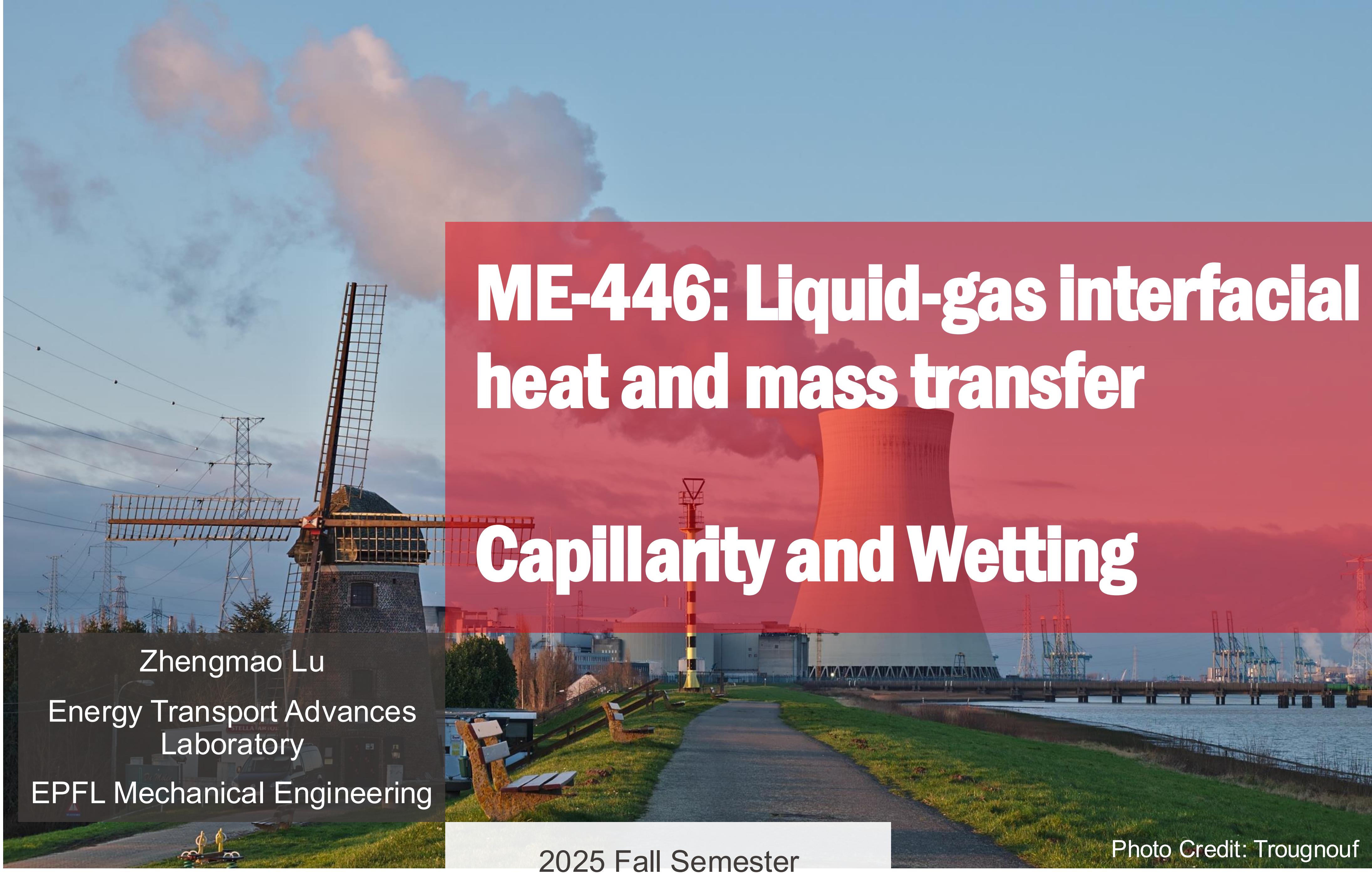


Photo Credit: Trougnouf

EPFL

ETA-Lab
Energy Transport Advances

ME-446: Liquid-gas interfacial heat and mass transfer

Capillarity and Wetting

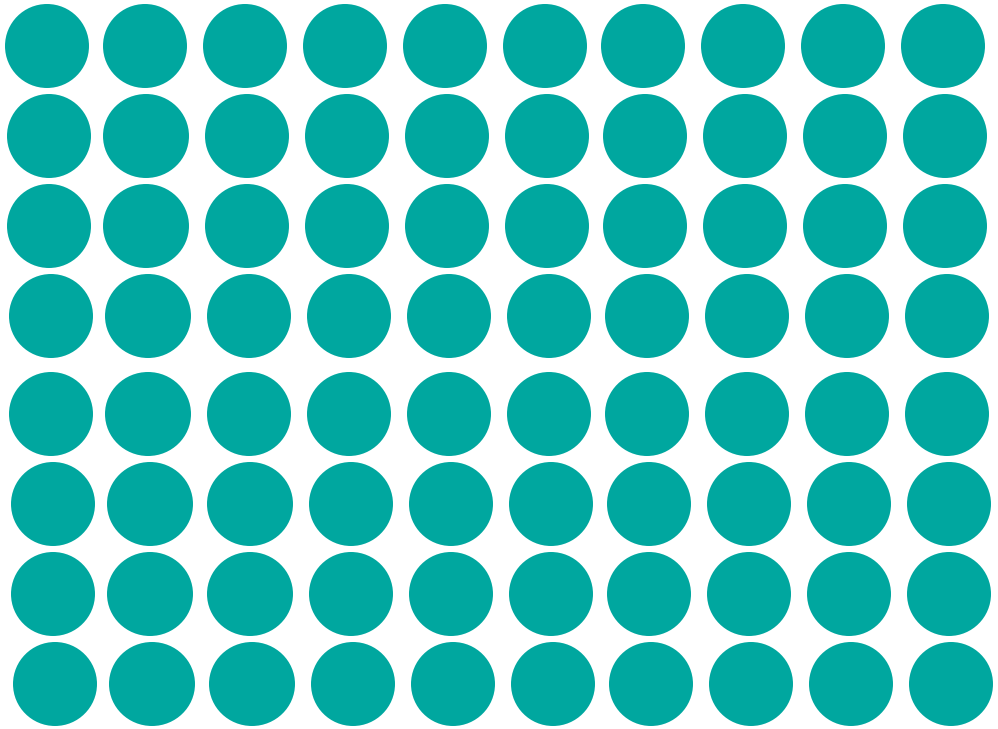
Zhengmao Lu

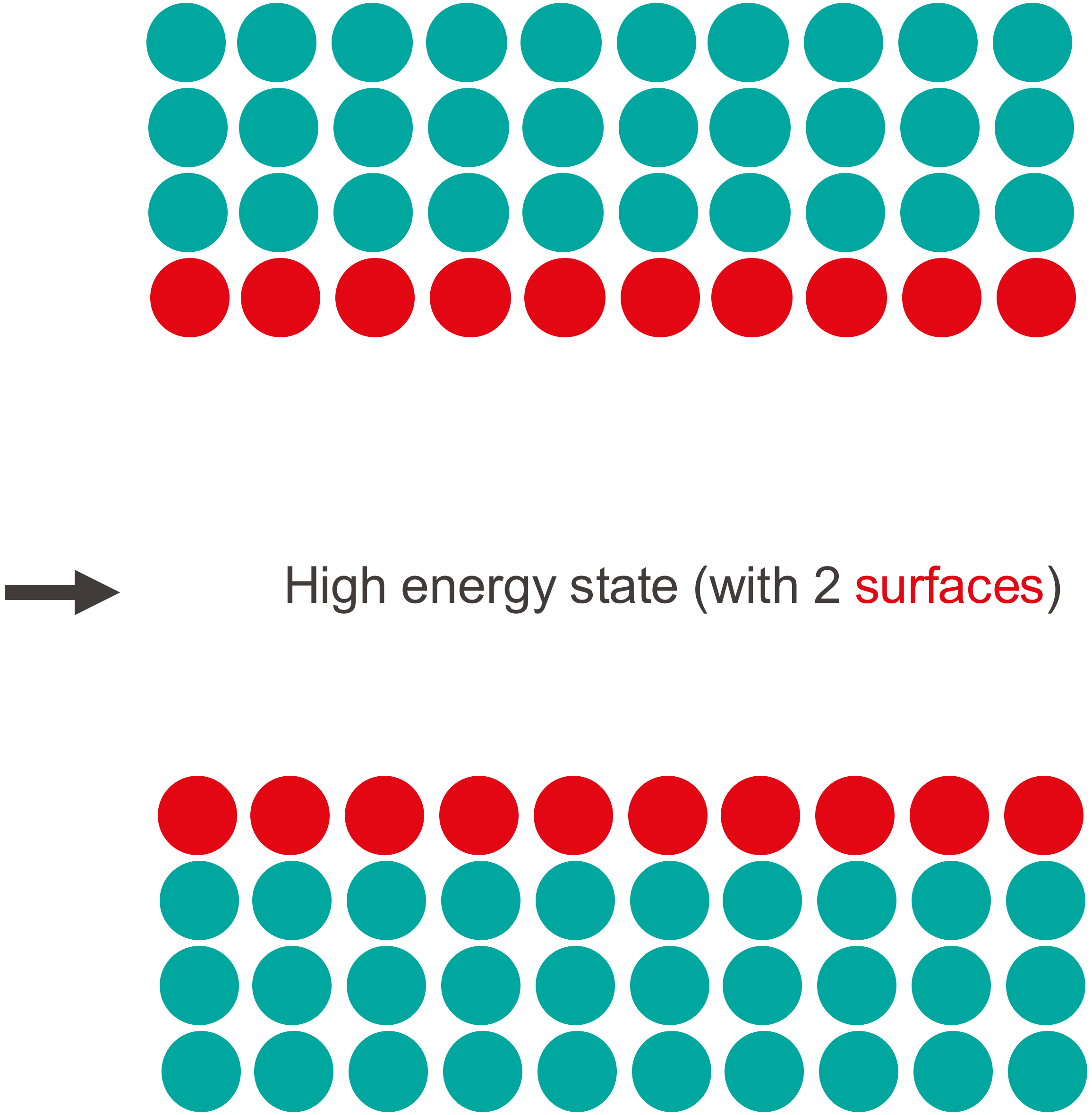
Energy Transport Advances Laboratory

EPFL Mechanical Engineering

2025 Fall Semester

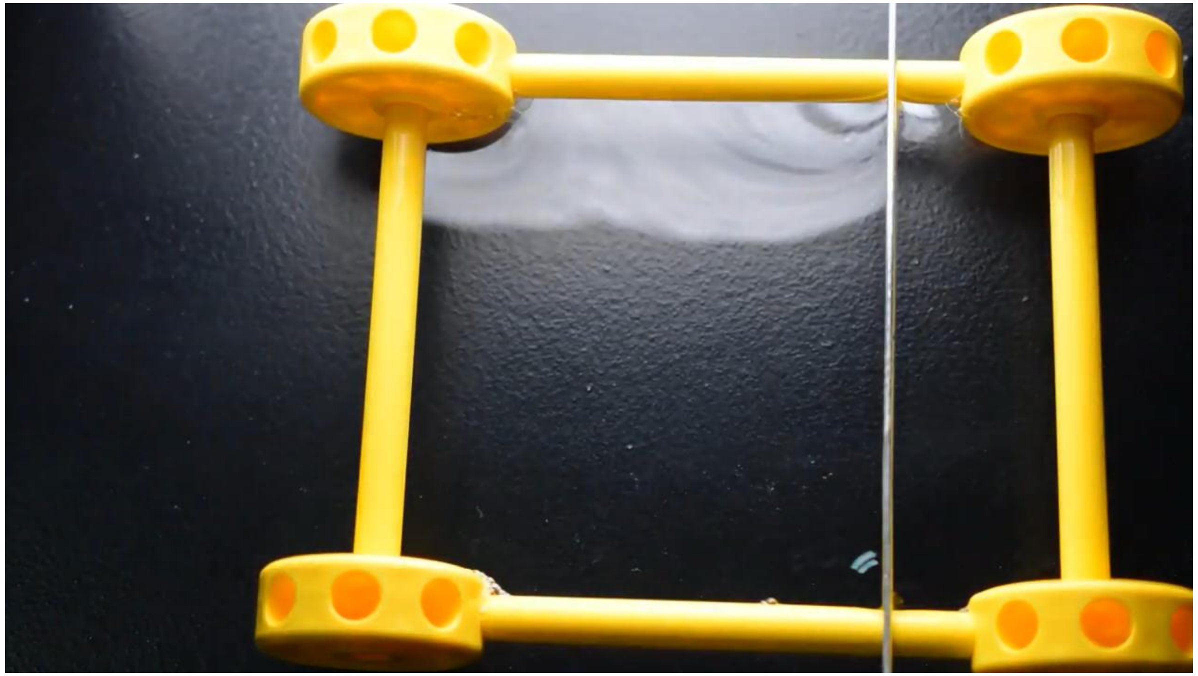
Surface Energy (J/m^2)





