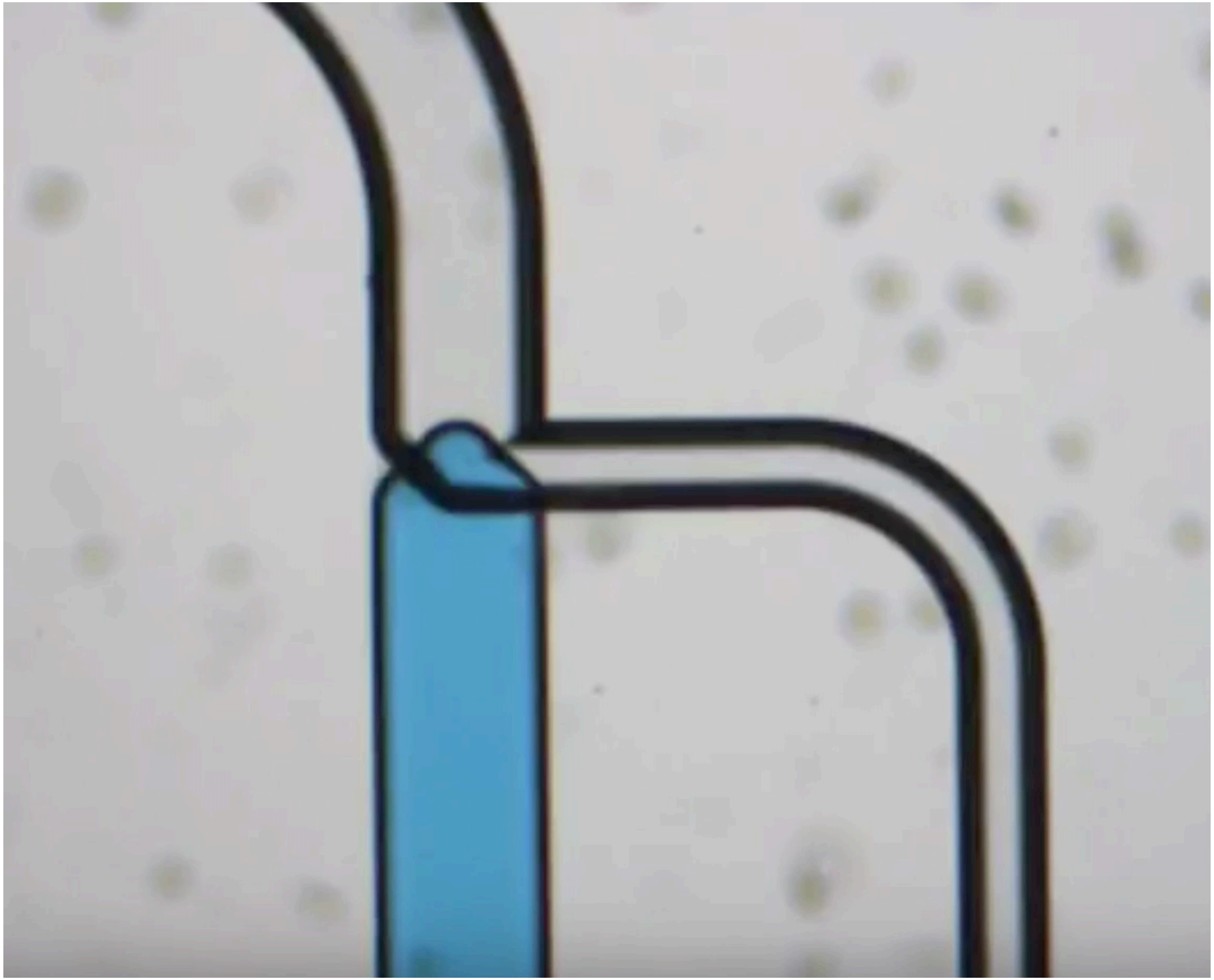
E.Delamarche Lab on a Chip, vol. 7, pp. 119–125, Jan. 2007.

Capillary driven microfluidics



E.Delamarche   IBM

Capillary driven microfluidics



Capillary driven microfluidics

Capillary driven microfluidics

Dehydration and rehydration of reagents

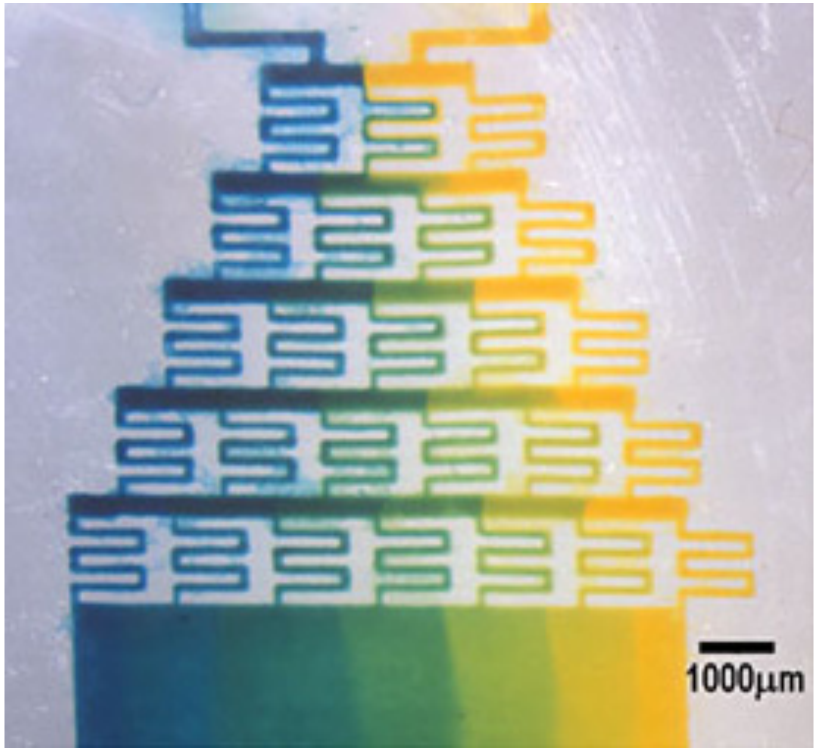
Integration of the rapid mixer

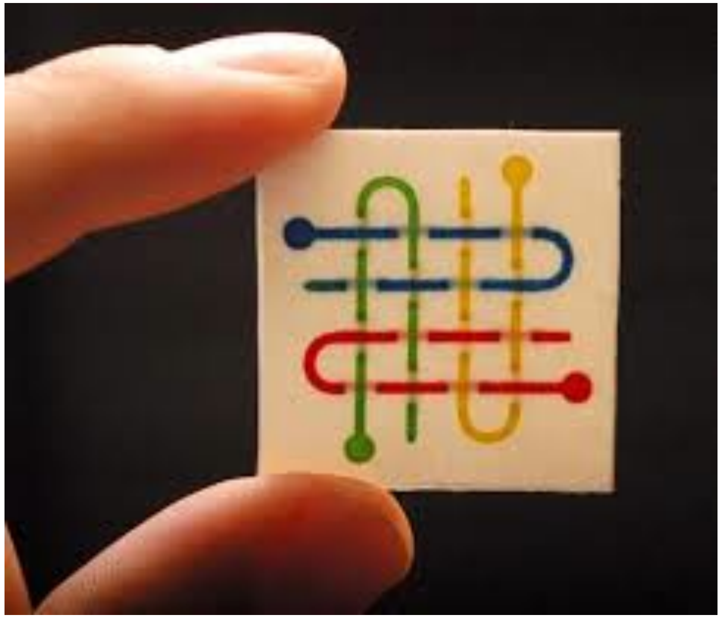
Accelerated 10X

Sensoreal 2014

Paper microfluidics

Use of a network of hydrophilic fibres to generate a flow





Paper microfluidics

Use of a network of hydrophilic fibres to generate a flow

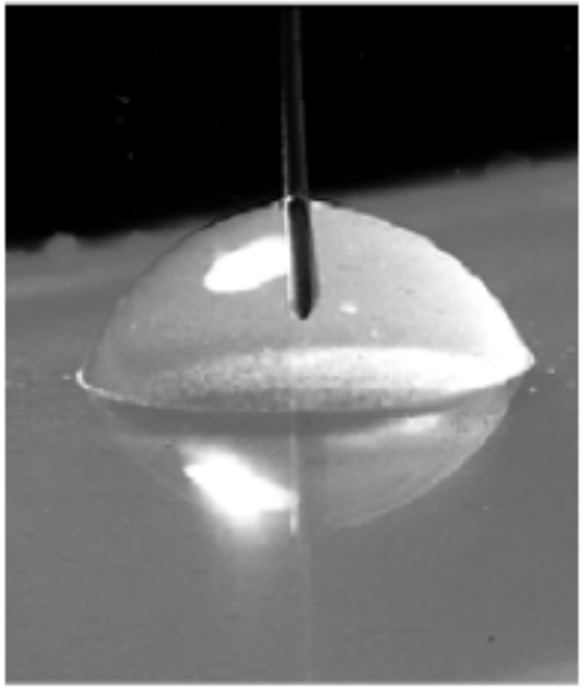
Electrowetting

Droplets microfluidics

Phenomenon :
Change in wetting angle by the polarisation of a droplet on an hydrophobic surface on top of an electrode

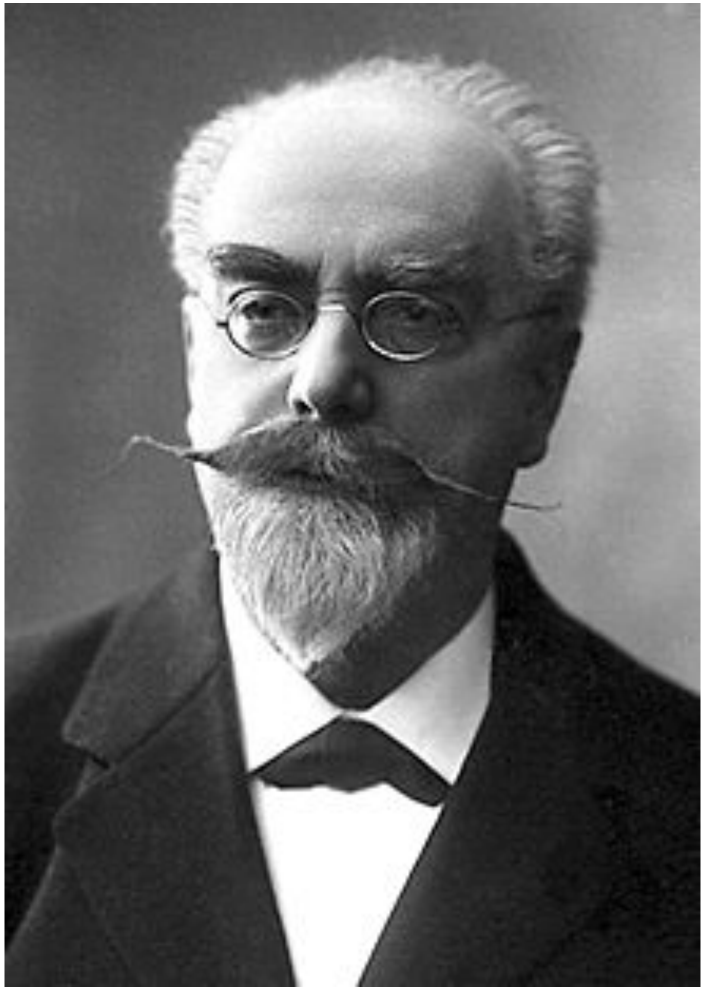
Gabriel Lippman
Nobel price 1908

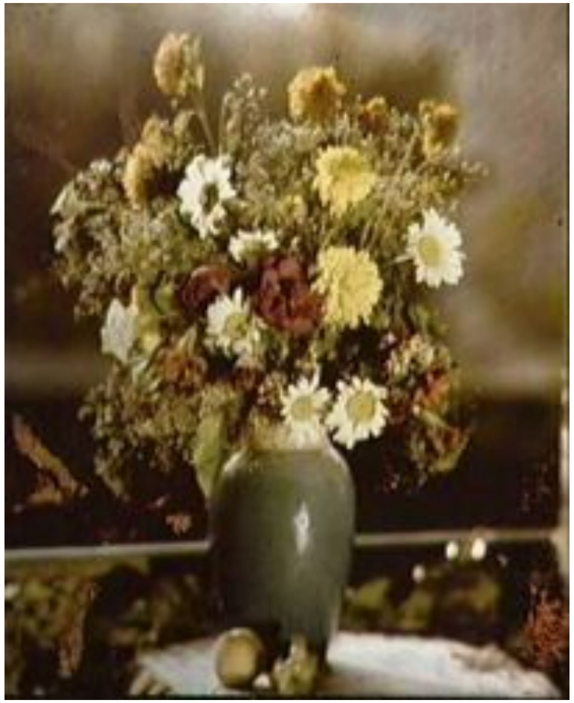
M.G. Lippmann,"Relation entre les phénomènes électriques et capillaires." Ann. Chim. Phys, 5:494, 1875



