18.357: Lecture 16

The wetting of textured solids

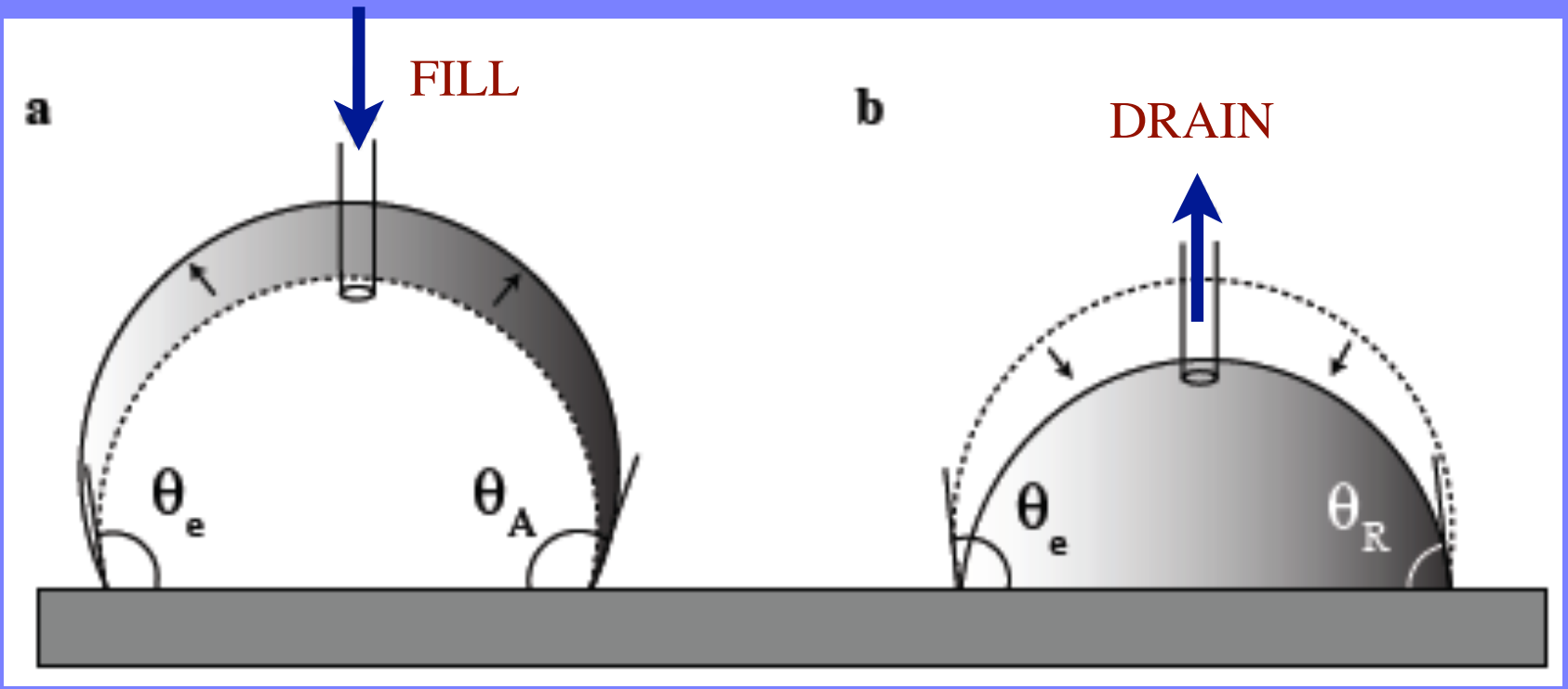
John W. M. Bush

Department of Mathematics
MIT

Contact angle hysteresis

Static contact angle is not uniquely θ_e

Reality: drop is stable over a range of $\theta_r < \theta < \theta_a$

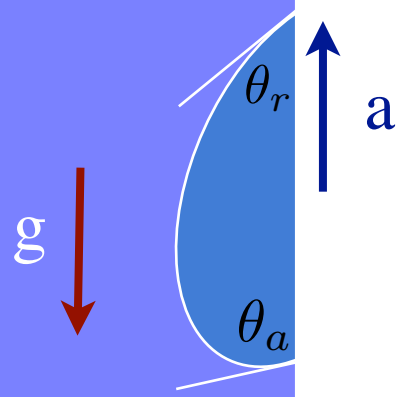


→ FORCE of ADHESION resists drop motion

increases with $\Delta\theta = \theta_a - \theta_r$

Origins: advancing contact lines pinned on surface irregularities

The force of adhesion (Dussan & Chow 1983)