Work needed to create surfaces

Surface Tension (N/m)



PD, CC BY-SA 3.0

Surface exerting line forces on objects

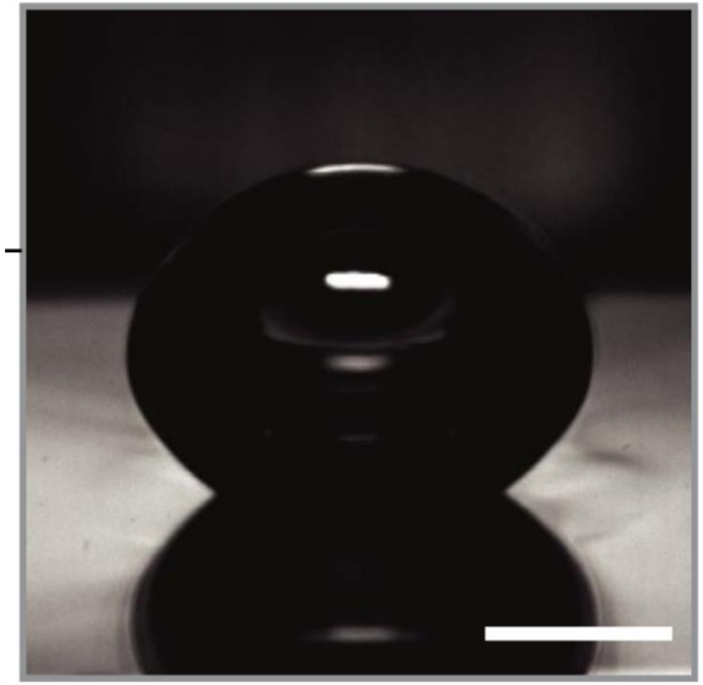
Young-Laplace Equation

ILOs Today

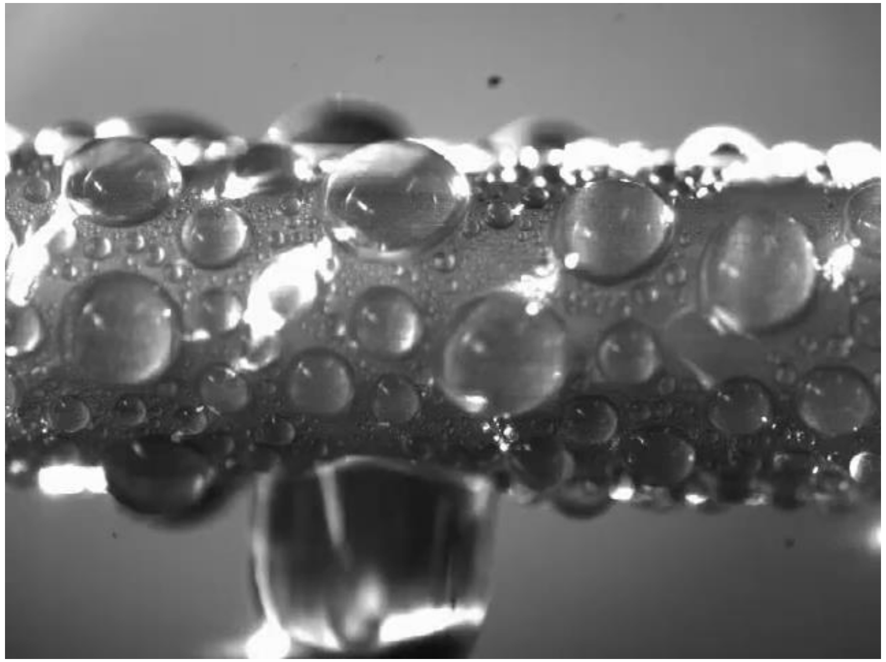
- Explain **the concept of contact angle**
- Evaluate **the effect of surface tension on contact angle**
- Explain **contact angle hysteresis**
- Analyze **wetting on rough surfaces**

Reading materials: **Carey** Chapter 3

Why We Care About Liquid-Solid Contact



Dhillon *et al.*, *Nat Commun* 2015



Miljkovic *et al.*, *Nano Lett.* (2013)

Contact Angle: Force Balance Perspective

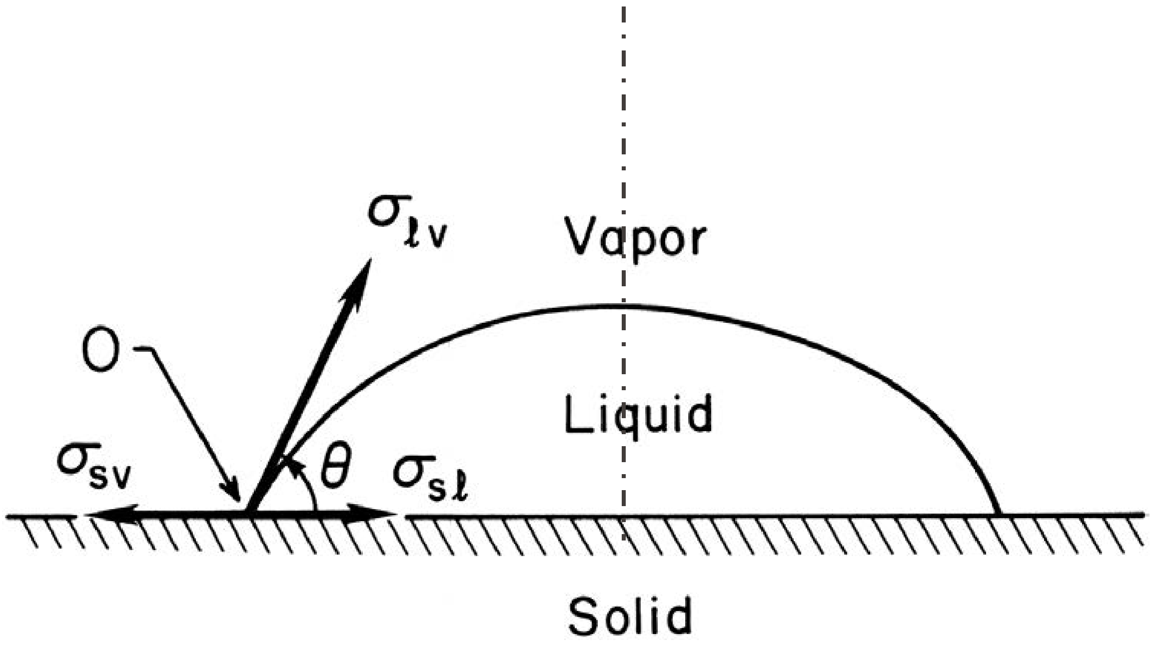


Figure 3.1 in Carey

Young's Equation

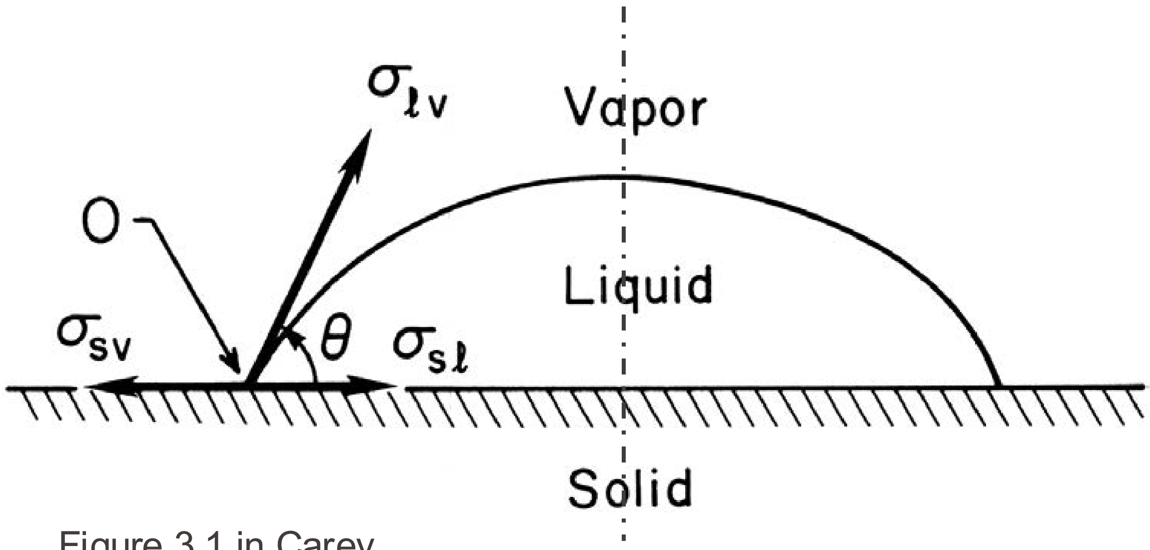
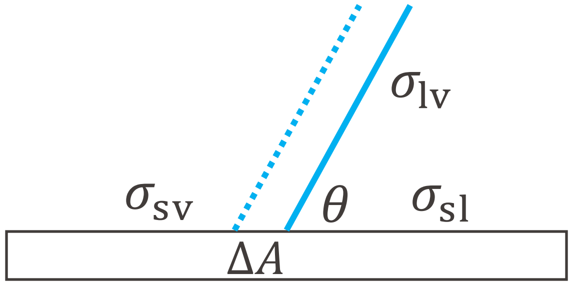


Figure 3.1 in Carey

An energy perspective



Wettability

- Hydrophilic surface (wetting)
- Hydrophobic surface (non-wetting)