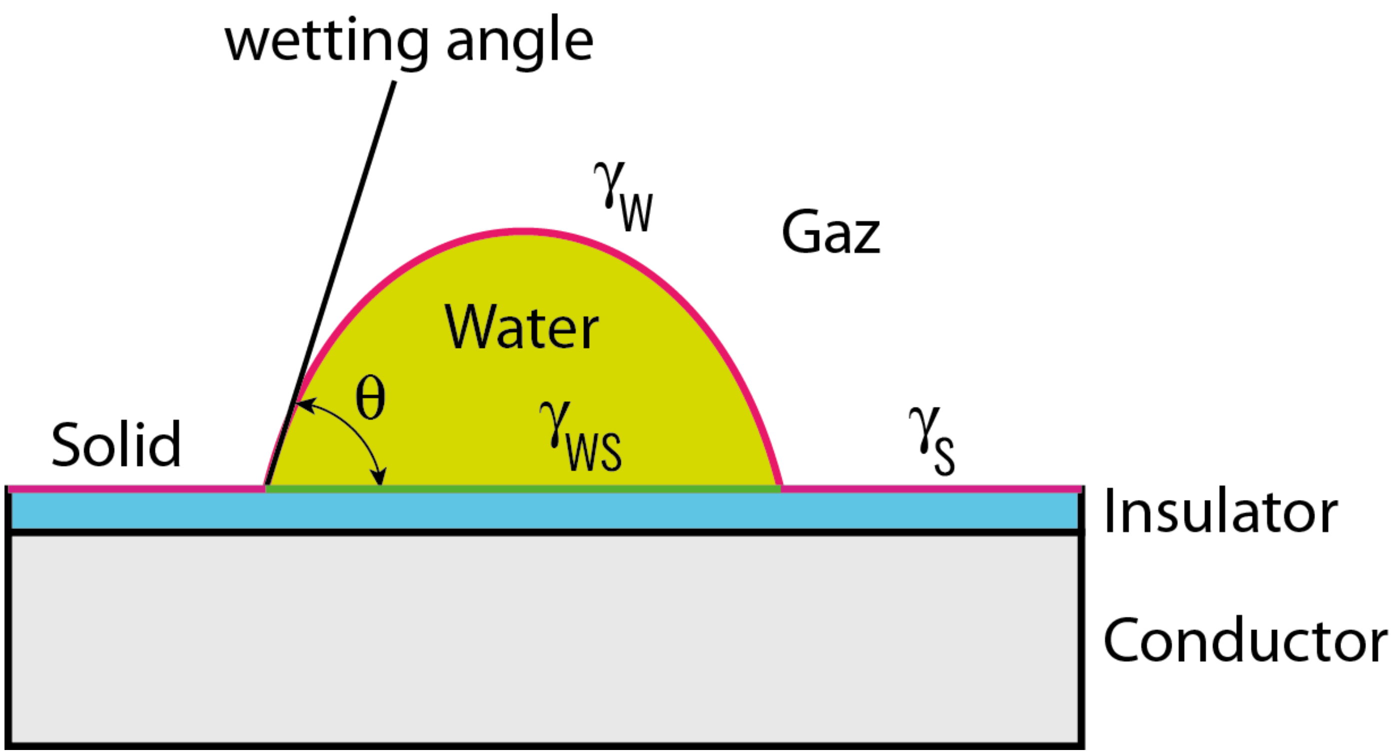
Gabriel LIPPMAN

Jonas Ferdinand Gabriel Lippmann (16 août 1845 - 13 juillet 1921) est un physicien français. Il est lauréat du prix Nobel de physique de 1908 « pour sa méthode de reproduction des couleurs en photographie, basée sur le phénomène d'interférence ». Sa découverte permet la reconstitution intégrale de l'ensemble des longueurs d'onde réfléchies par un objet. (wikipedia)





Electrowetting



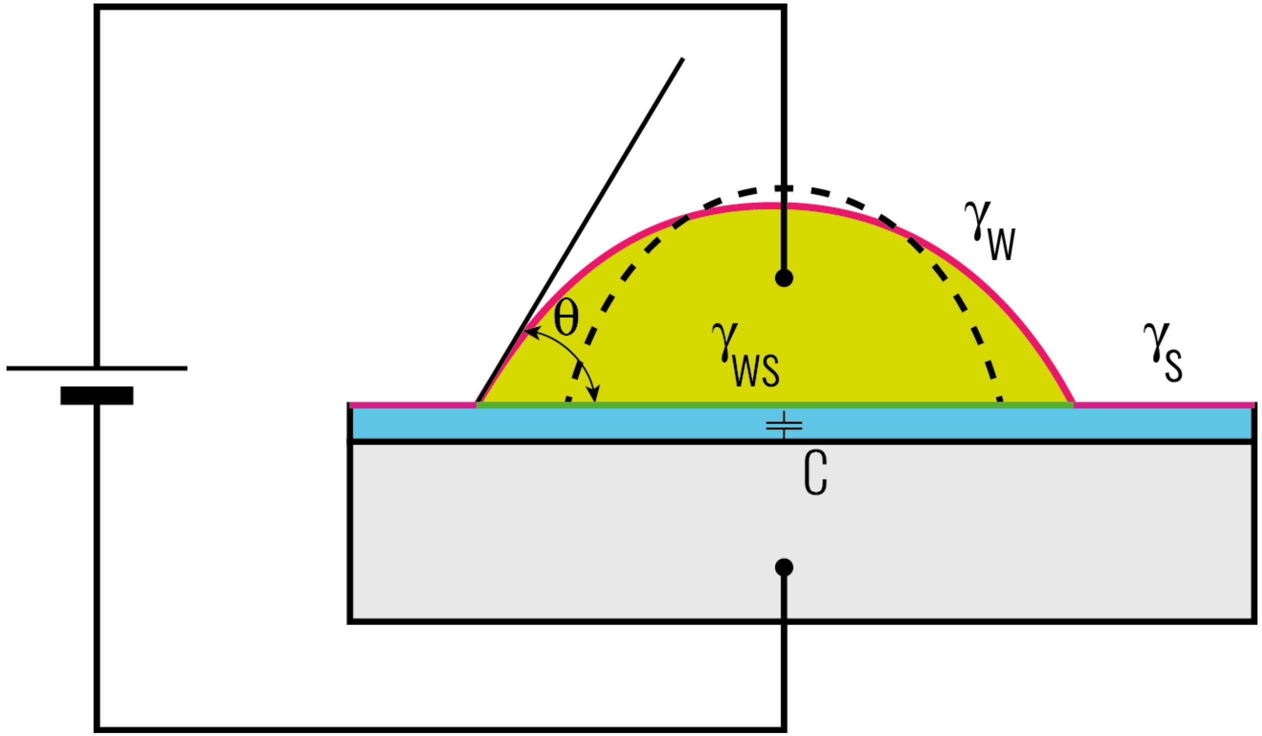
Young-Dupré equation

$$\gamma_{ws} = \gamma_s - \gamma_w \cos(\theta)$$

Electrowetting

Lippman equation

$$\gamma_{ws} = \gamma_{ws} - \frac{CV^2}{2}$$



$$C = \frac{\varepsilon_0 \varepsilon_r S_{SL}}{d}$$

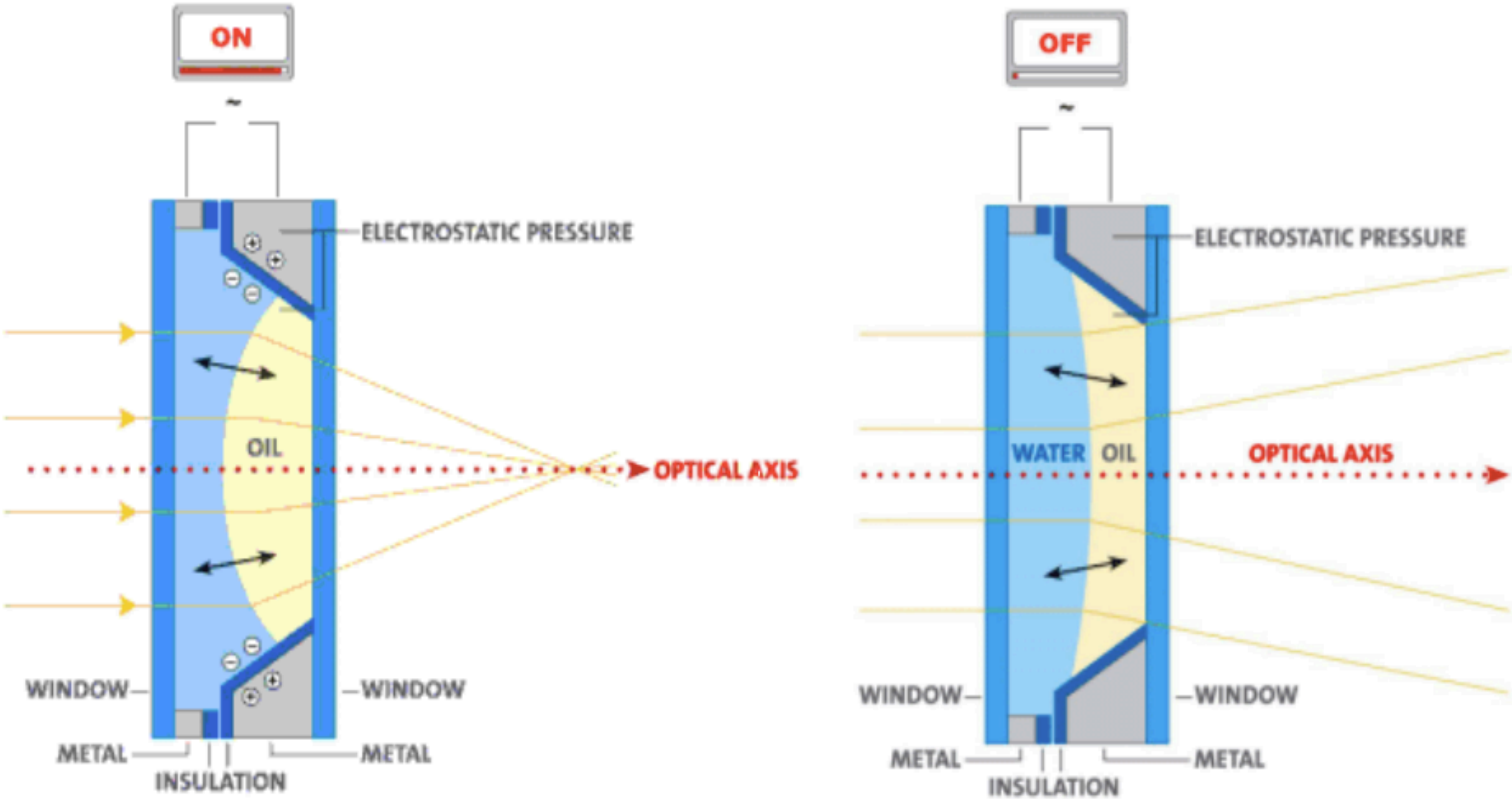
$$\cos(\theta) = \left(\frac{\gamma_s - \gamma_{ws}^0 + \frac{CV^2}{2}}{\gamma_w} \right)$$