Raindrop stuck on a window

- small drops supported by contact line resistance

$$F_c \sim 2\pi a\, \sigma\, (\cos\theta_r - \cos\theta_a)$$

- drops grow by accretion until weight prompts rolling

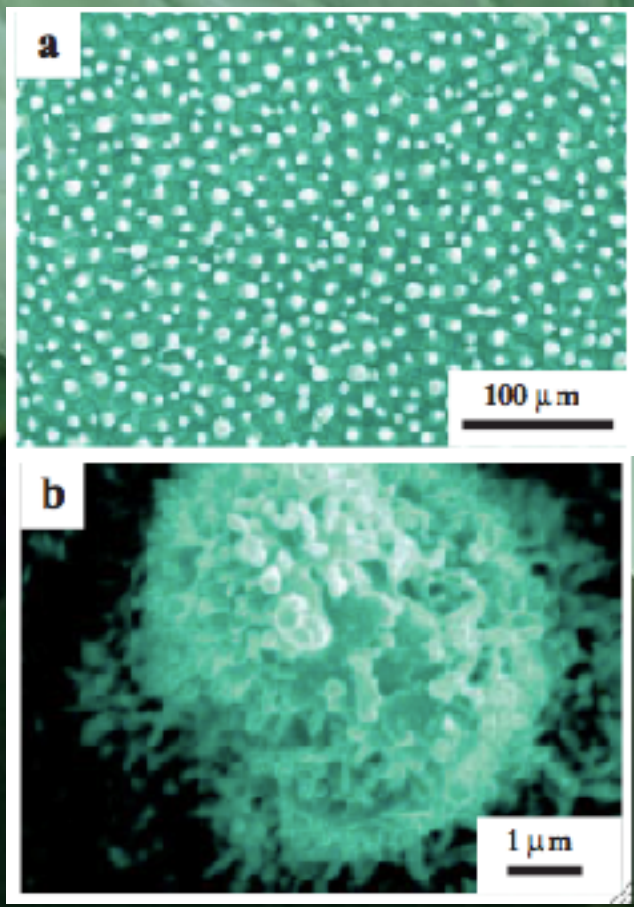
Water-repellency

- impinging drops roll off rather than adhering
- requires large θ_e , small $\Delta\theta = \theta_a - \theta_r$

How can we reduce the force of adhesion?

Water repellency in nature

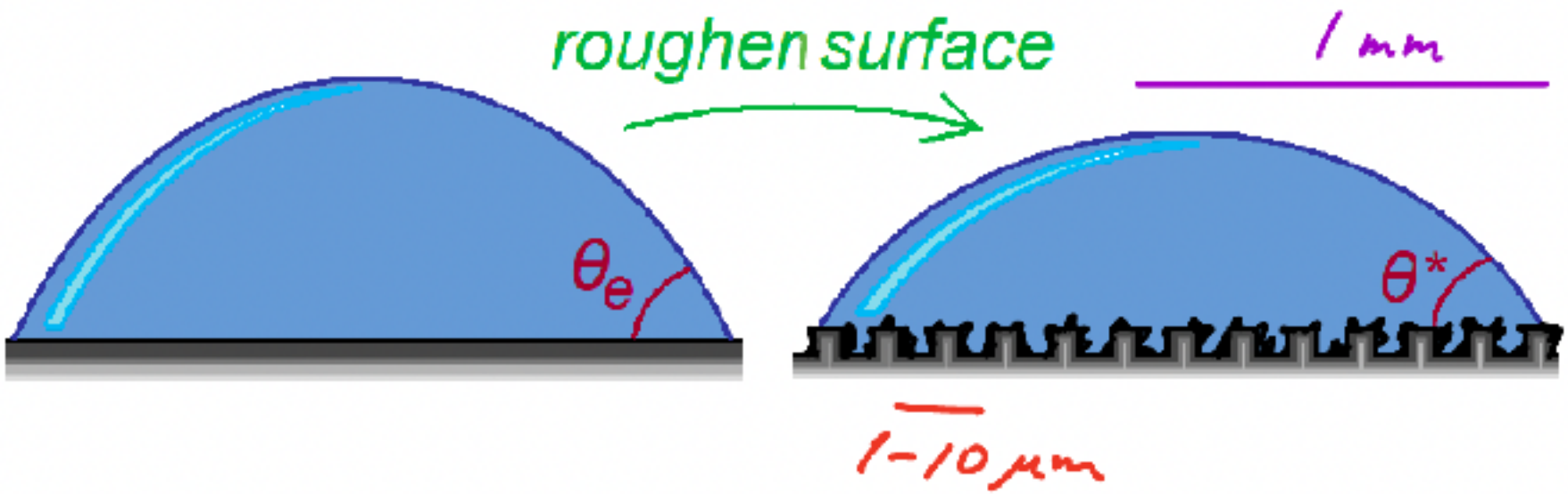
"One who performs his duty without attachment, surrendering the results unto the Supreme Being, is unaffected by sinful action, as the lotus leaf is untouched by water."
Bhagavad Gita 5.10