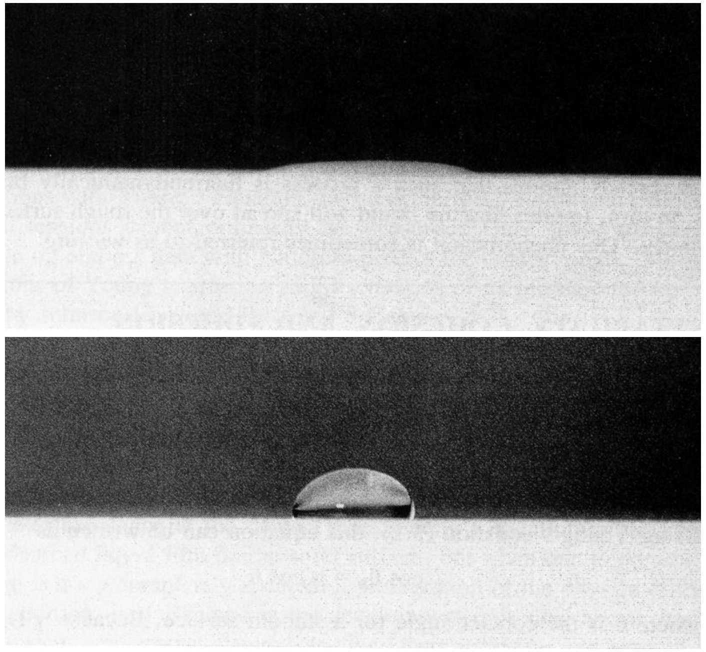


Figure 3.3 in Carey

Capillary Rise/Fall

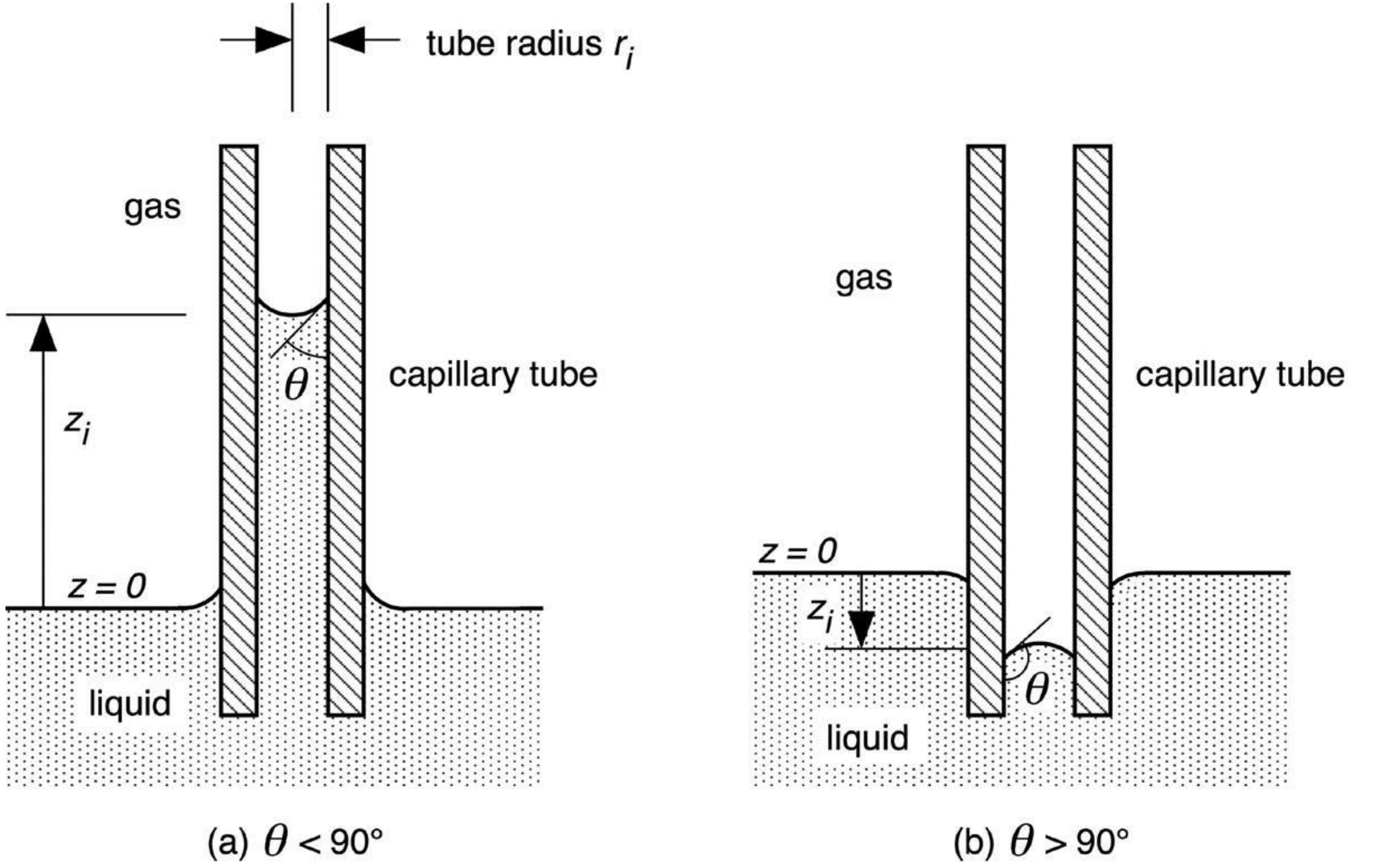
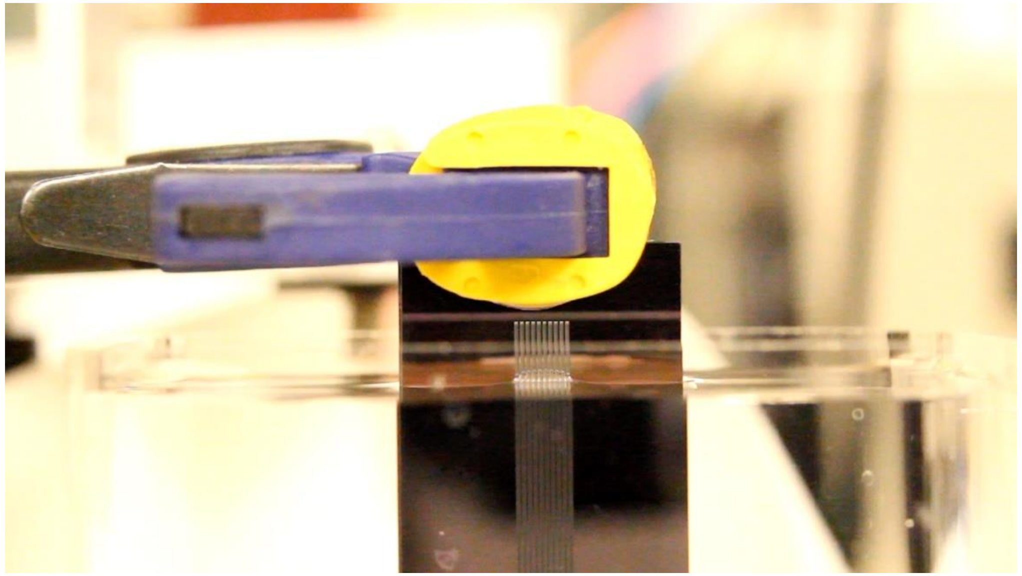
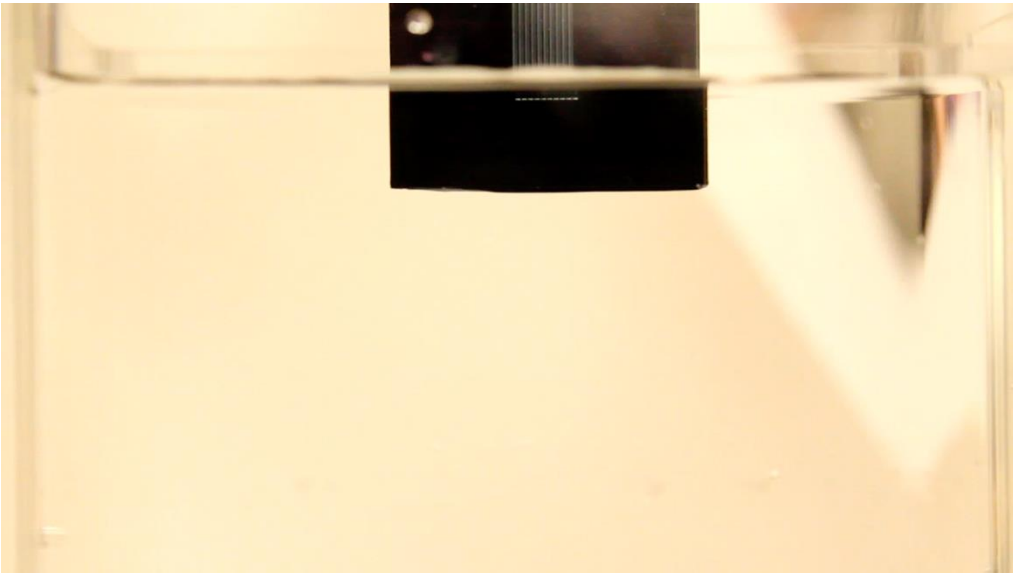


Figure 3.14 in Carey

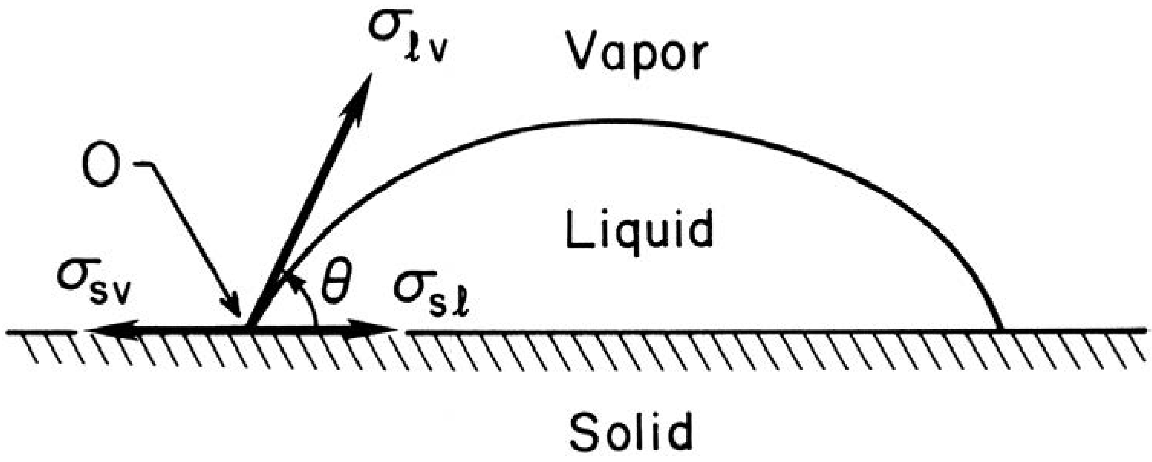
Capillary Rise/Fall





Adv. Mater. Interfaces 2023, 10, 2201967

Extreme Cases



$$\cos\theta = \frac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}}$$

What if $(\sigma_{sv} - \sigma_{sl})/\sigma_{lv} < -1$?

What if $(\sigma_{sv} - \sigma_{sl})/\sigma_{lv} > 1$?

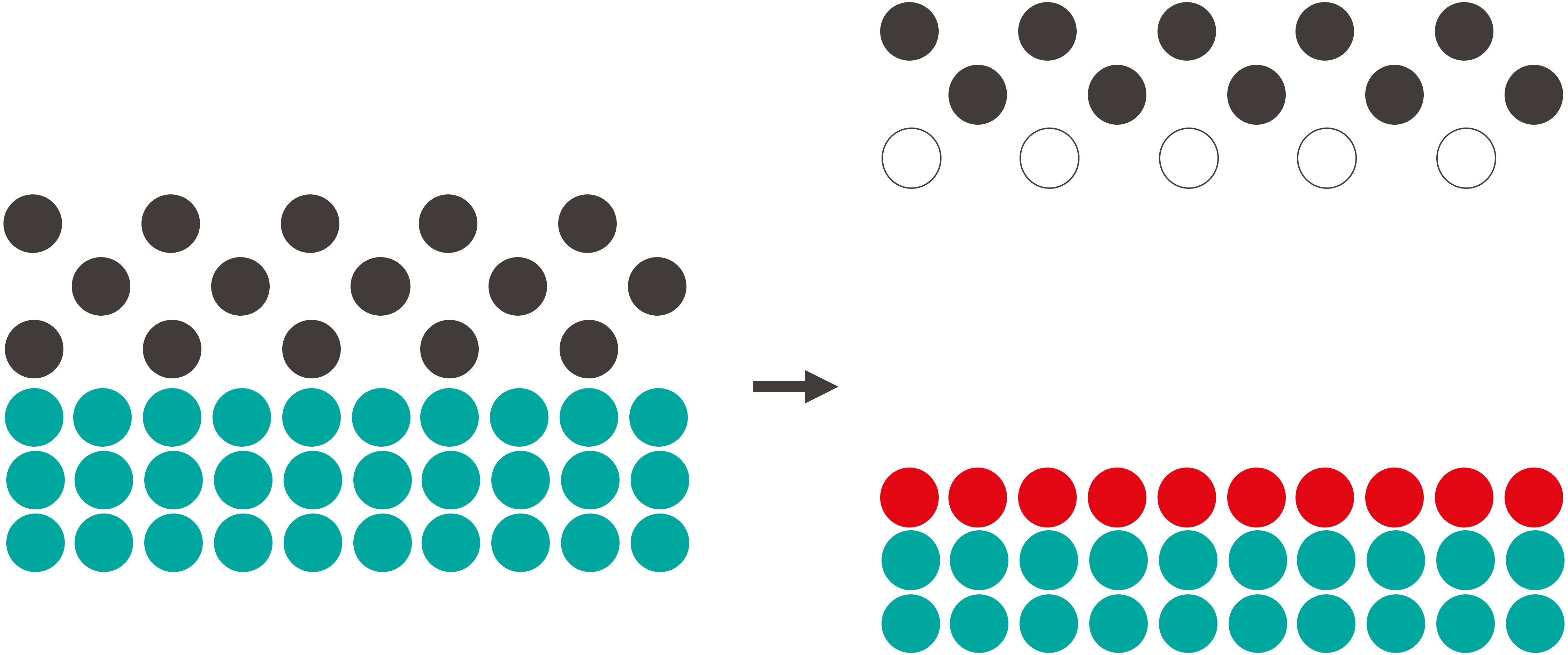
Surface Energy and Contact Angle

Typical θ (σ_{lv} \ σ_{sv})	Low (e.g., fluoropolymer)	Medium (e.g., nitride, oxide)	High (e.g., metal)
Low (e.g., alcohol, refrigerant)	< 90°	< 90°	< 90°
Medium (e.g., water)	> 90°	< 90°	< 90°
High (e.g., molten salt, liquid metal)	> 90°	> 90°	Mixed