When voltage increases the wetting angle decreases, the droplet smashes

There is a saturation regime

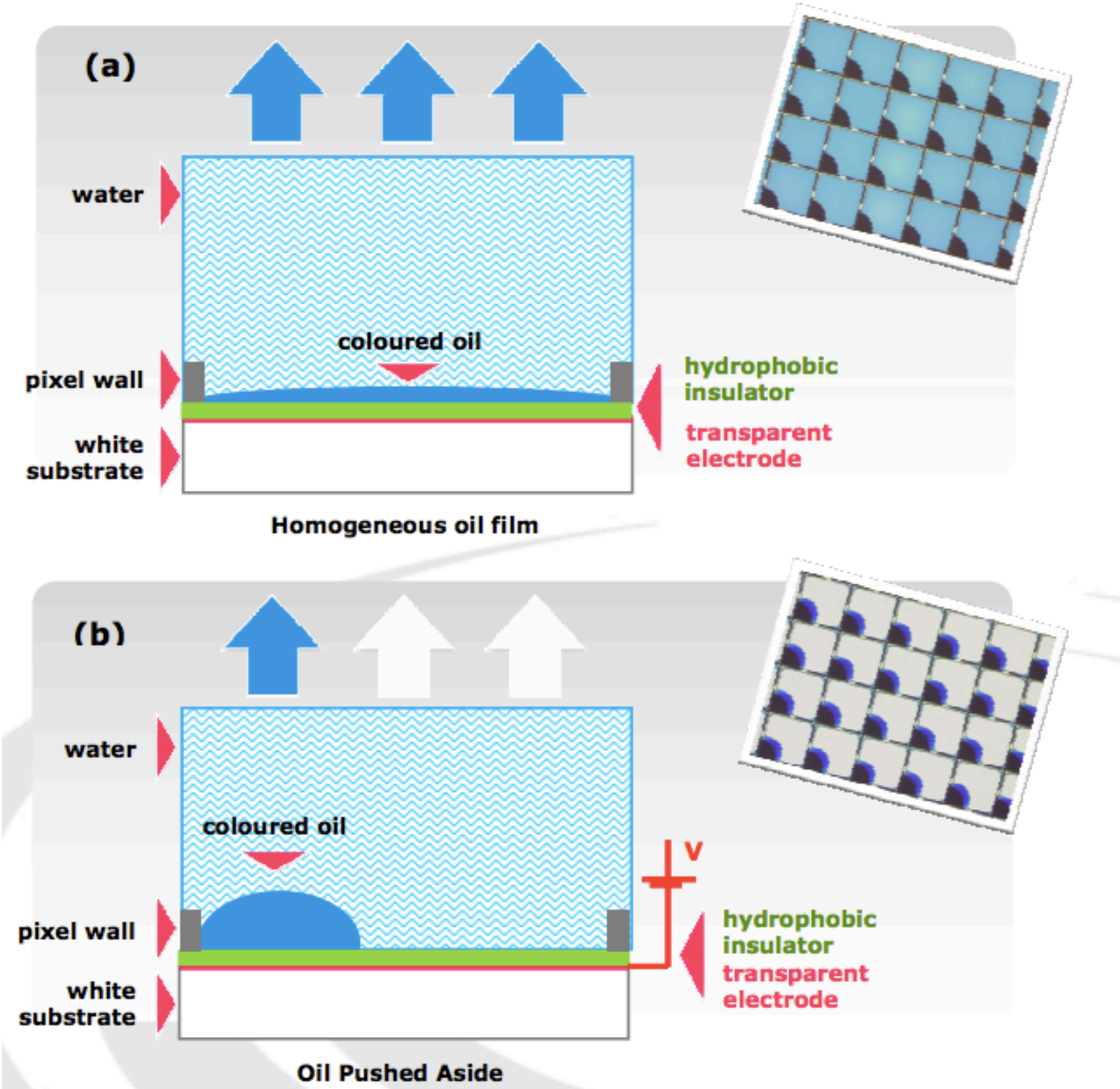
Electrowetting

Application : variable focus lenses



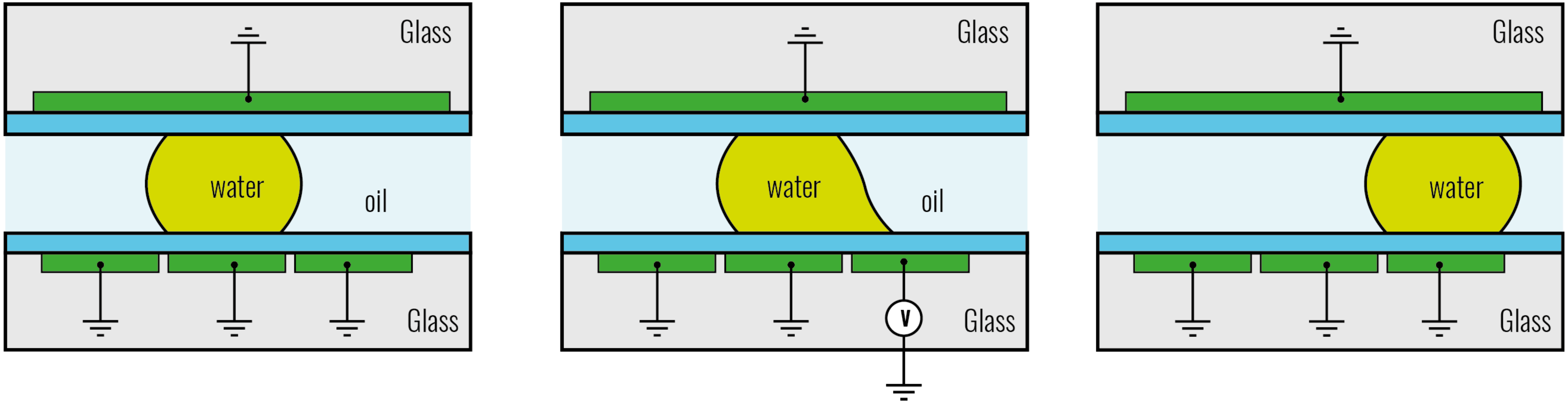
Electrowetting

Application : flat screens



Electrowetting

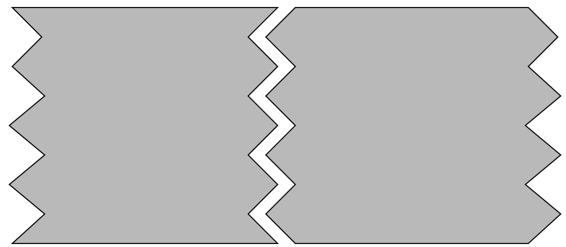
How to move a droplet ?



To avoid evaporation : droplet caught between glass blades + oil encapsulation

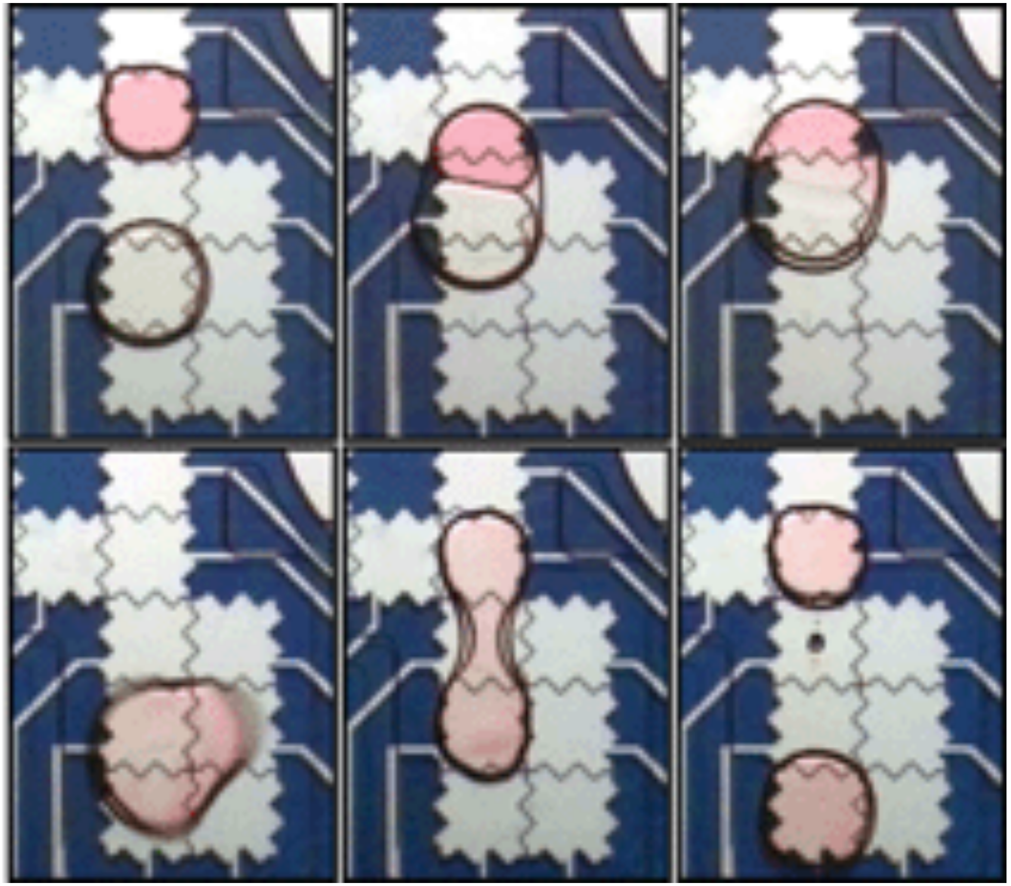
Contact angle modification near one cell border -> global movement of the droplet from one cell to another