Feng et al. (2004)

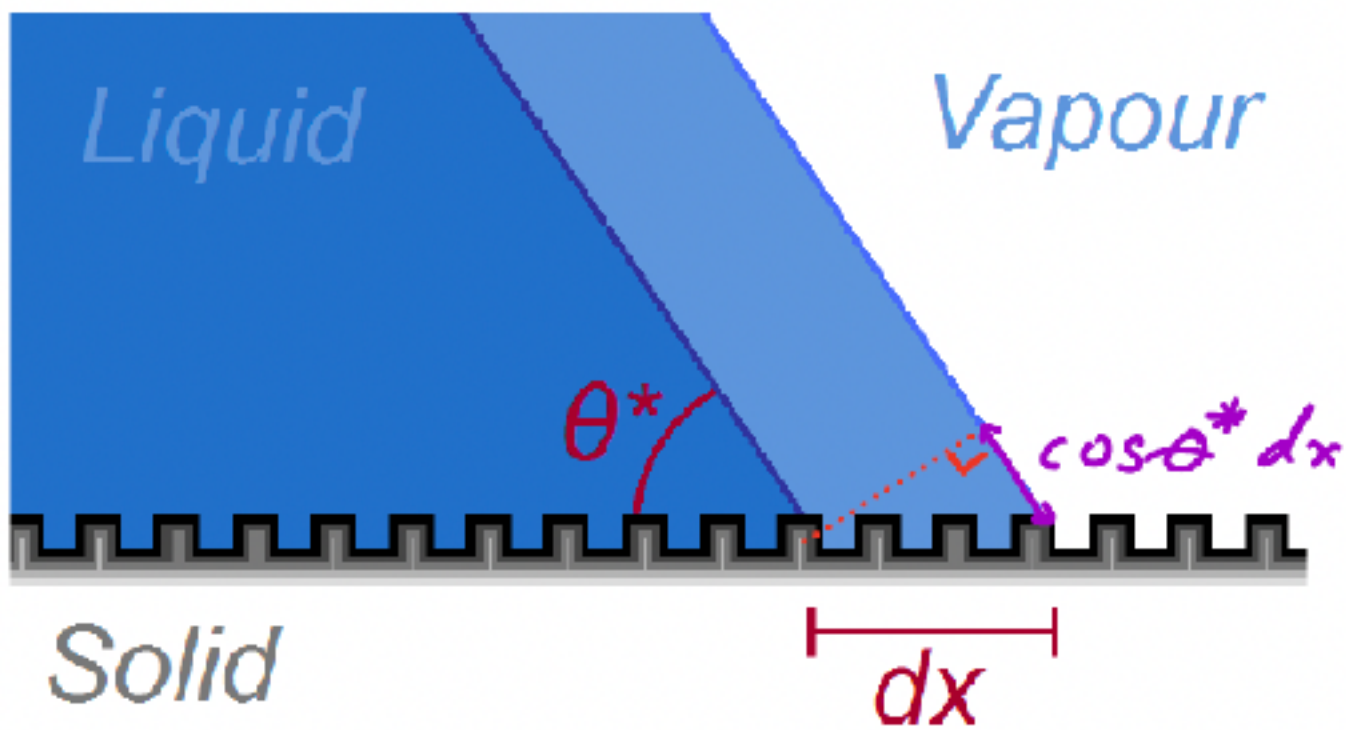
- the lotus leaf is superhydrophobic and self-cleaning by virtue of its waxy surface roughness