Wilke *et al.*, *PNAS* 2021

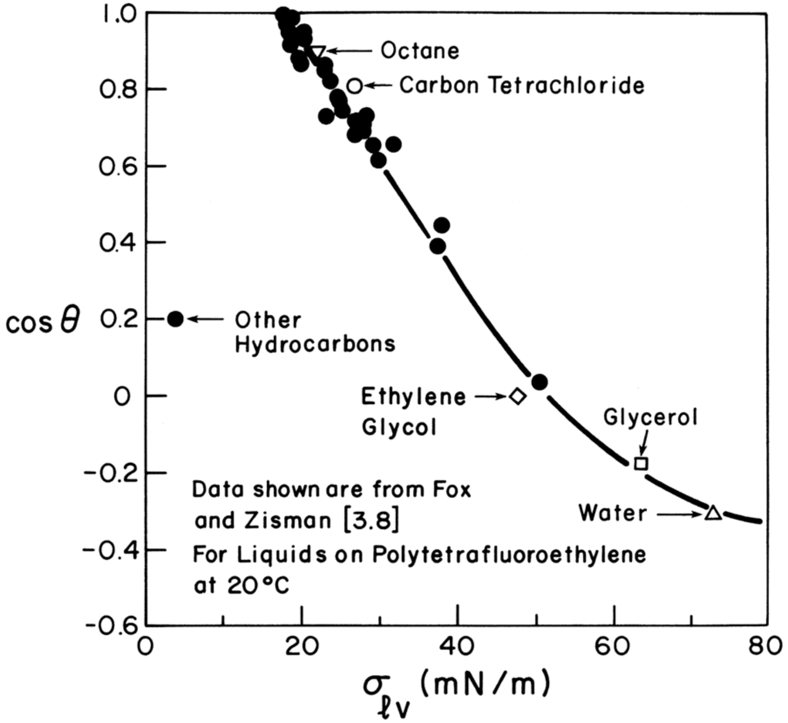
$$\cos\theta = \frac{\sigma_{sv} - \sigma_{sl}}{\sigma_{lv}}$$

Interface Energy

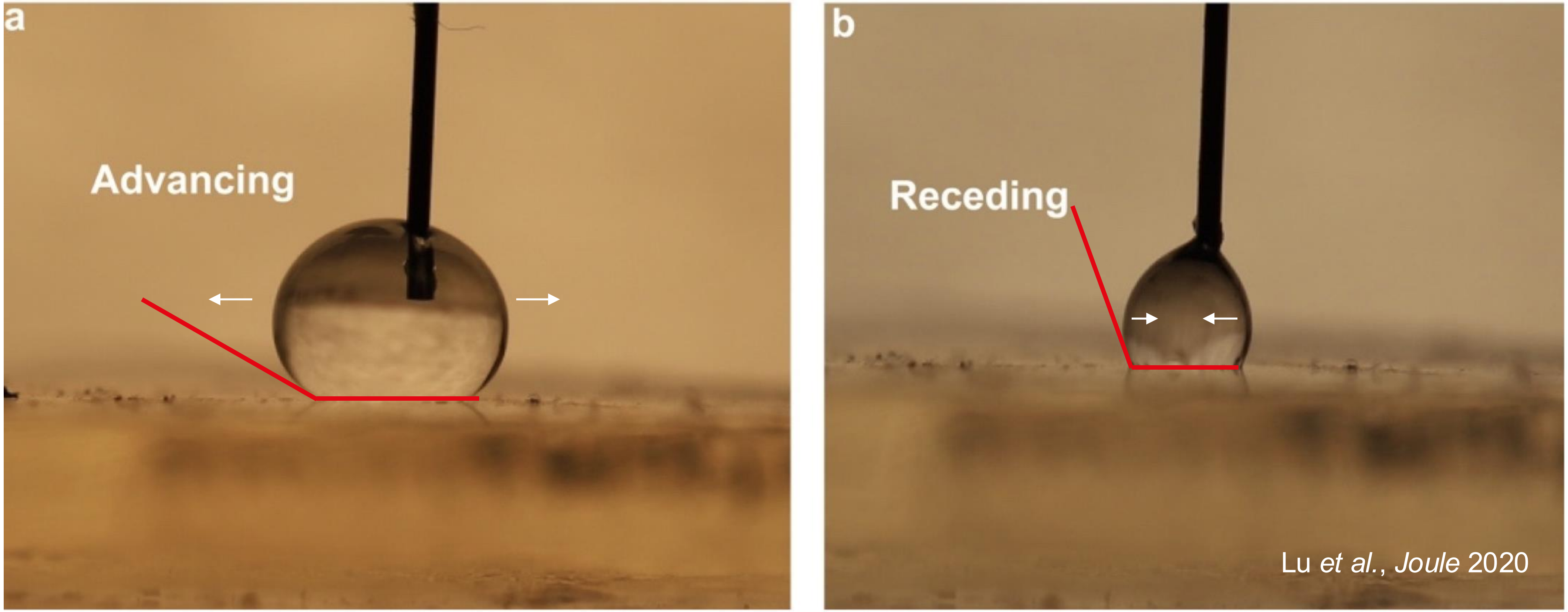


Additional Notes

- Spreading coefficient (Eq. 3.20 in Carey)
- Critical surface tension (Chapter 3.3 in Carey)



Contact Angle Hysterisis



- Equilibrium contact angle: a thermodynamic concept defined for smooth homogeneous surfaces
- Real surface wettability is characterized by advancing and receding contact angles, which are almost always different from each other