! Requires overlapping electrodes



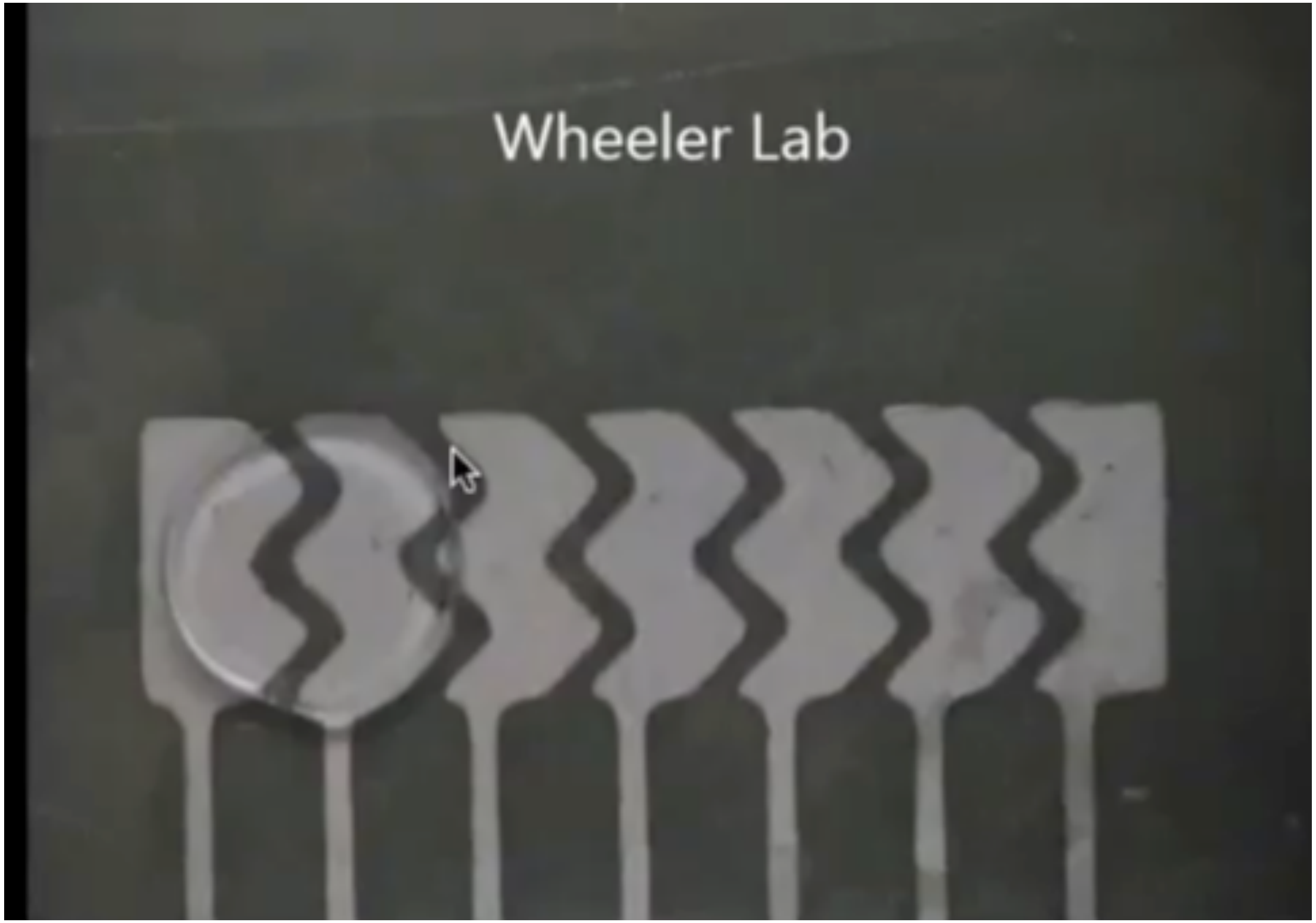
Electrowetting

How to move a droplet ?

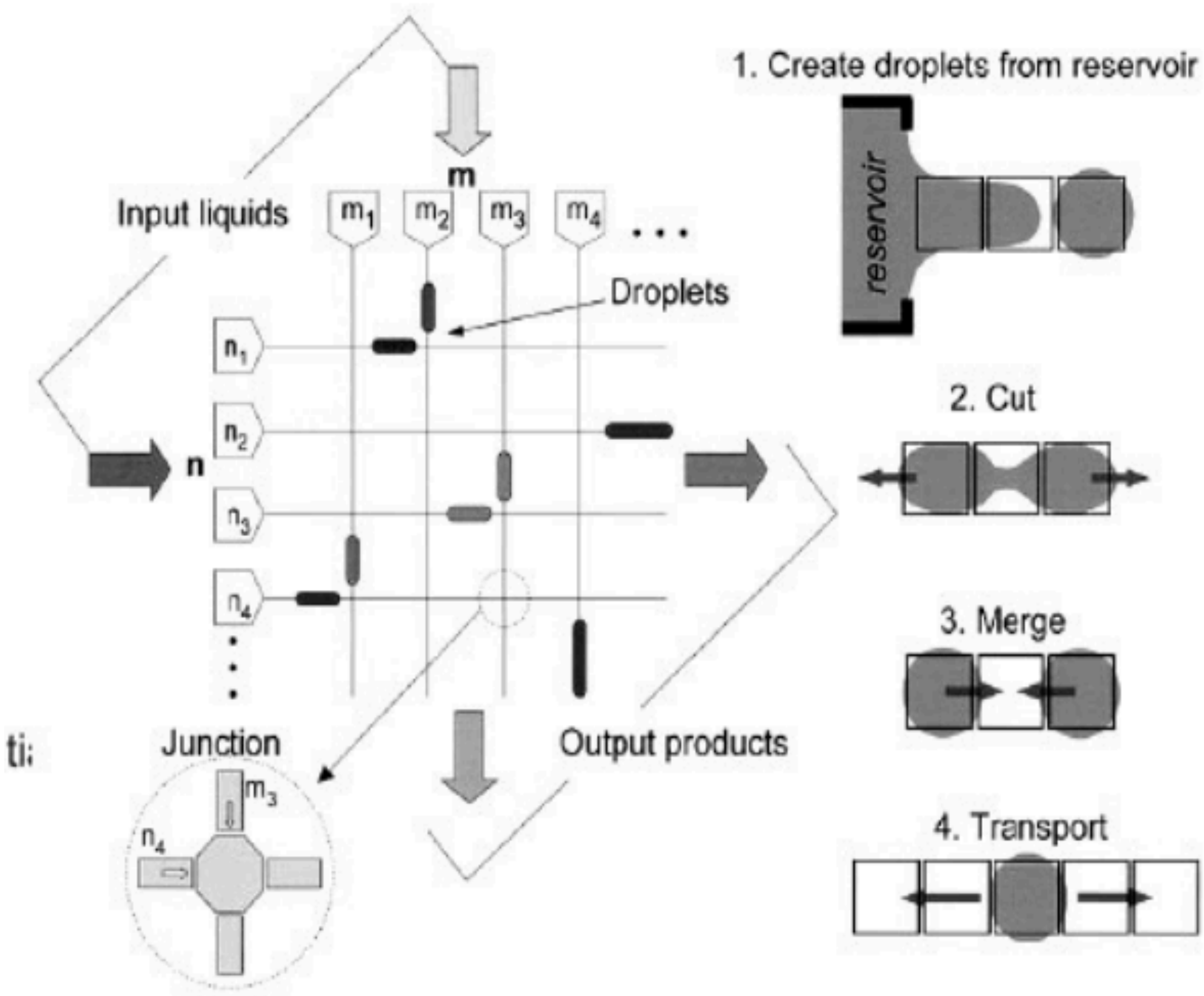


Electrowetting

How to move a droplet?