Effective contact angle on a rough solid

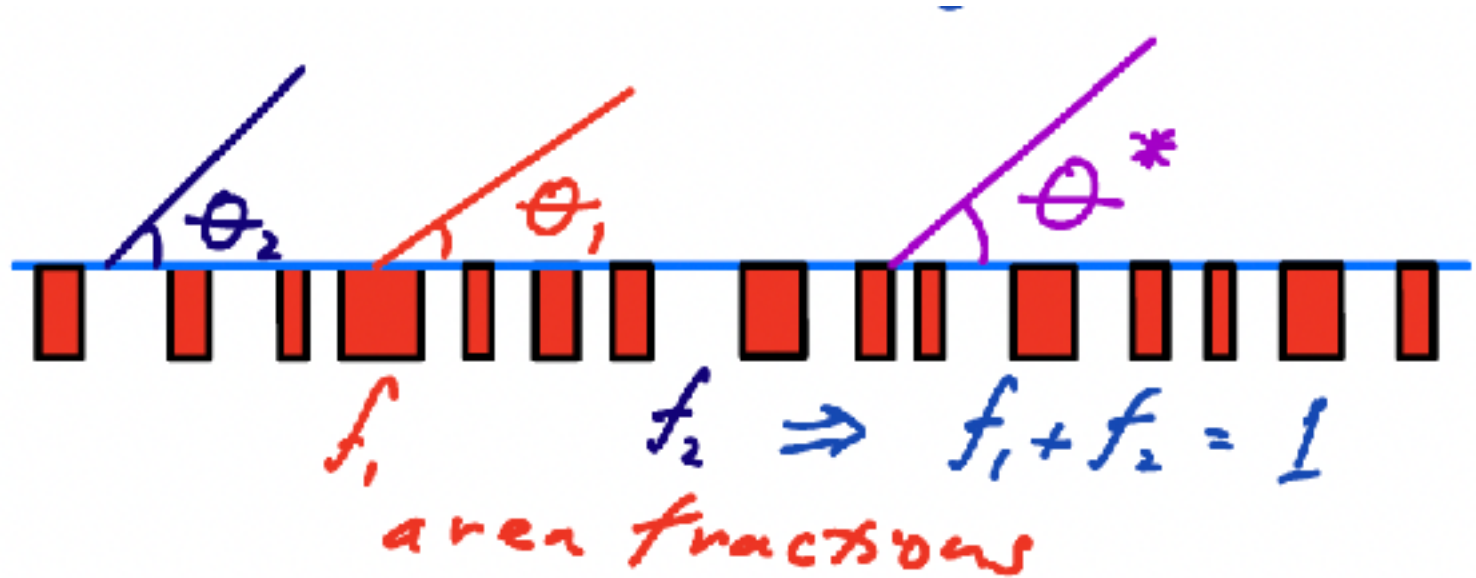


Three possible states

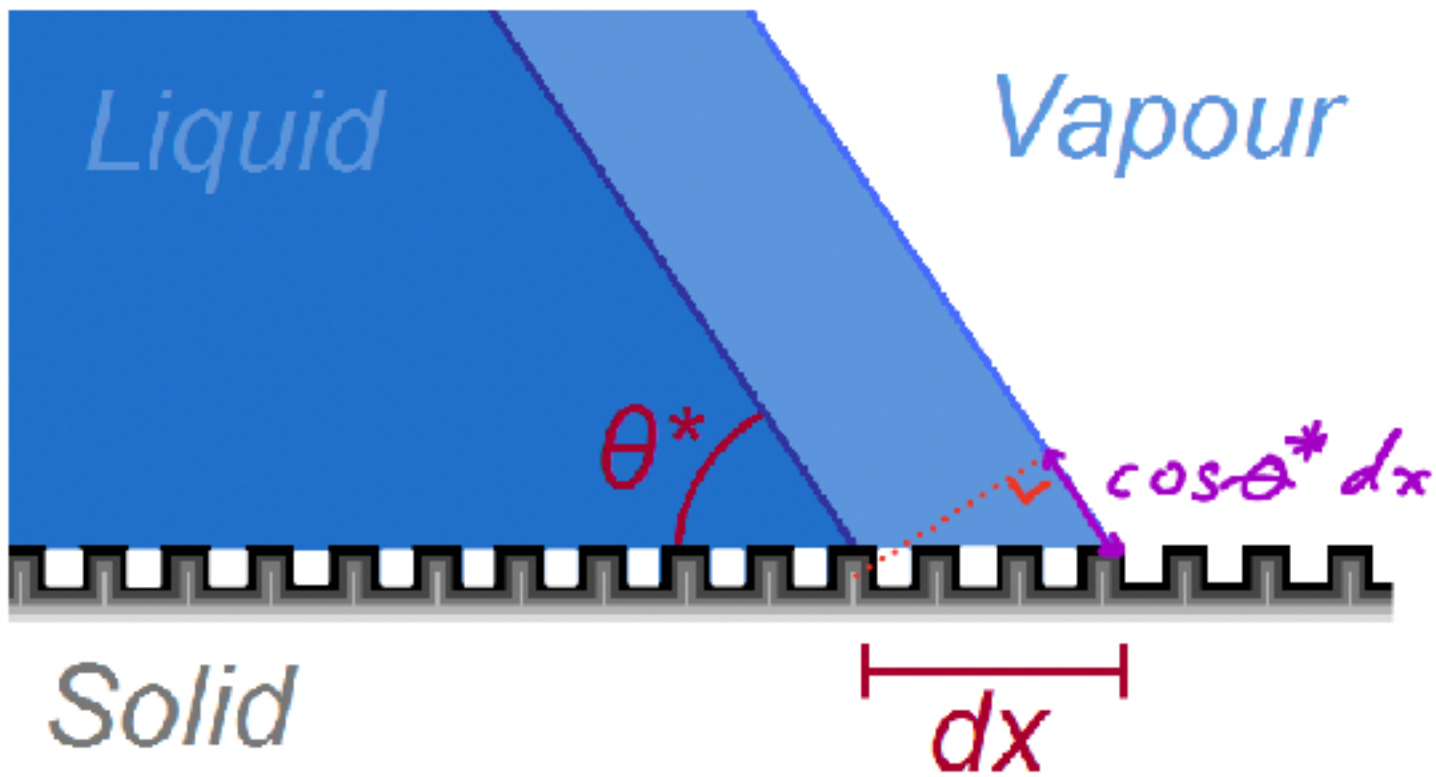
Wenzel model



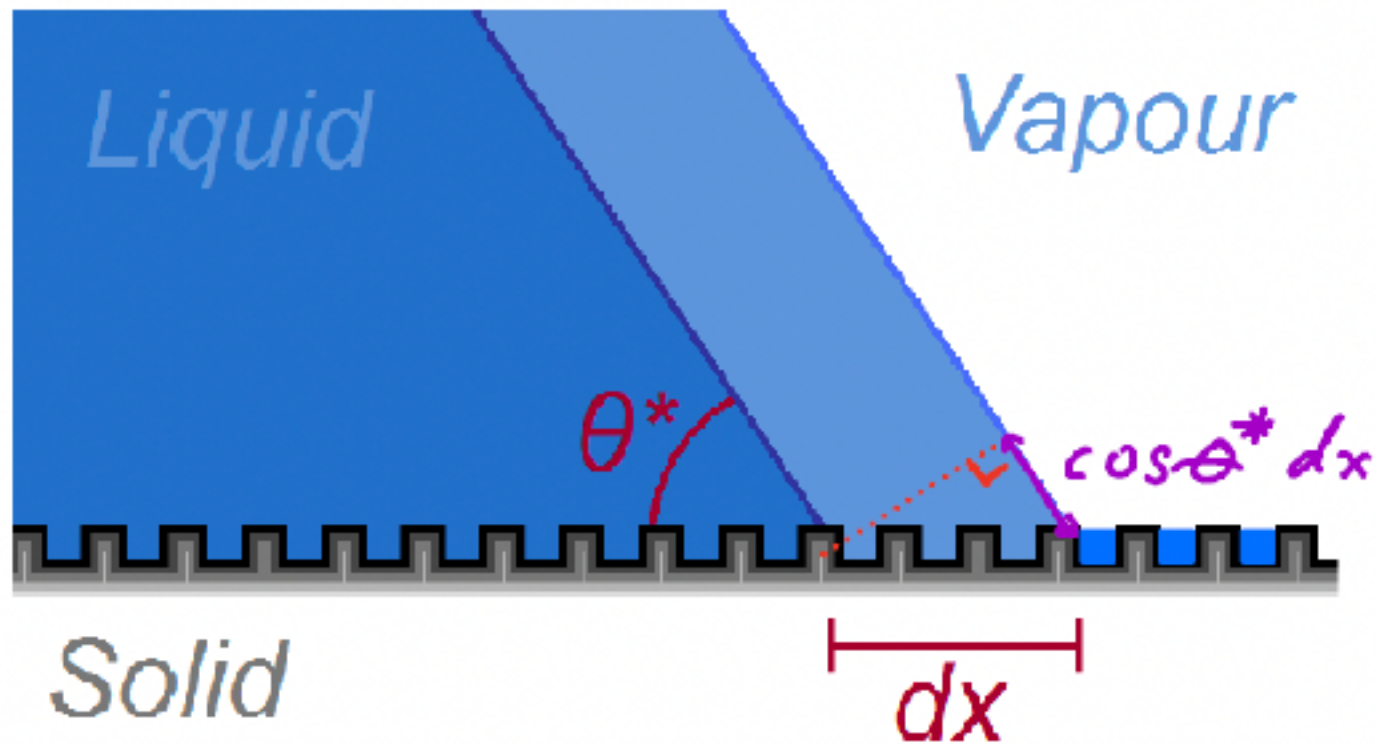