Effect of Surface Inhomogeneity

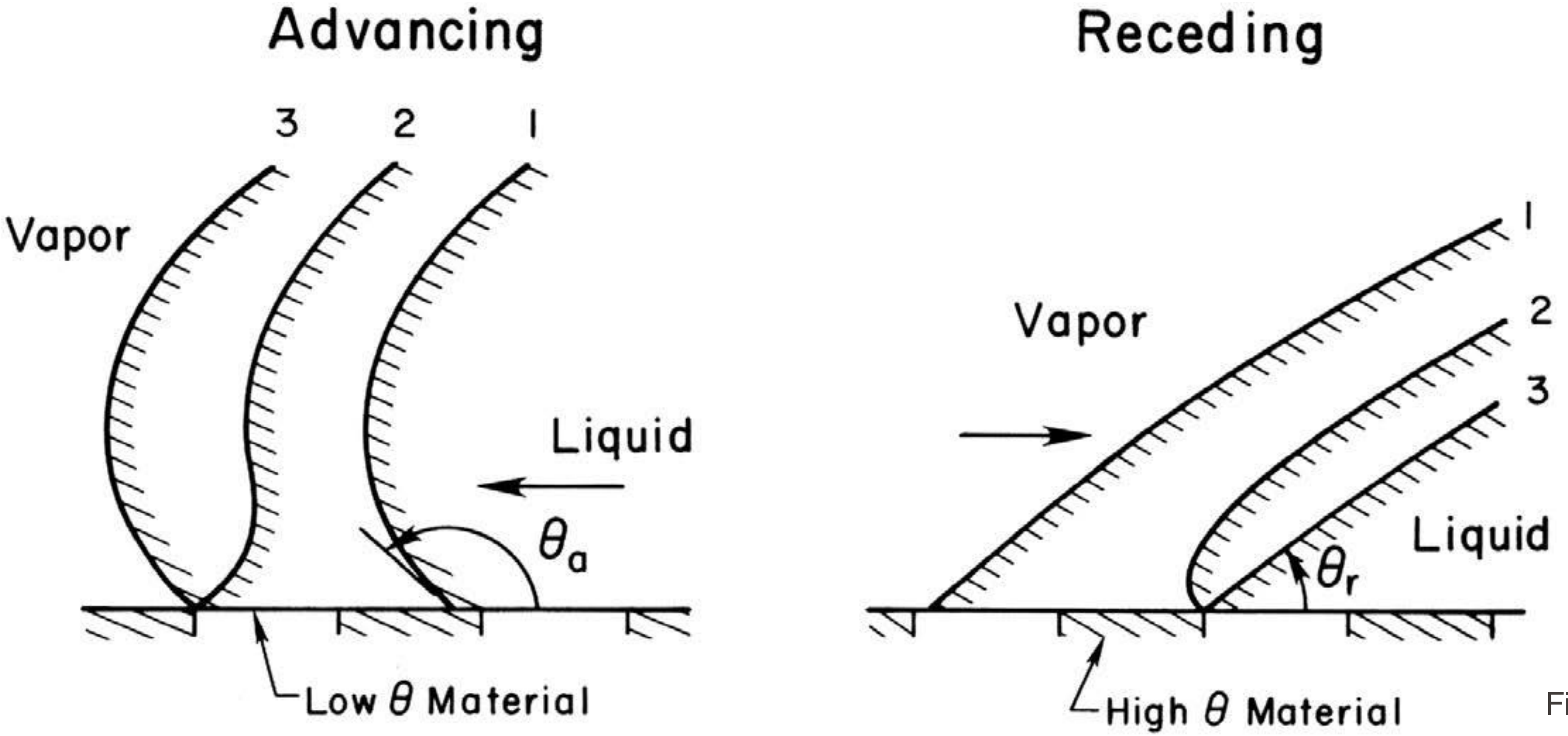


Figure 3.12a in Carey

Effect of Surface Inhomogeneity

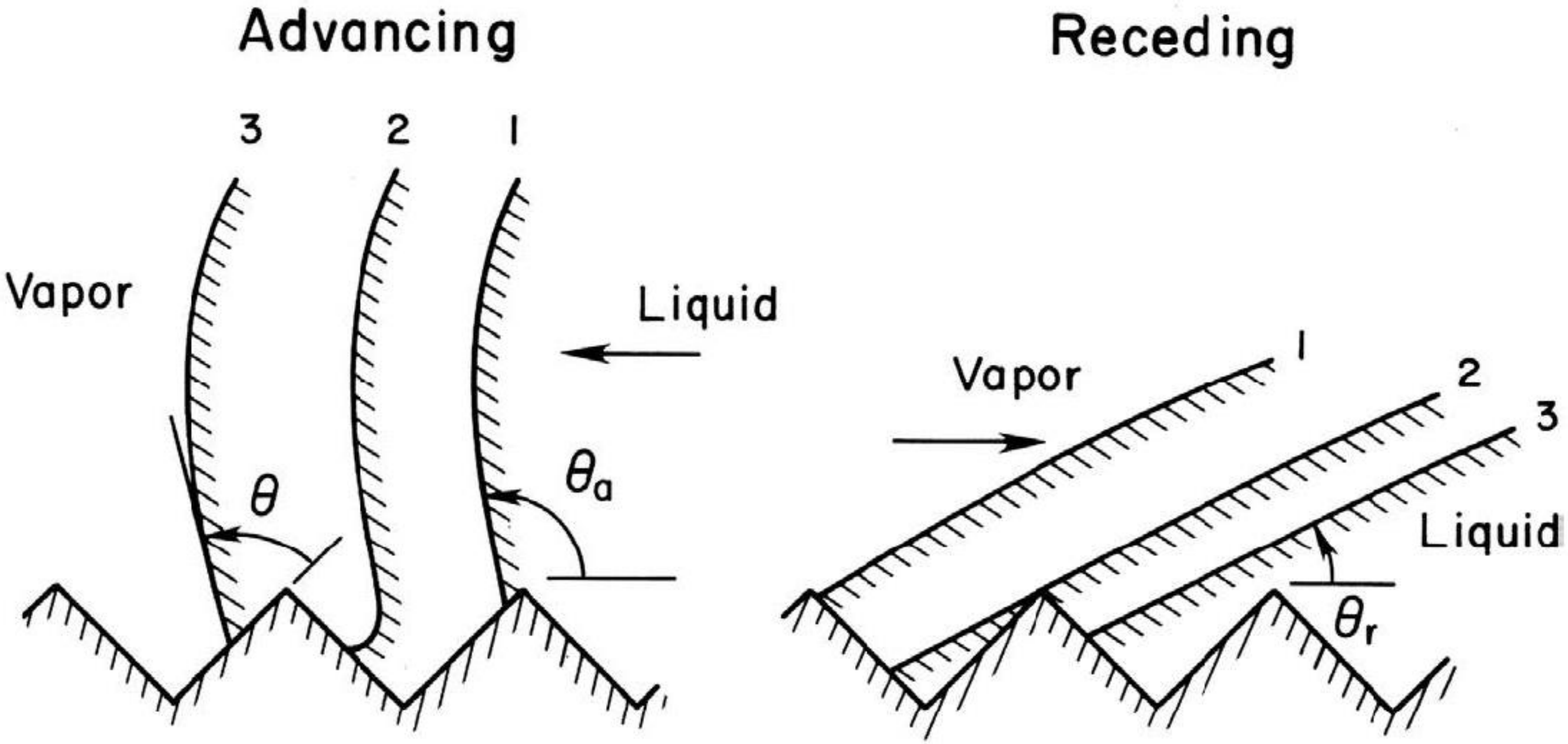


Figure 3.12b in Carey

Contact Angle Hysterisis

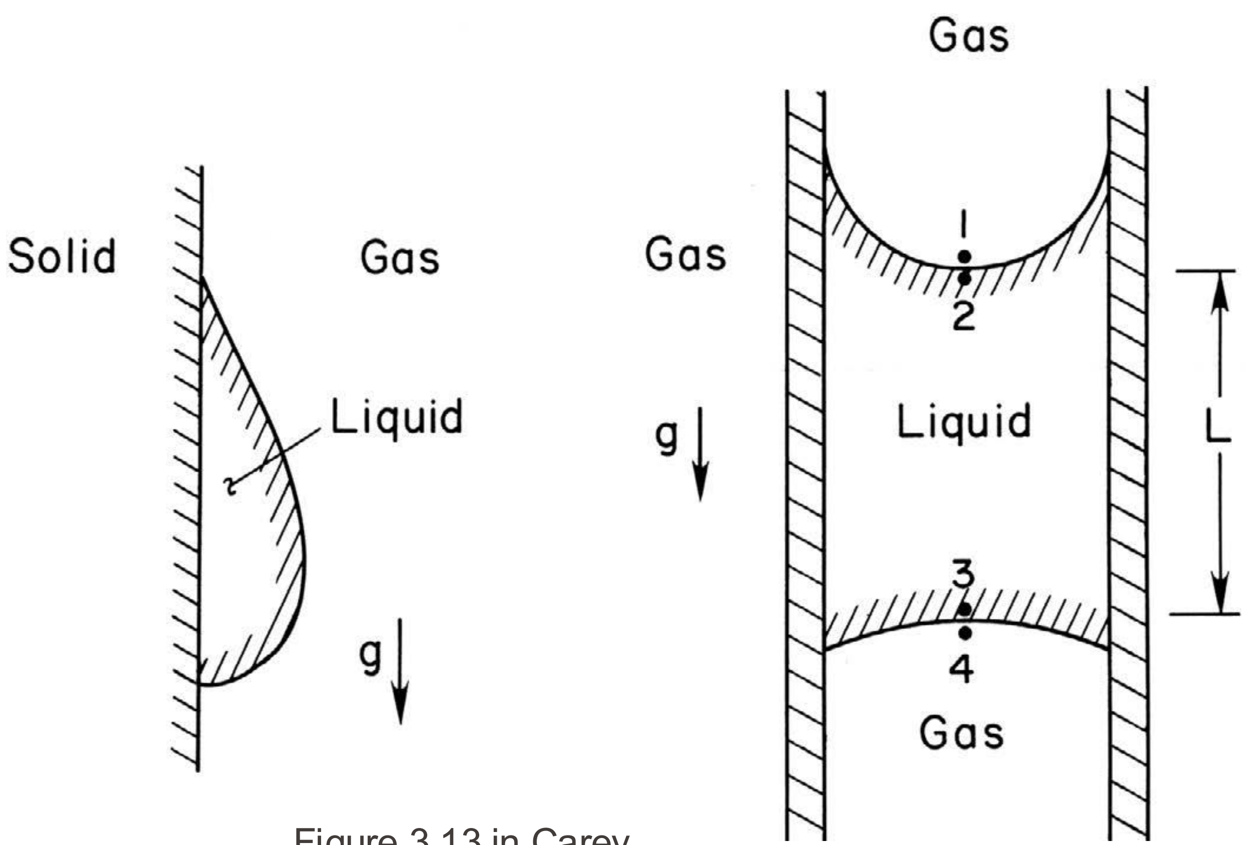
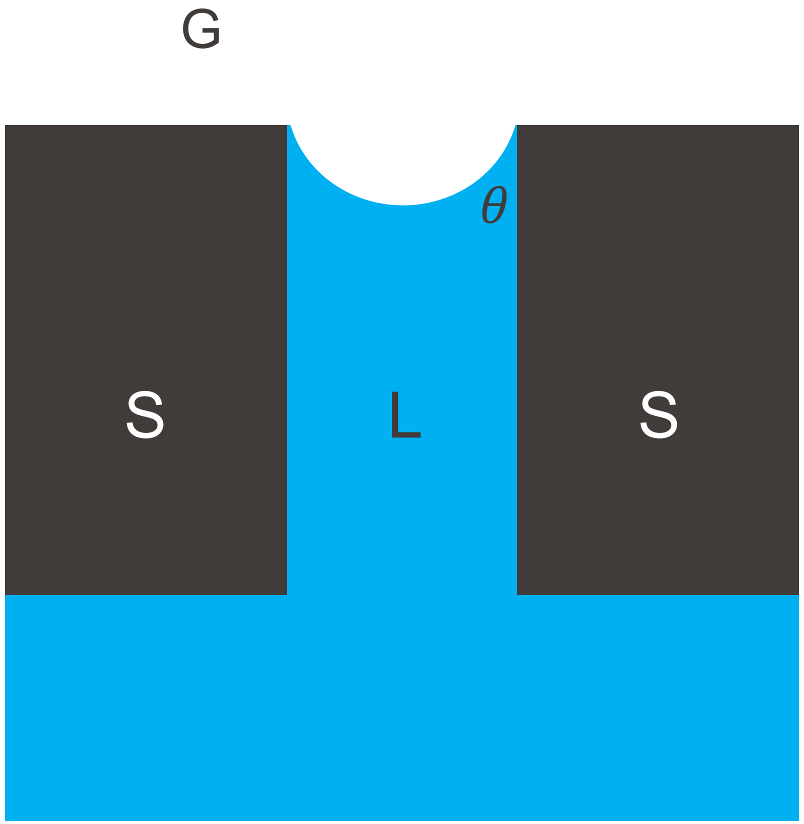


Figure 3.13 in Carey

Contact Line Pinning



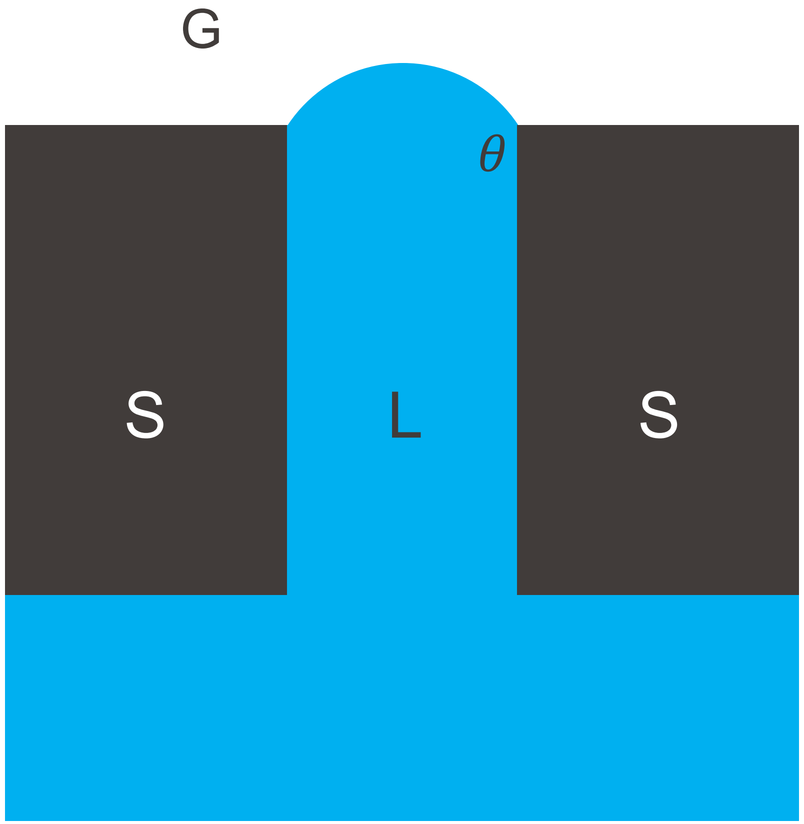
Cylindrical pore with radius r_p

Initially $P_L = P_G = P_0$, interface flat

ACA = 95°, RCA = 60°

Now, start increasing P_G

Contact Line Pinning



Cylindrical pore with radius r_p

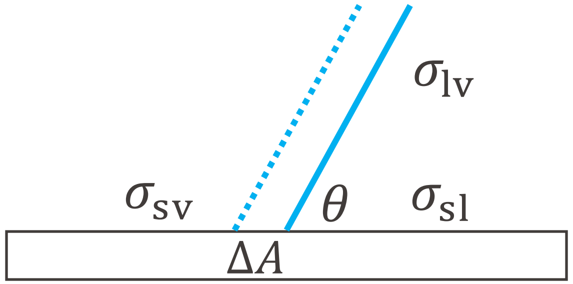
Initially $P_L = P_G = P_0$, interface flat