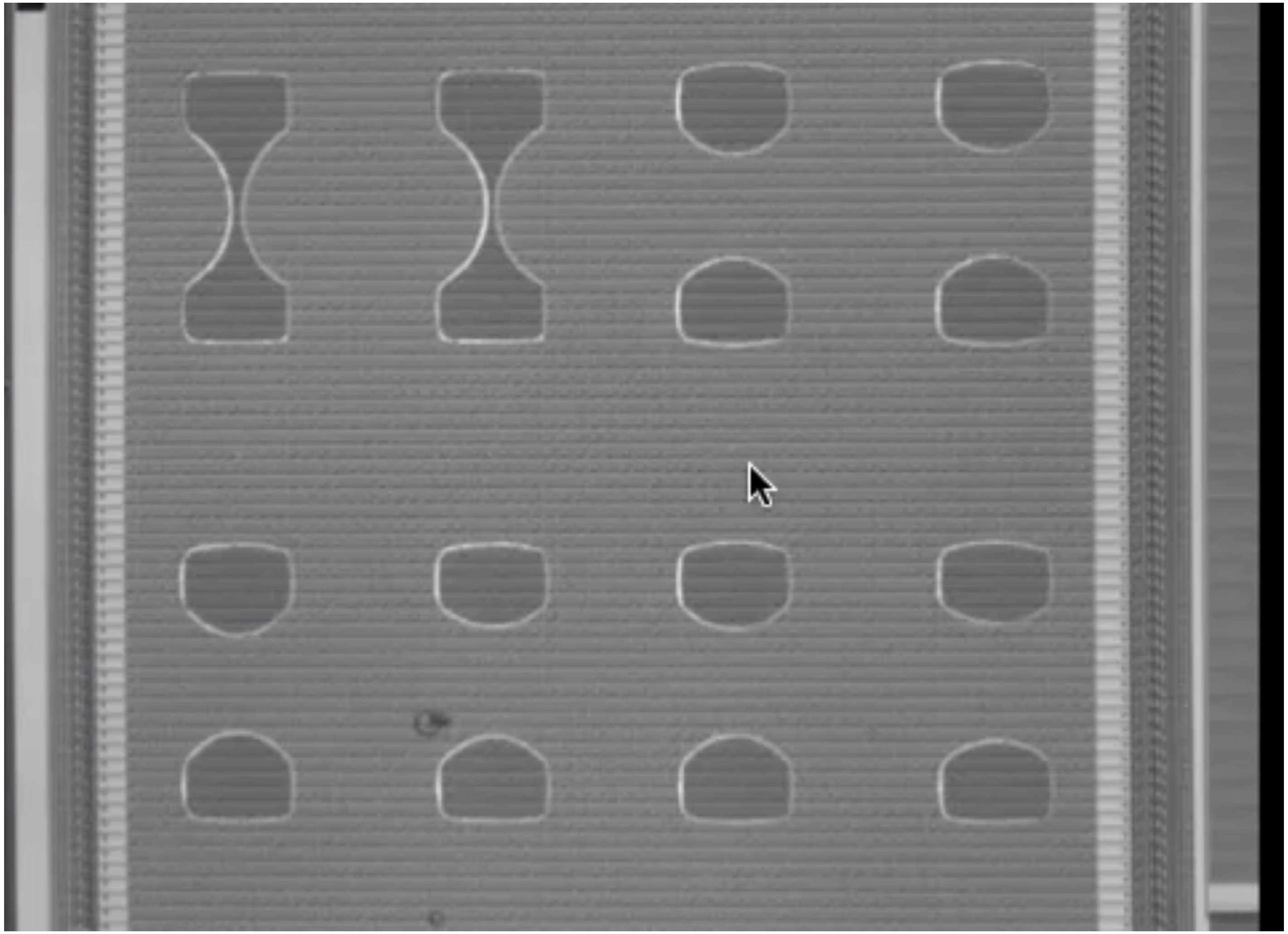


Electrowetting

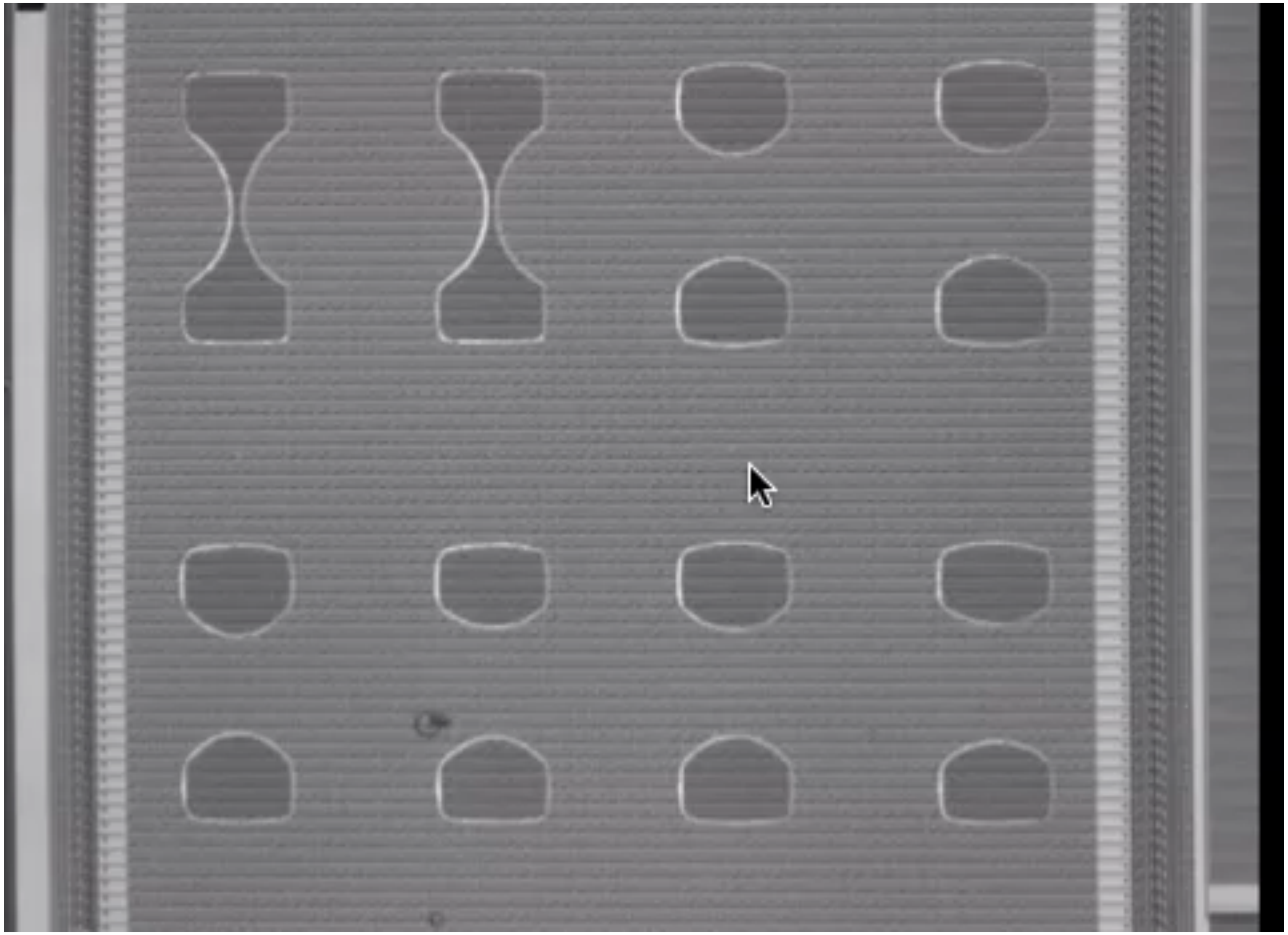


Electrowetting

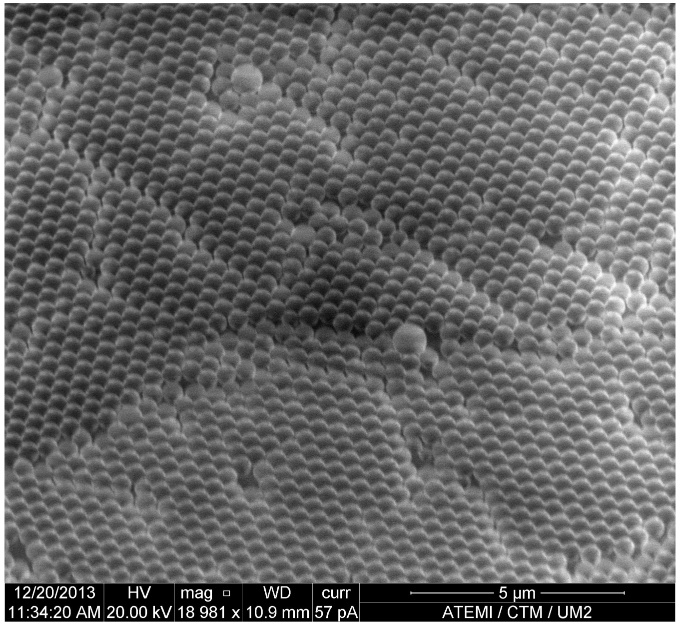
Electrowetting

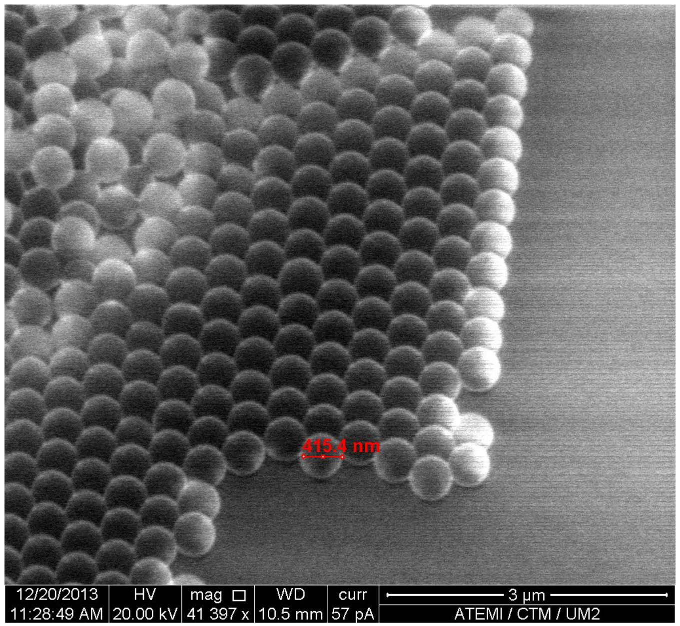


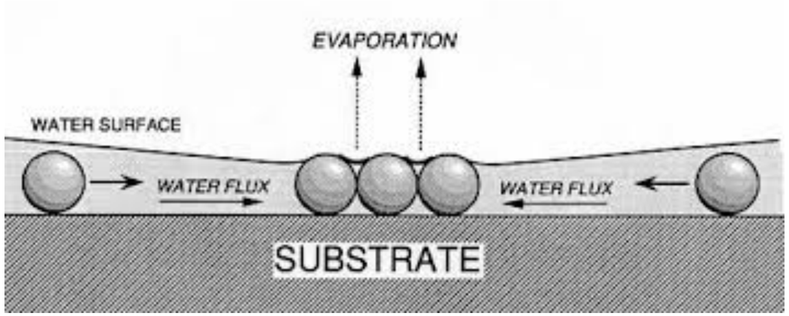
Electrowetting

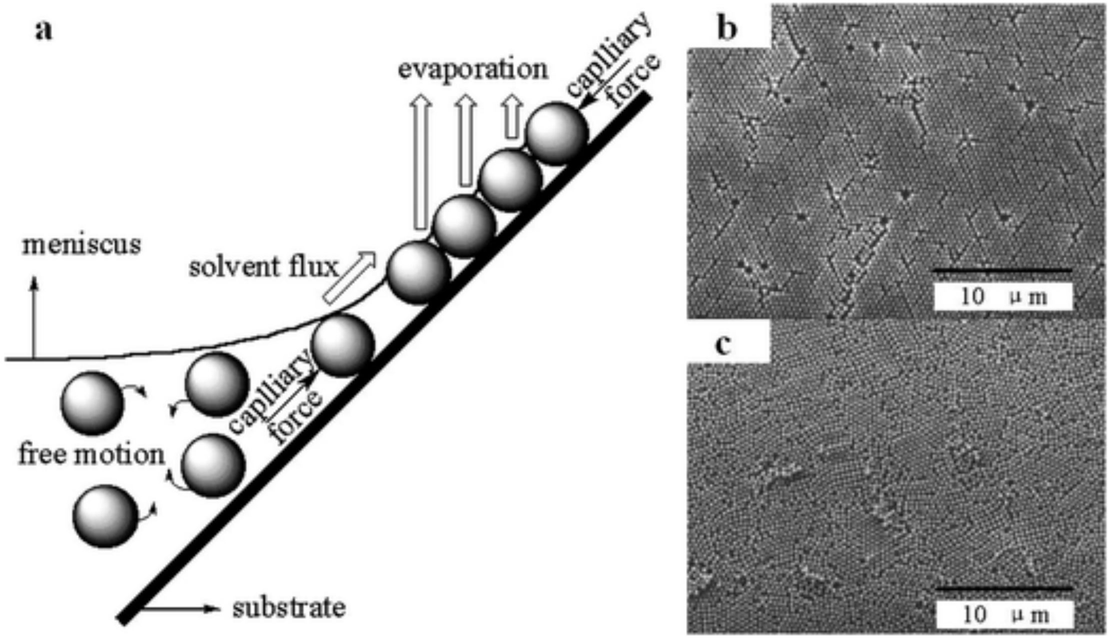


Capillary Force Assembly



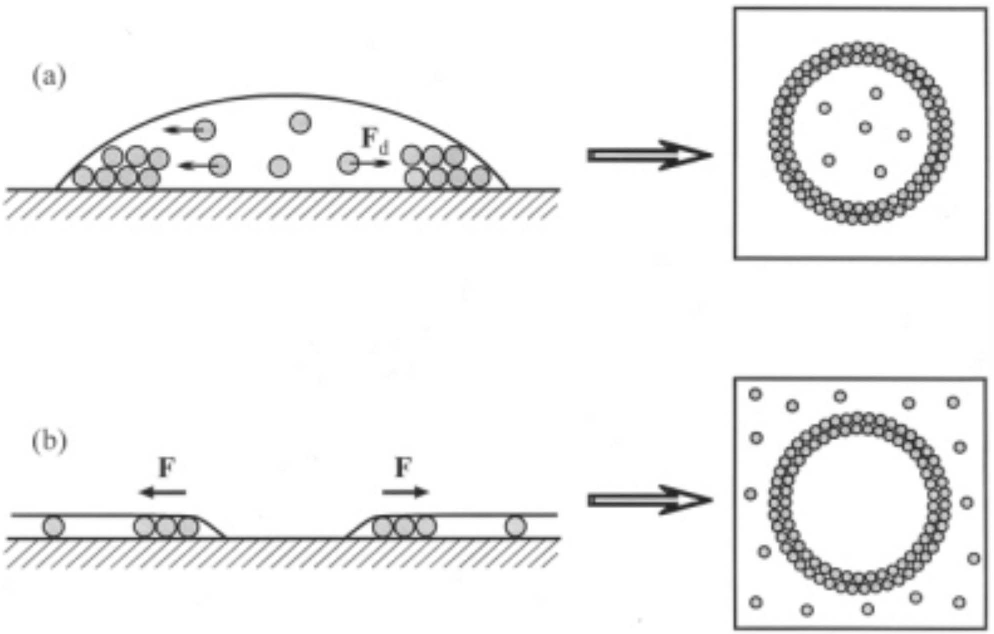


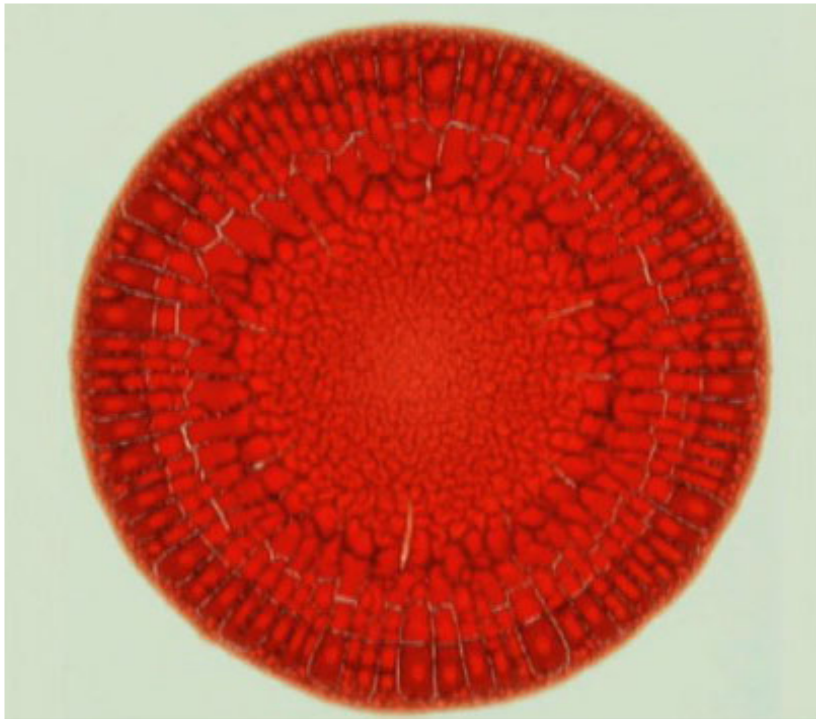




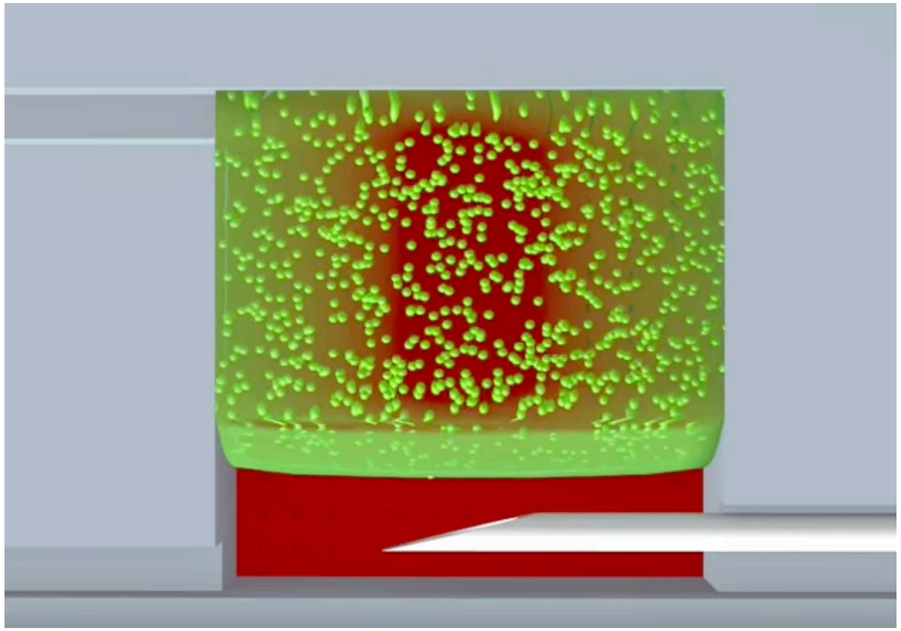
Capillary Force Assembly

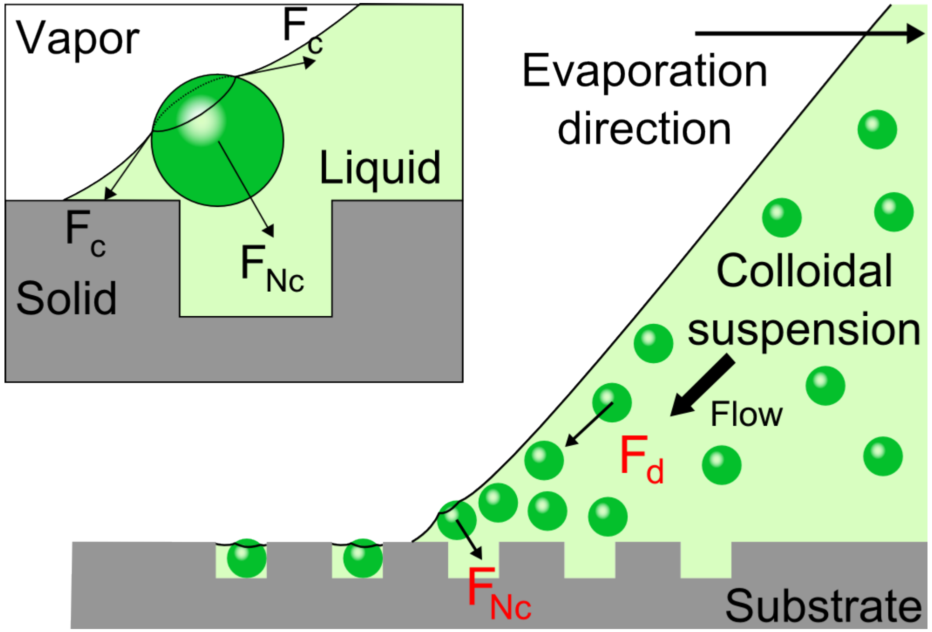
Capillary force assembly : interactions between particles mediated by fluid interfaces.