Cassie-Baxter model



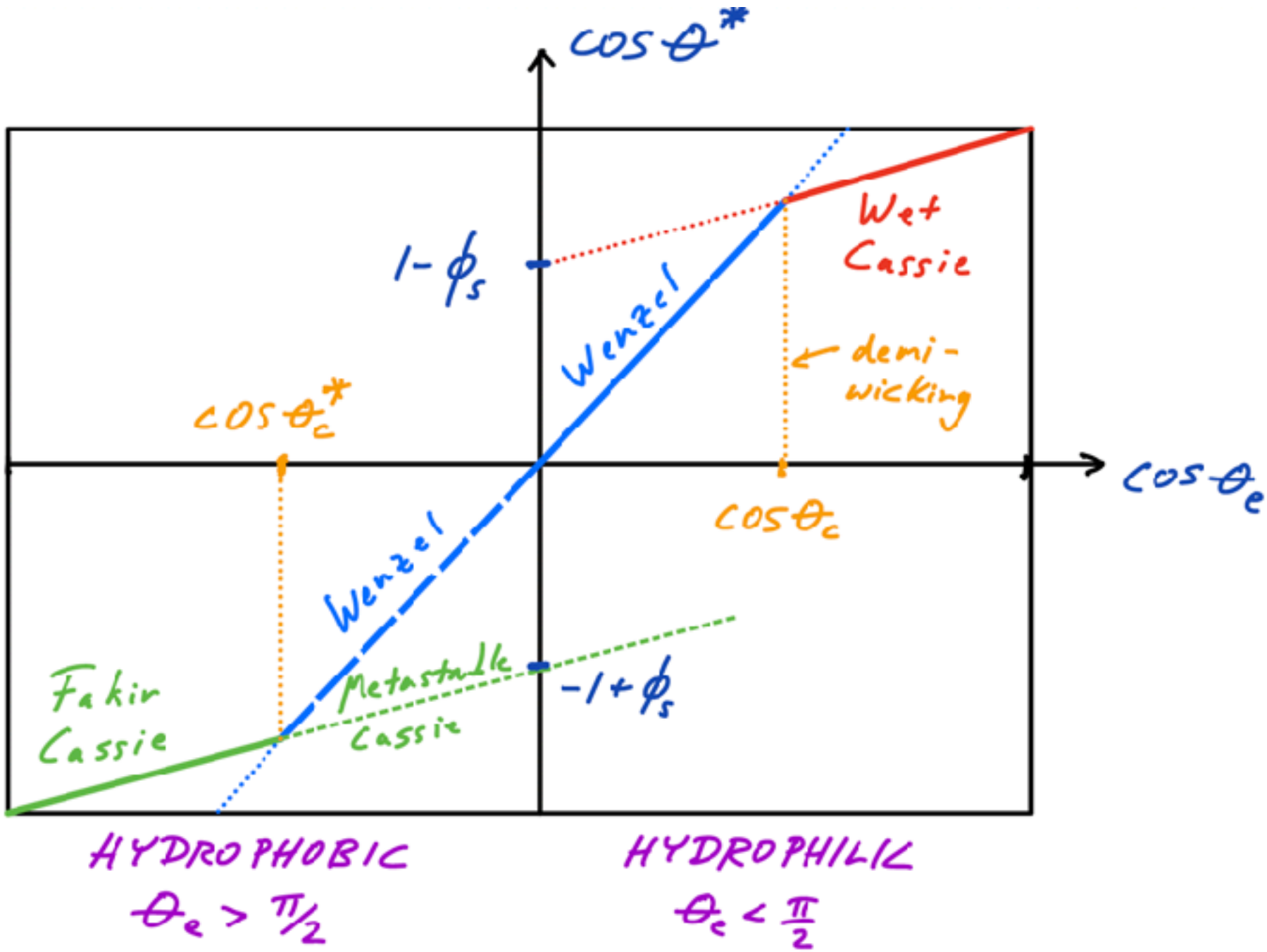
Dry Cassie state



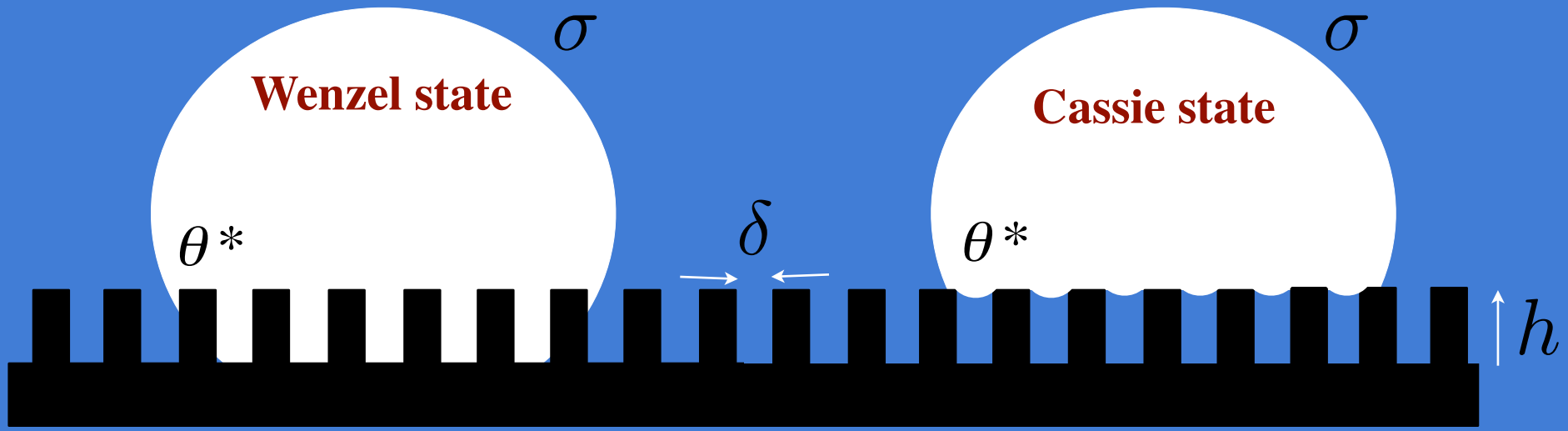
Wet Cassie state



Summary


cos θ*
1 - φs
Wet
Cassie
Wenzel
← demi-
wicking
cos θc*
cos θe