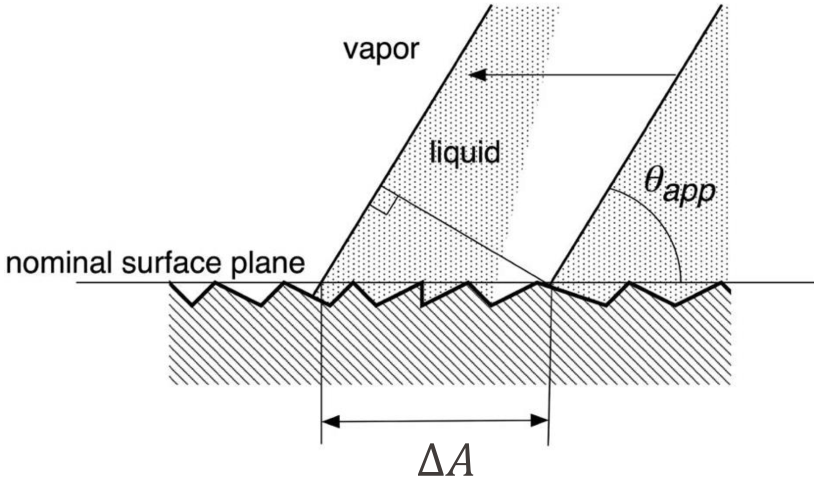
ACA = 95°, RCA = 60°

If we instead increase P_L

Wetting on a Structured Surfaces

Energy perspective of Young's Equation





Wenzel State

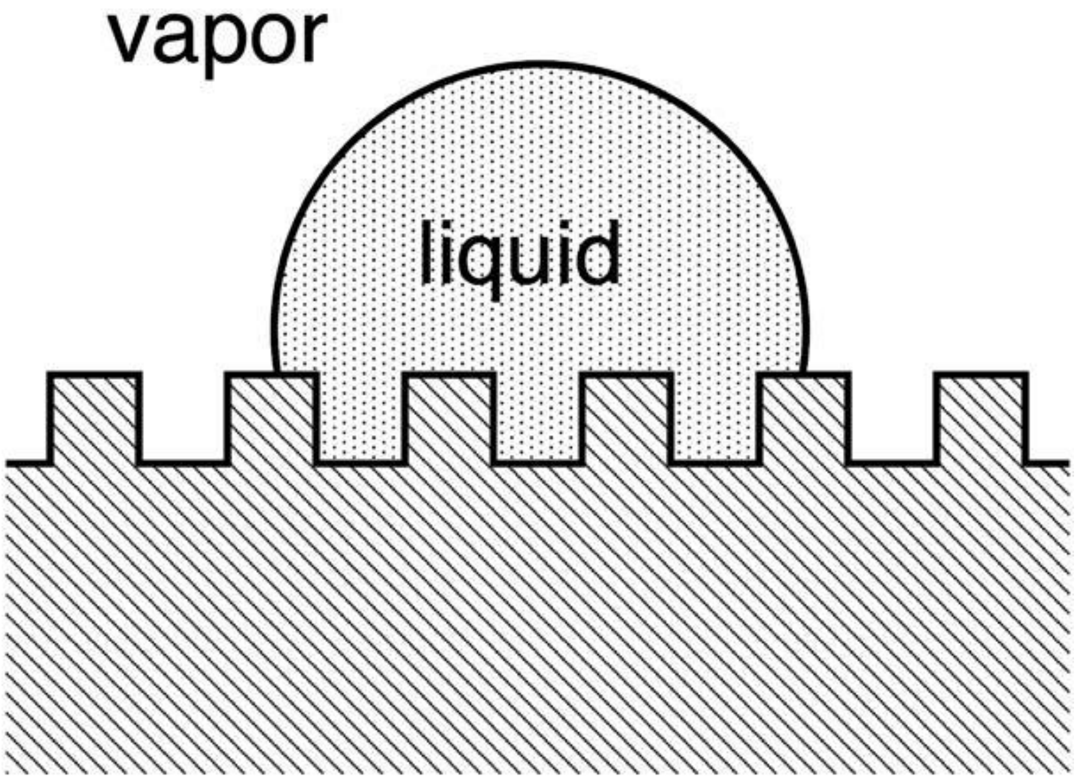


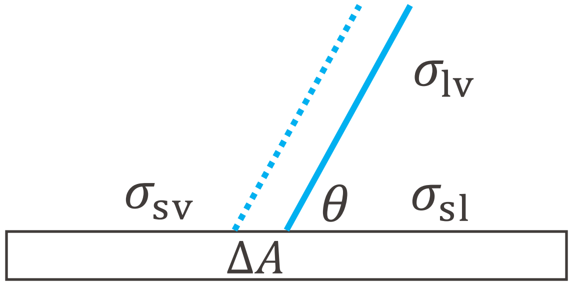
Figure 3.19 in Carey

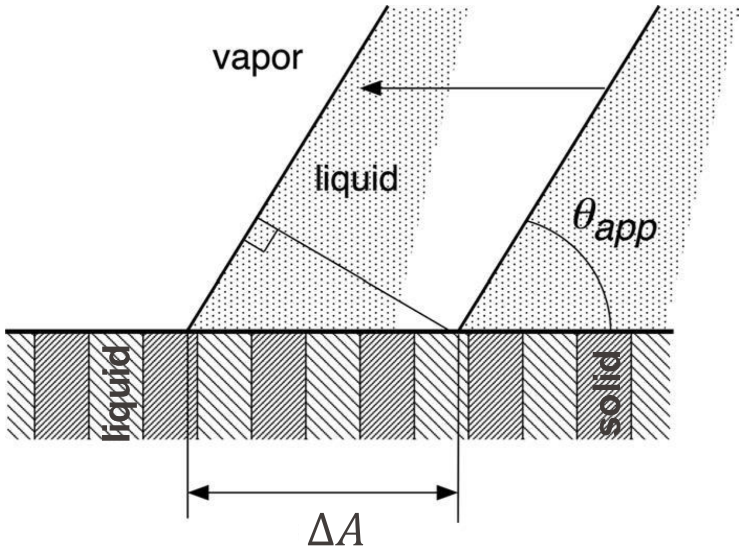
Liquid penetrates through the surface structure underneath the droplet, yet not spreading further

$$\cos\theta_{\mathrm{app}} = r\frac{\sigma_{\mathrm{sv}} - \sigma_{\mathrm{sl}}}{\sigma_{\mathrm{lv}}} = r\cos\theta_E$$

Hemi-Spreading State

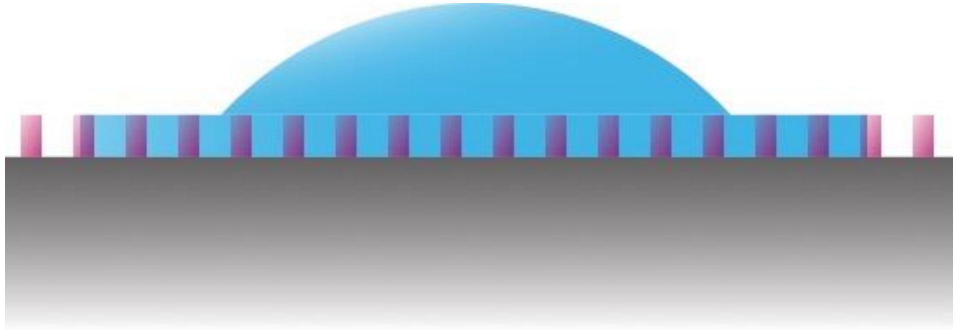
Energy perspective of Young's Equation





In the case that liquid infiltrates the surface structure beyond the original liquid footprint

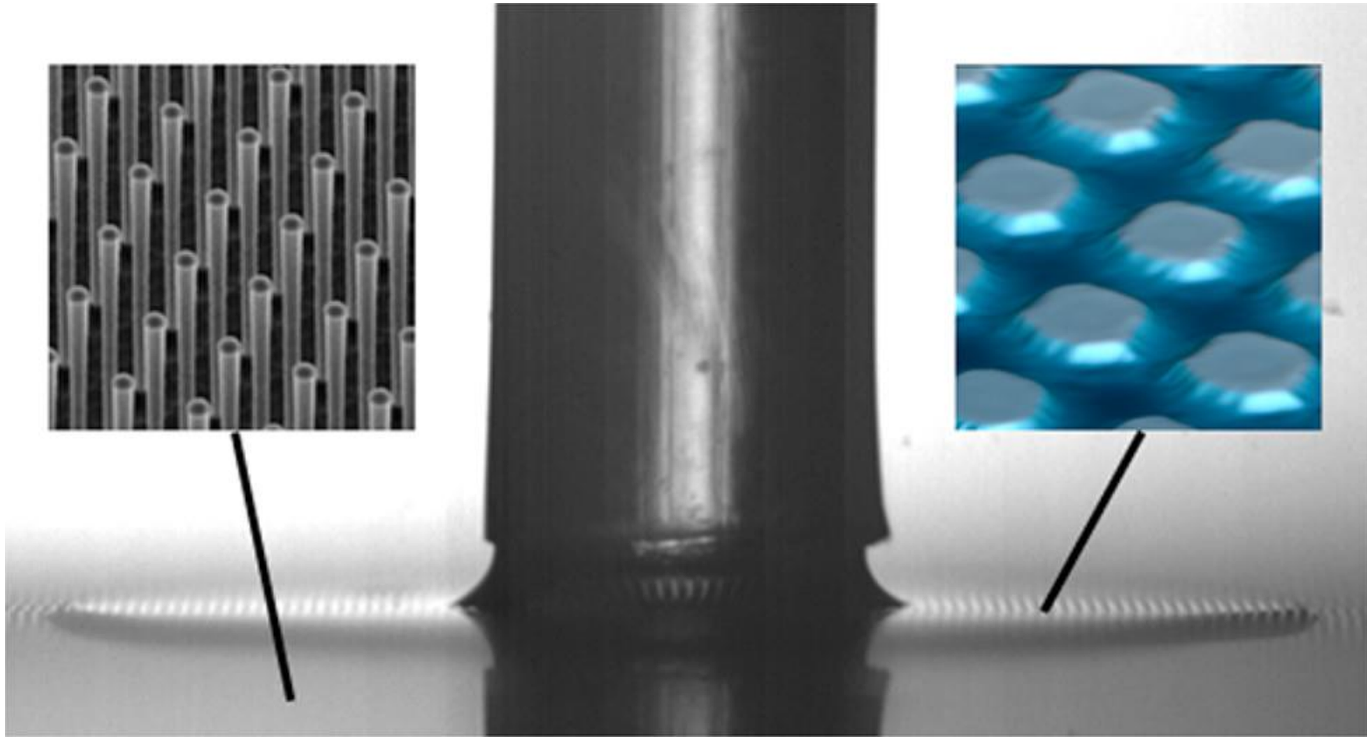
Hemi-Spreading State



Liquid penetrates into surface structures ahead of macroscopic contact lines

$$\cos\theta_{\mathrm{app}} = \phi\cos\theta + (1-\phi) = (\cos\theta - 1)\phi + 1$$