Capillary Force Assembly

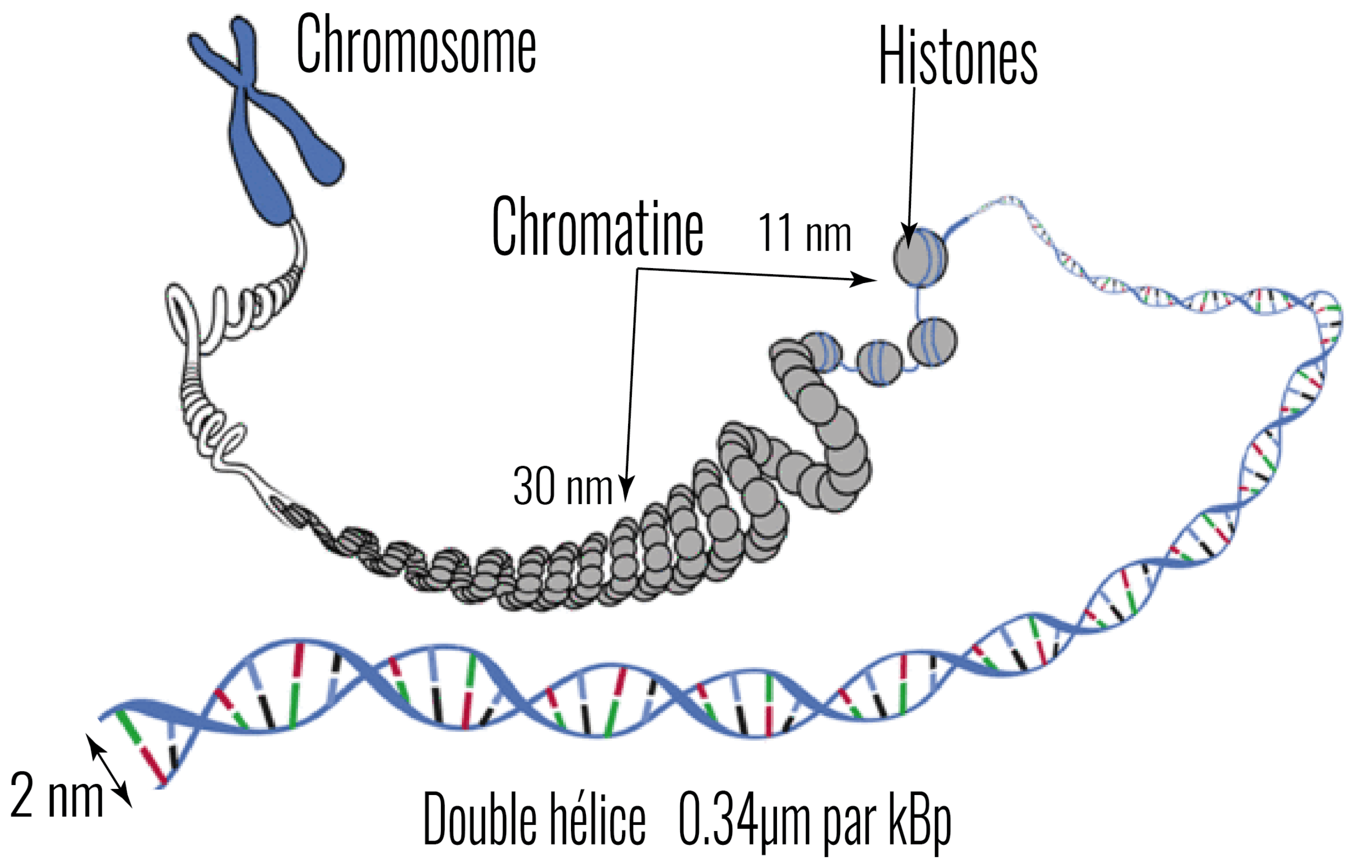




D.Peyrade, LTM

Capillary Force Assembly : DNA Combing

→ DNA organisation



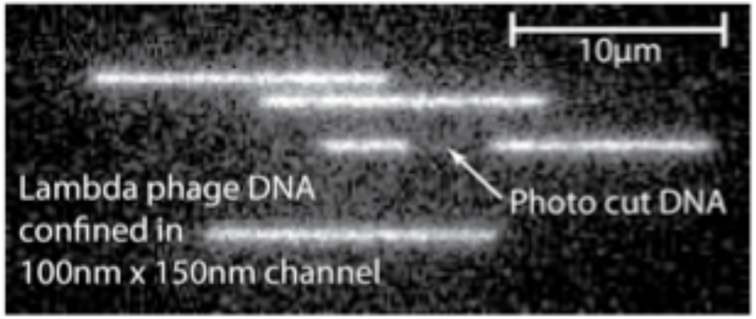
Persistance length: 100 nm for dsDNA and 2 nm for ssDNA

In solution : Pellets, Coiling

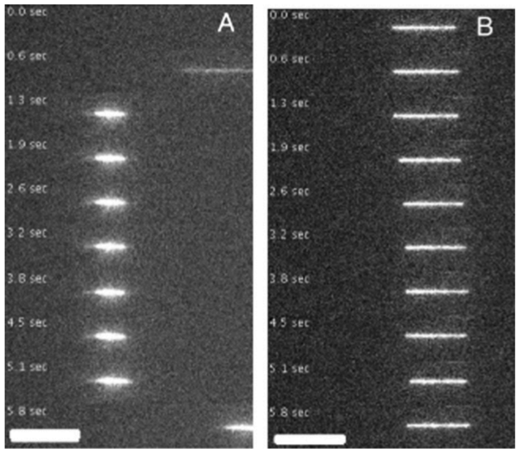
Capillary Force Assembly : DNA Combing

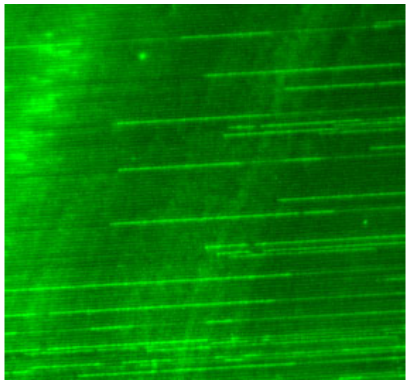
How to uncoil DNA ?

➔ Nanofluidic containment



F. Westerlund, Chalmers

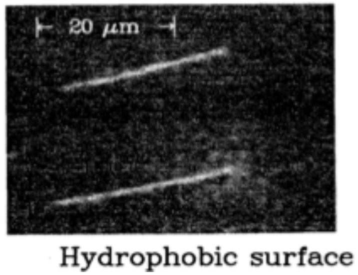




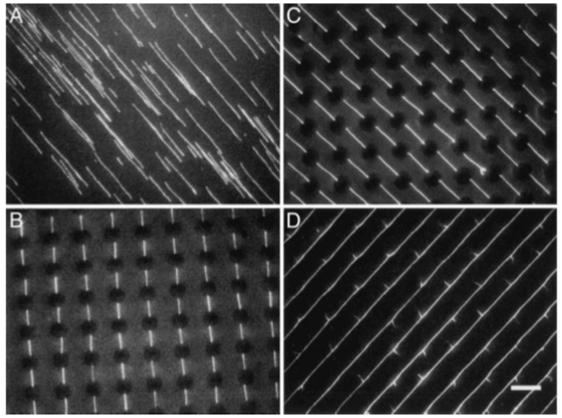
D.E.Streng; North Carolina

state Univ.