cos θc
Wenzel
Fakir
Cassie
Metastable
Cassie
-1 + φs
HYDROPHOBIC
θe > π/2
HYDROPHILIC
θe < π/2

Wetting of a rough hydrophobic surface: Wenzel vs. Cassie



$$dW = r\, dx\, (\sigma_{SG} - \sigma_{SL}) - dx\, \sigma\, cos\theta^*$$

$$\cos\theta^* = r\, \cos\theta$$

where r is total/planar area

θ^* INCREASES, but $\Delta\theta$ INCREASES

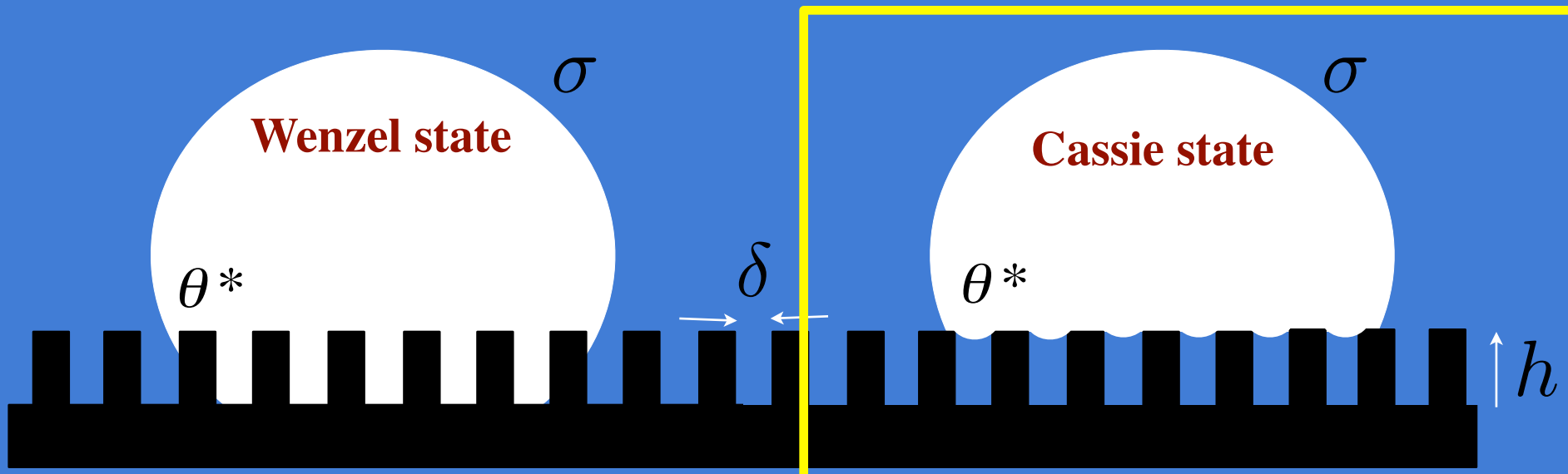
$$\cos\theta^* = -1 + f_s + f_s \cos\theta$$