Hemis-Spreading State



Allred *et al.*, *Langmuir* 2017

Spontaneous Hemi-Spreading Condition

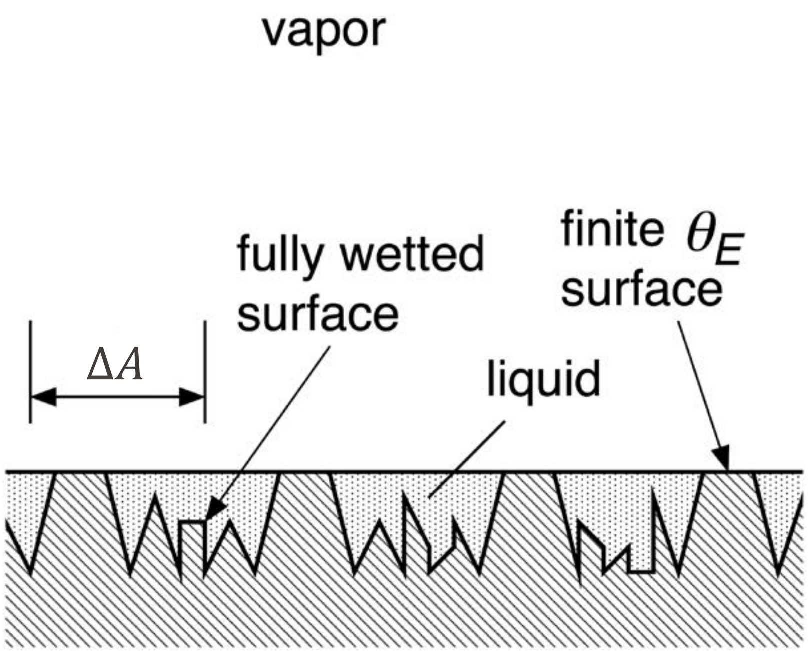
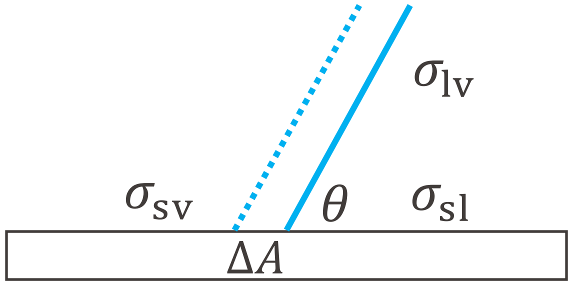
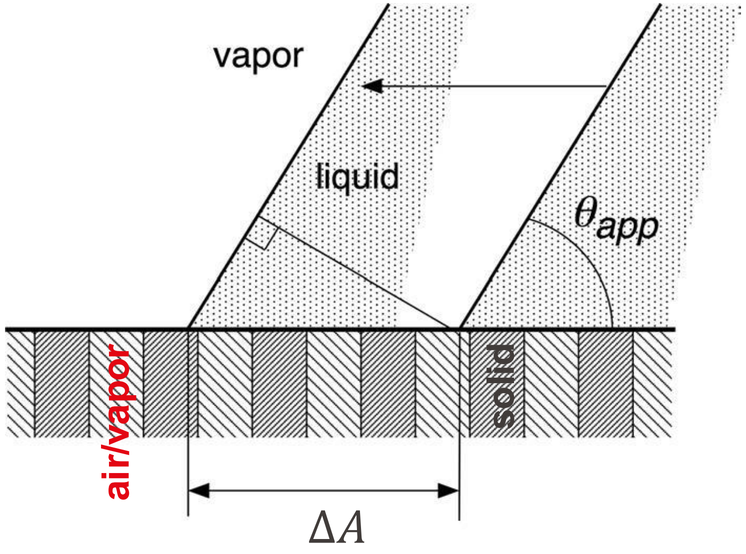


Figure 3.19 in Carey

Air Pocket Case

Energy perspective of Young's Equation





In the case that liquid cannot enter the interstitial space between the surface structure at all

Cassie-Baxter State

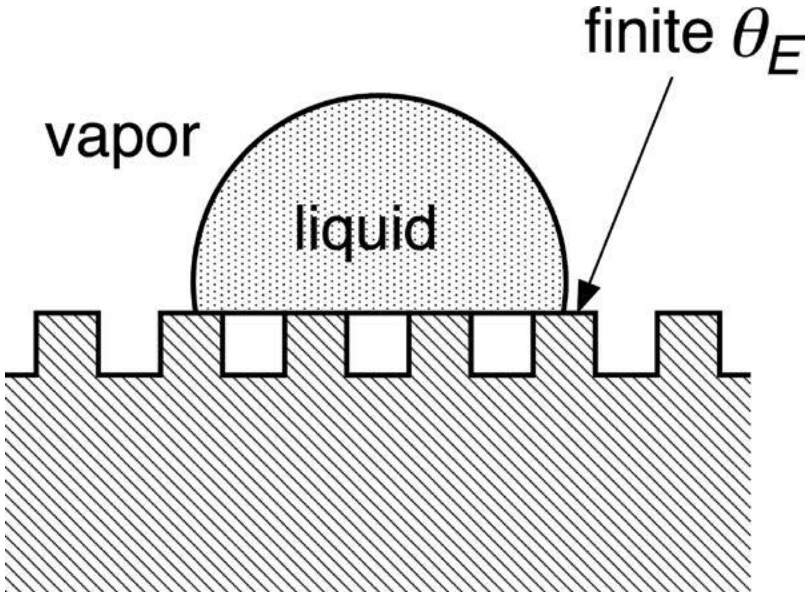


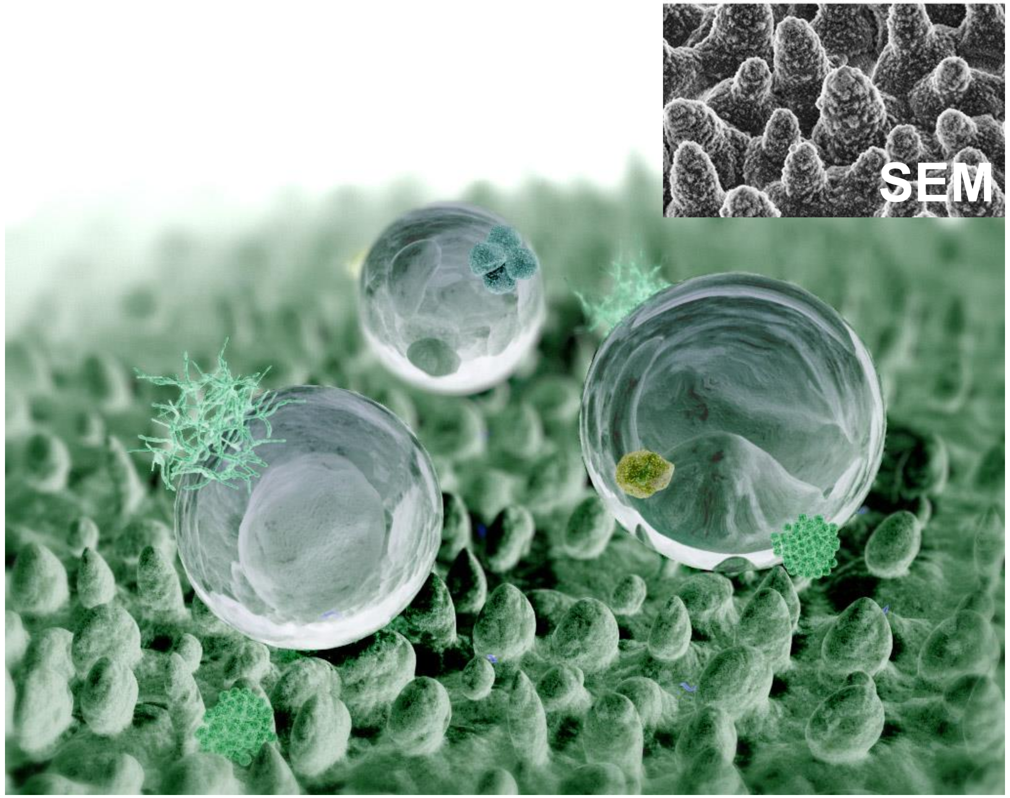
Figure 3.23 in Carey

Air/vapor trapped between the roughness elements underneath the droplet

$$\cos\theta_{\text{app}} = \phi\cos\theta + \phi - 1$$

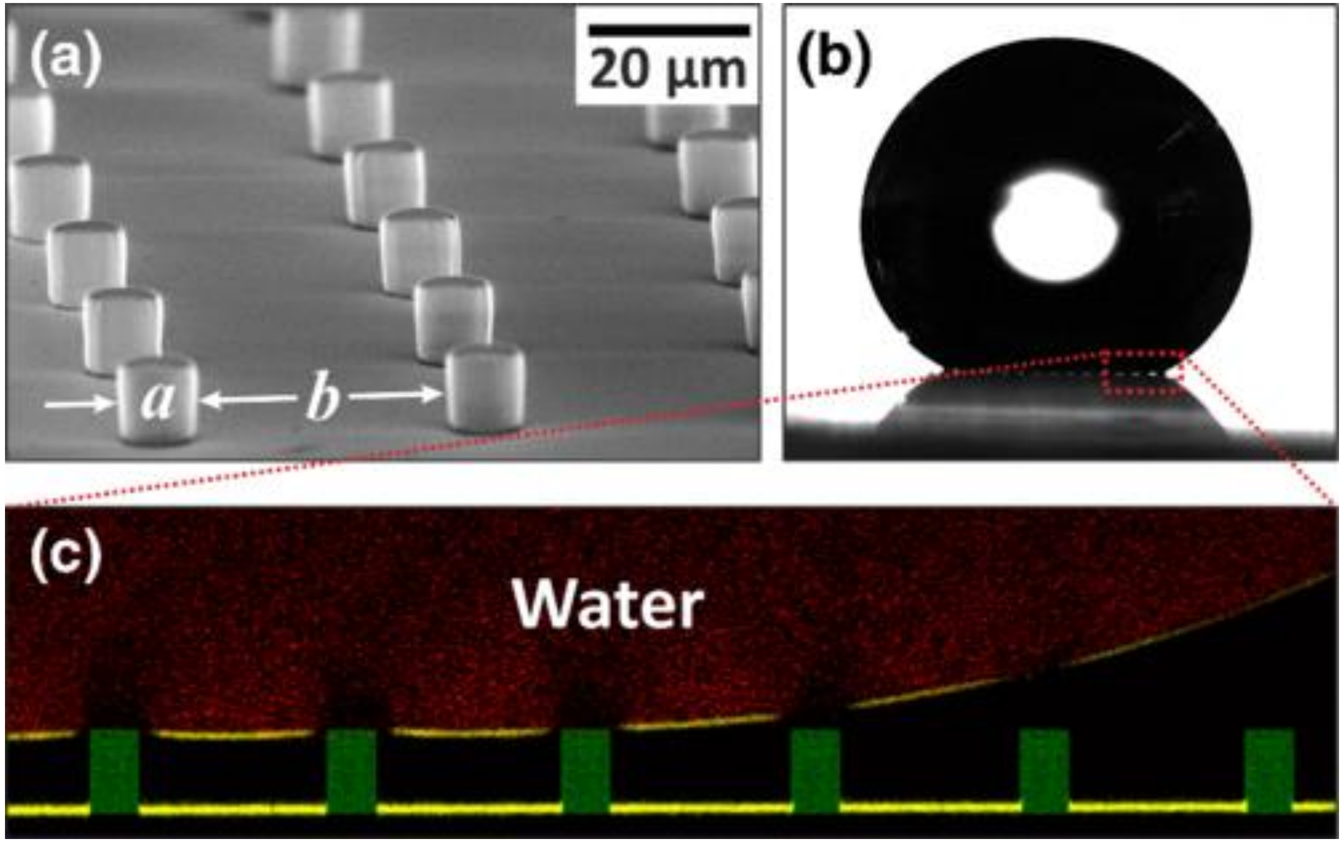
Lotus Leaf

http://davewirth.blogspot.com/2011/11/final-lotus-of-year.html



Computer graphic of a lotus leaf surface, William Thielicke, CC BY-SA 4.0

Conditions for Air Pocket Formation



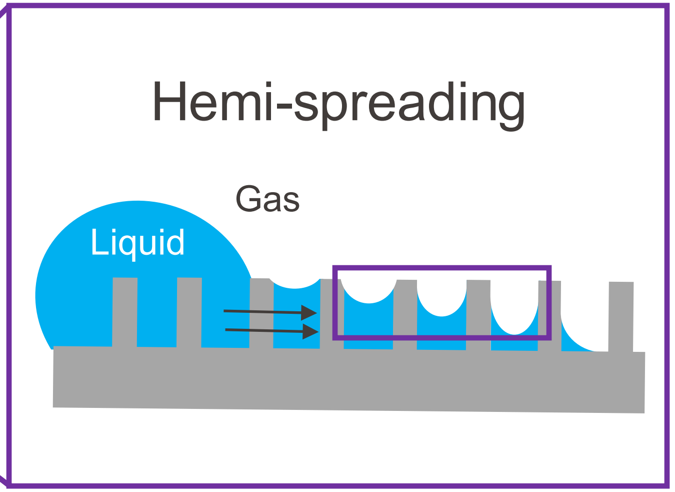
Schellenberger *et al.*, *Physical Review Letters* 2016