➔ Deposition by dewetting

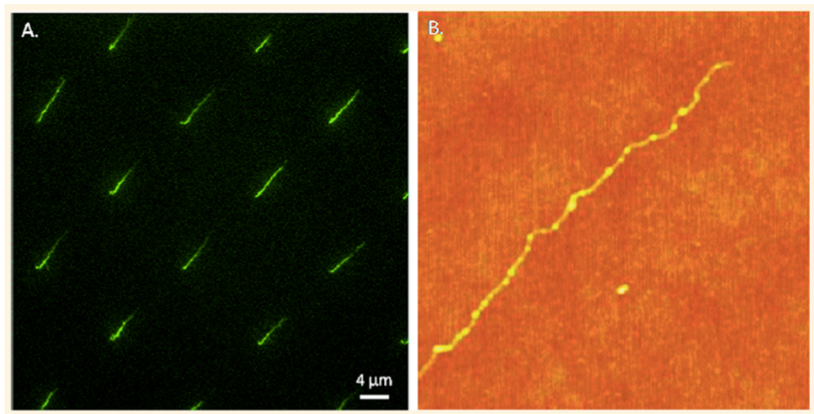


D.Bensimon, ENS



J. Guan and L. J.Lee Ohio

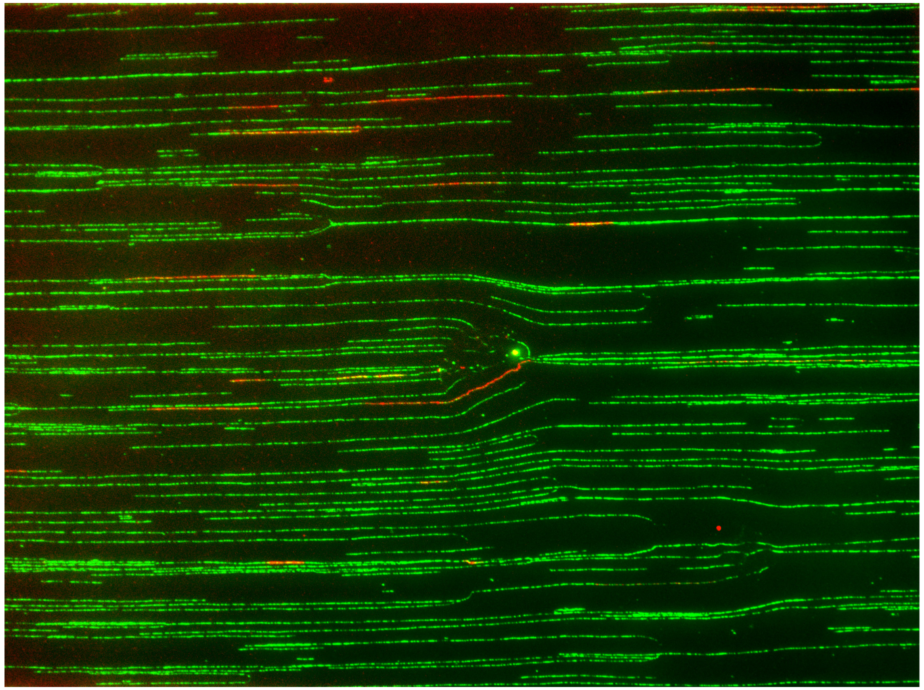
State University

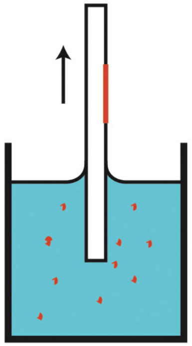


A.Cerf, LAAS CNRS

Capillary Force Assembly : DNA Combing

The standard DNA combing technique used everyday at IGMM





Human genomic DNA, YOYO tagged, 237 x 177 µm image

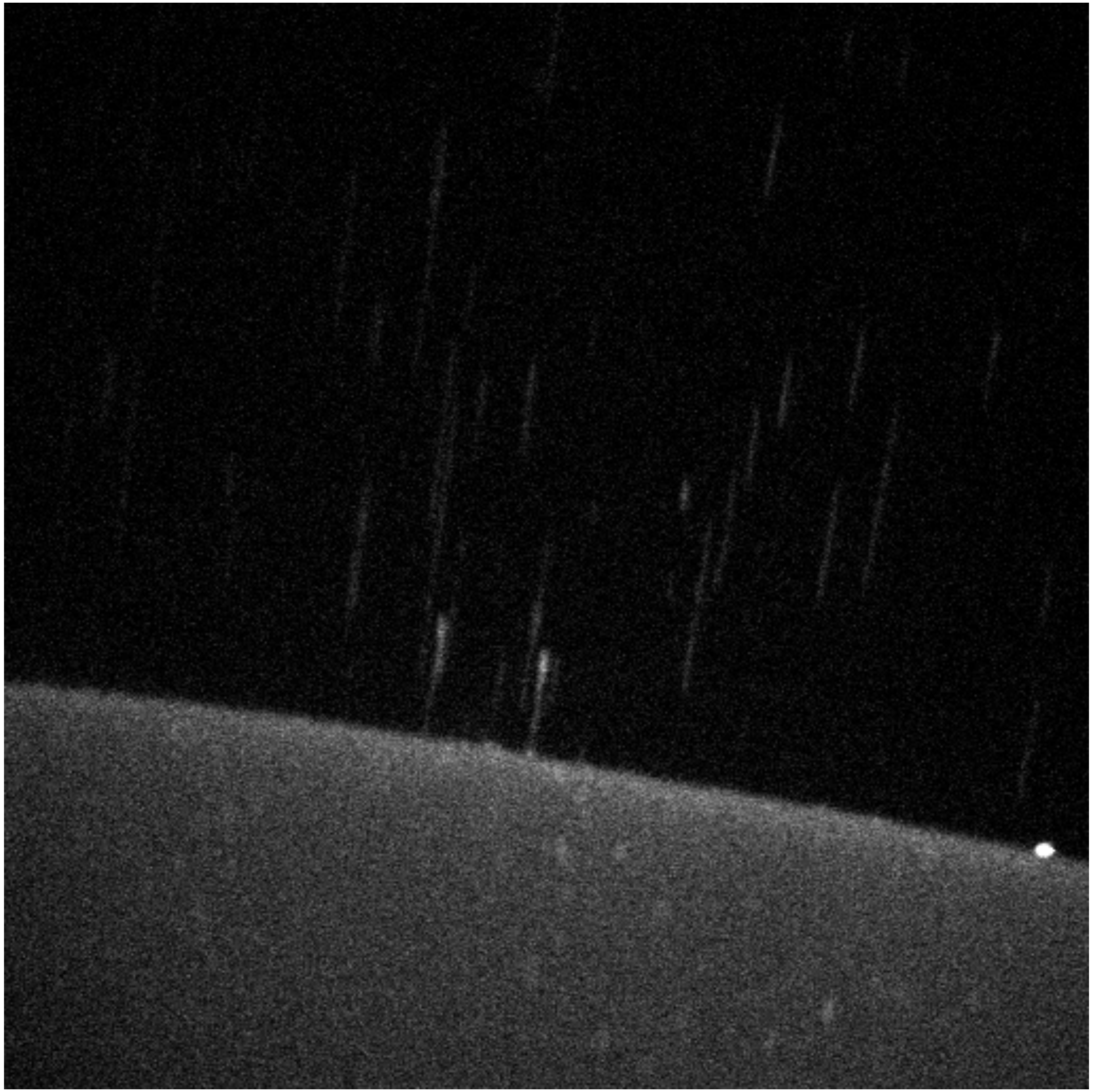
Substrate Silanization

DNA ends anchoring at pH 5,4

Slow dewetting

Capillary Force Assembly : DNA Combing

Combing of Genomic DNA from Droplets Containing Picograms of Material
Jochem Deen, Wouter Sempels, Raf De Dier, Jan Vermant, Peter Dedecker, Johan Hofkens, and Robert K. Neely
ACS Nano 2015 9 (1), 809-816
DOI: 10.1021/nn5063497