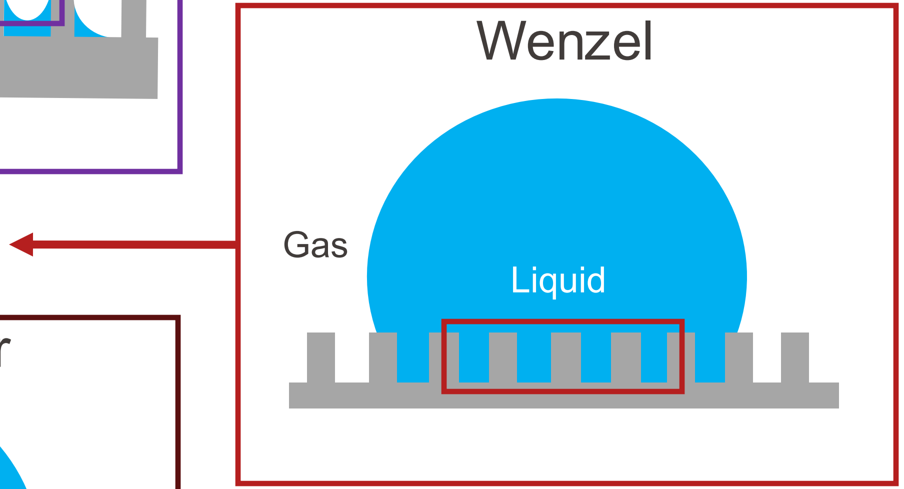
Capillary pressure preventing liquid from entering surface structures

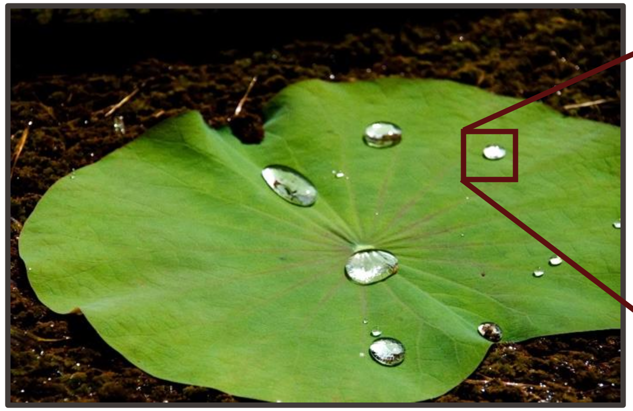
Different Regimes

Texas horned lizard

Burton Robert, U.S. Fish and Wildlife Service

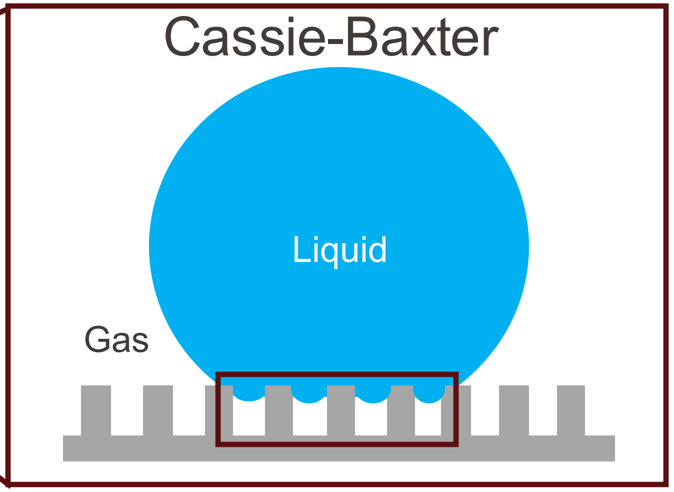






Lotus leaf

GJ Bulte (Own work) [CC BY-SA 3.0]



Different Regimes

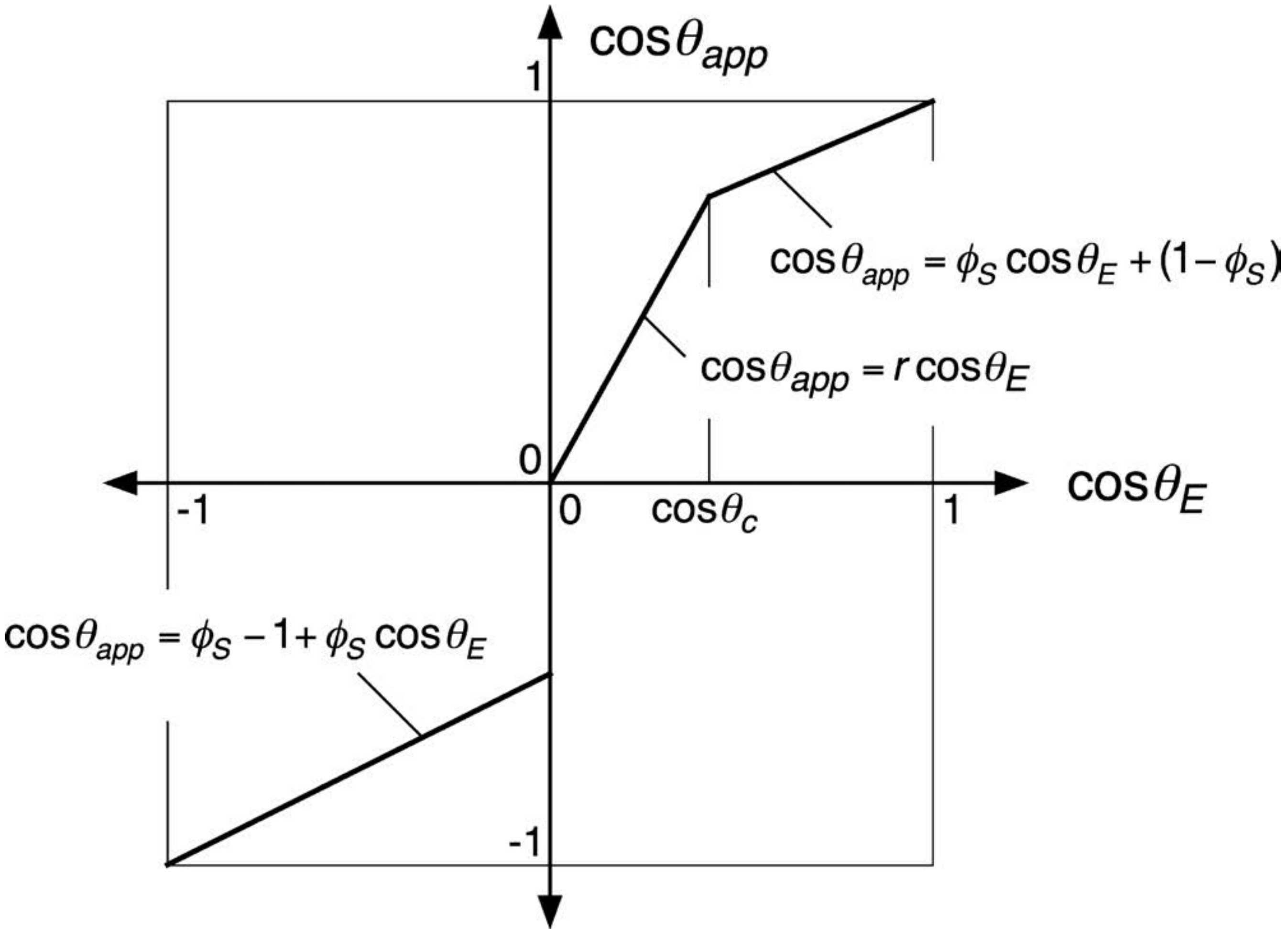
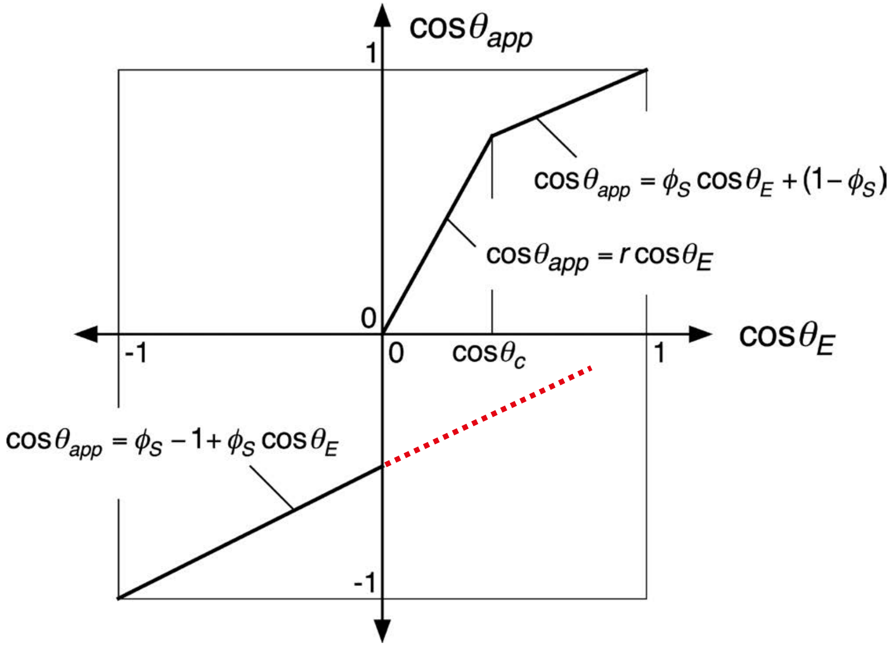


Figure 3.24 in Carey

What We Have Learned Today

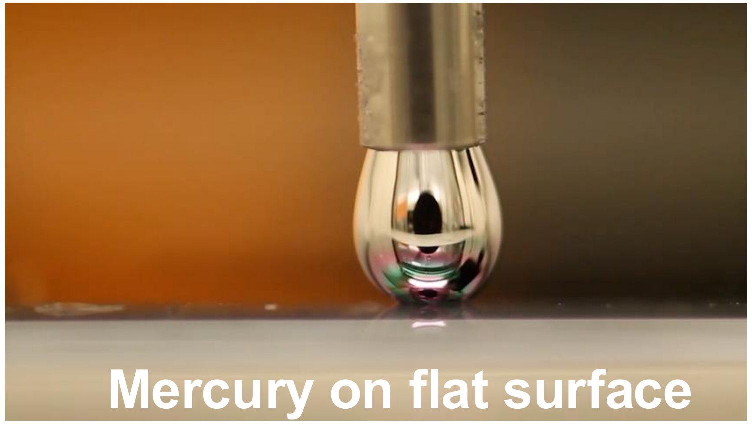
- What is **contact angle** and how it is generally affected by **surface tension/surface energy**?
- What is **contact angle hysteresis**?
- What is the effect of surface structures/roughness on contact angle? **Hemi-spreading, Wenzel, Cassie-Baxter**

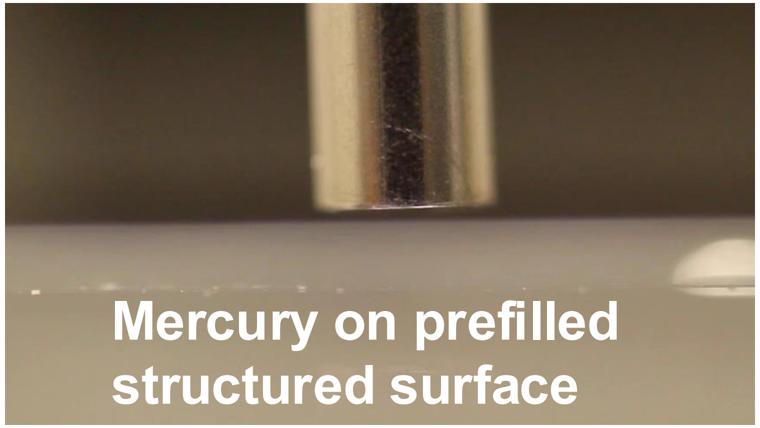
Omniphobic Surfaces



Liu *et al.*, *Science* 2014

Omniphilic Surfaces





Wilke *et al.*, *PNAS* 2021