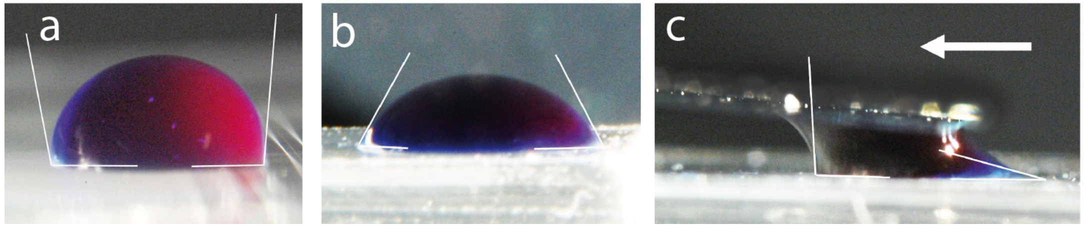
Capillary Force Assembly : DNA Combing

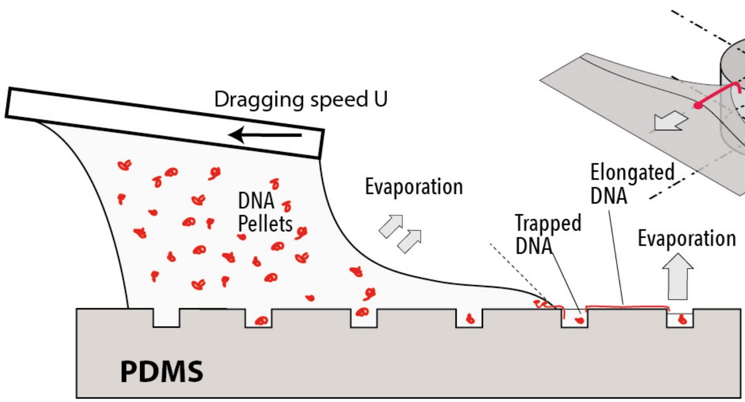
Ordered deposition

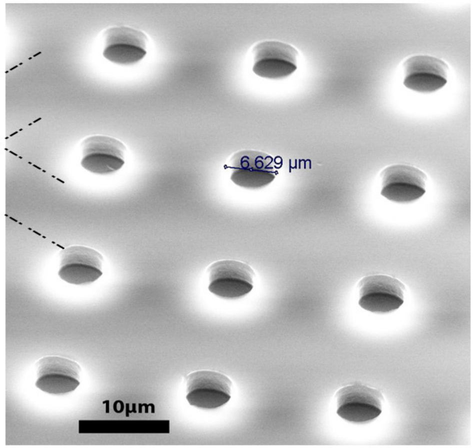
Forced dewetting on perturbations

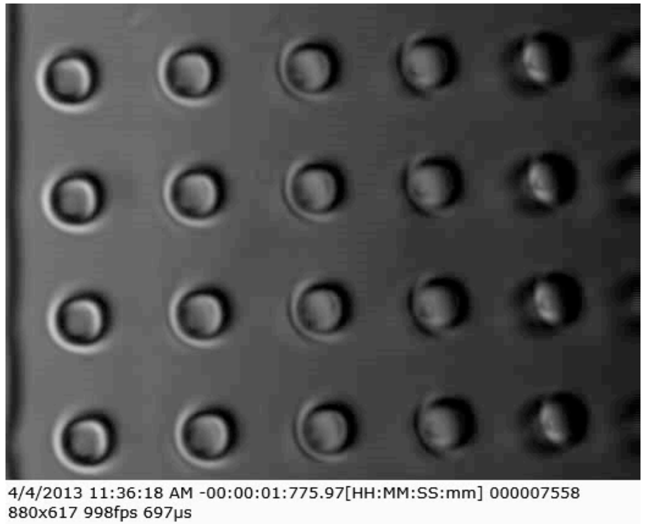
PDMS substrate

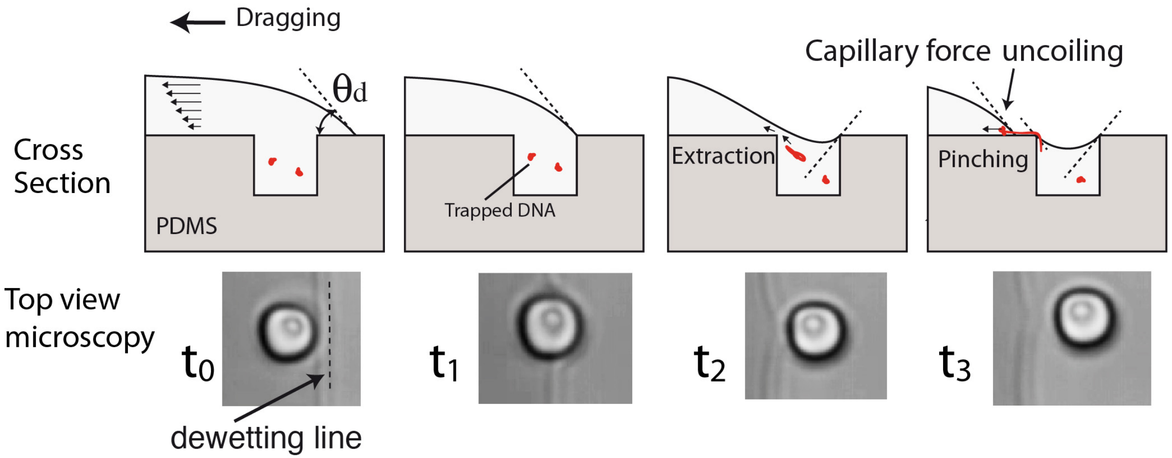
No functionalization



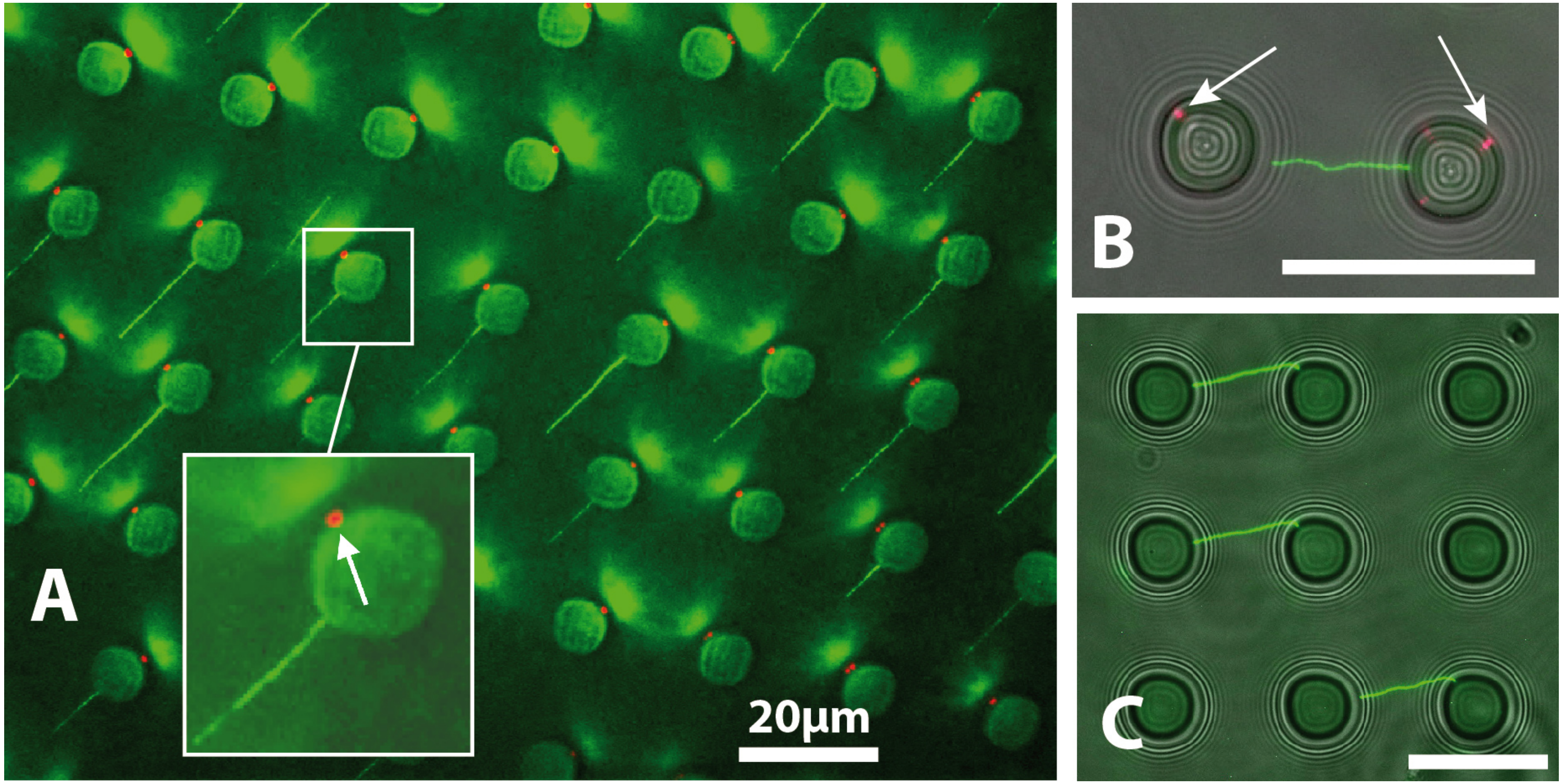








Capillary Force Assembly : DNA Combing



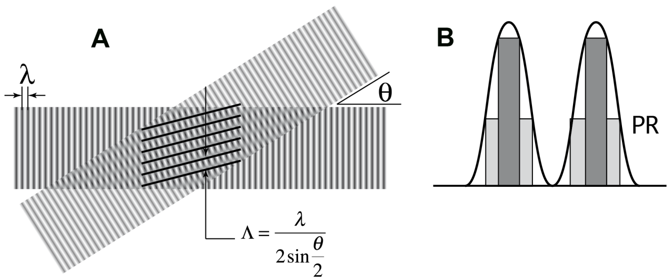
composite Image (GFP Fluorescence + transmited light) of λ phage DNA (48kbp) tagged with YOYO intercalating dye. Dewetting 400µm/s. Red: uncoiled DNA pellets, 5µm below surface

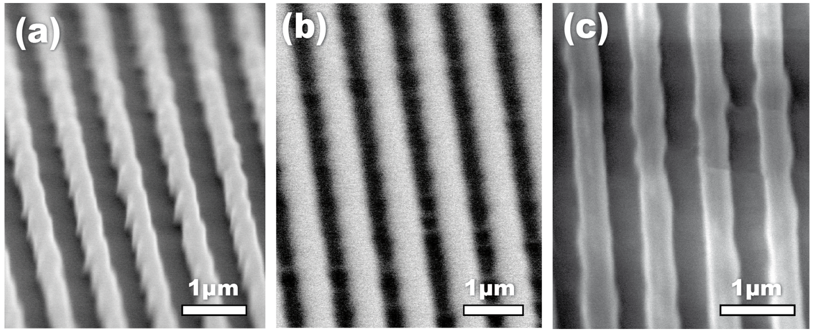
B. Charlot, et al. "Elongated unique DNA strand deposition on microstructured substrate by receding meniscus assembly and capillary force", Biomicrofluidics 8, 014103 (2014).

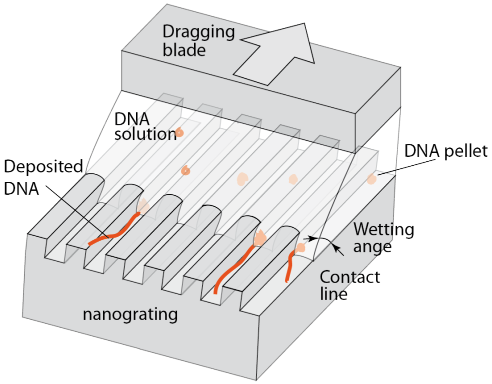
Capillary Force Assembly : DNA Combing

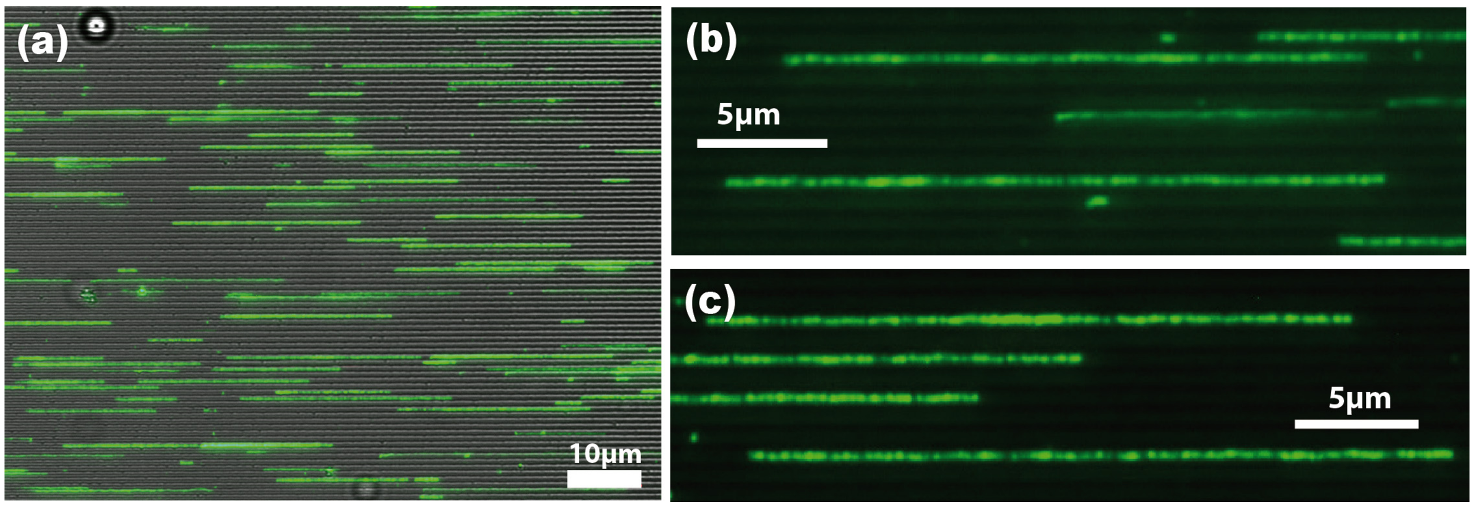
Combing on nanogratings : rectilinear conformation

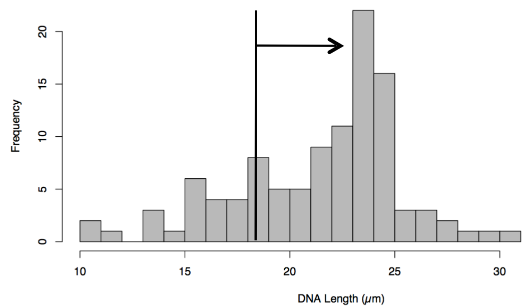
800nm pitch nanogratings : Interference lithography











Stretching ratio 150%

B.Charlot, R.Teissier, M.Drac, E.Schwob, "DNA on rails: Combing DNA fibers on nanogratings", **Applied Physics Letters**, 105, 243701 (2014).