where f_s is exposed/planar area

θ^* INCREASES

$\Delta\theta$ DECREASES

Wetting of a rough hydrophobic surface: Wenzel vs. Cassie



$$dW = r\, dx\, (\sigma_{SG} - \sigma_{SL}) - dx\, \sigma\, cos\theta^*$$

$$\cos\theta^* = r\, \cos\theta$$

where r is total/planar area

θ^* INCREASES, but $\Delta\theta$ INCREASES

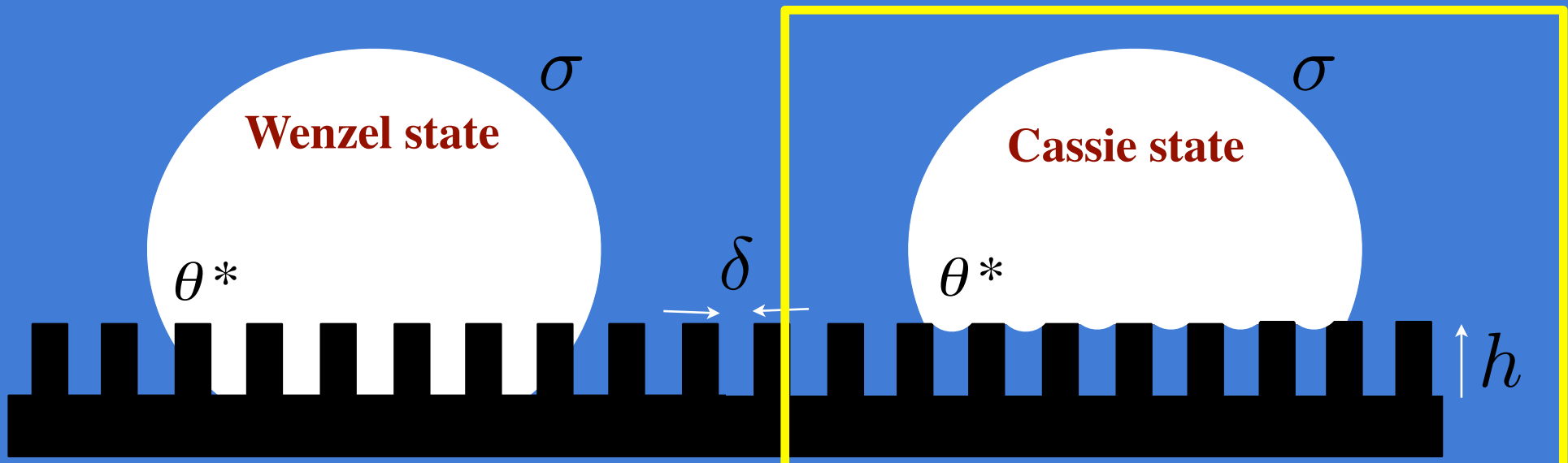
$$\cos\theta^* = -1 + f_s + f_s \cos\theta$$

where f_s is exposed/planar area

θ^* INCREASES

$\Delta\theta$ DECREASES

Wetting of a rough hydrophobic surface: Wenzel vs. Cassie



$$dW = r\, dx\, (\sigma_{SG} - \sigma_{SL}) - dx\, \sigma\, cos\theta^*$$

$$\cos\theta^* = r\, \cos\theta$$

where r is total/planar area

θ^* INCREASES, but $\Delta\theta$ INCREASES

$$\cos\theta^* = -1 + f_s + f_s \cos\theta$$

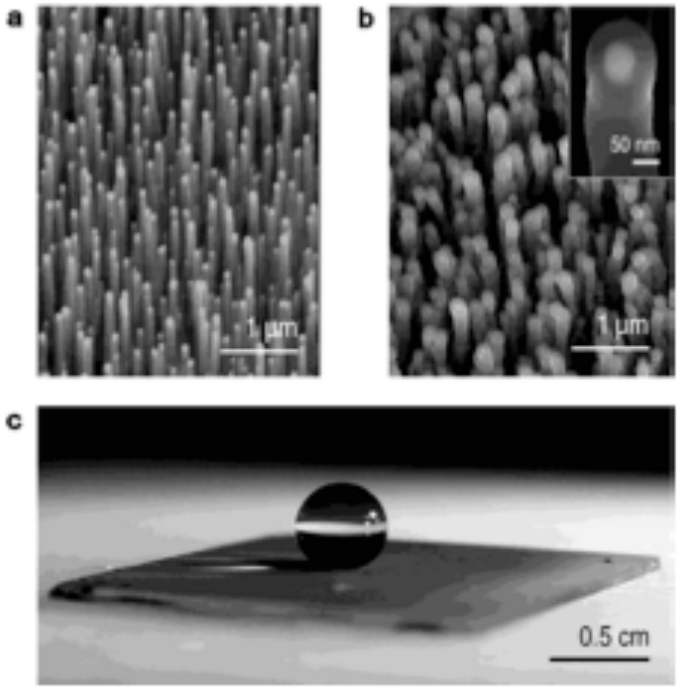
where f_s is exposed/planar area

θ^* INCREASES

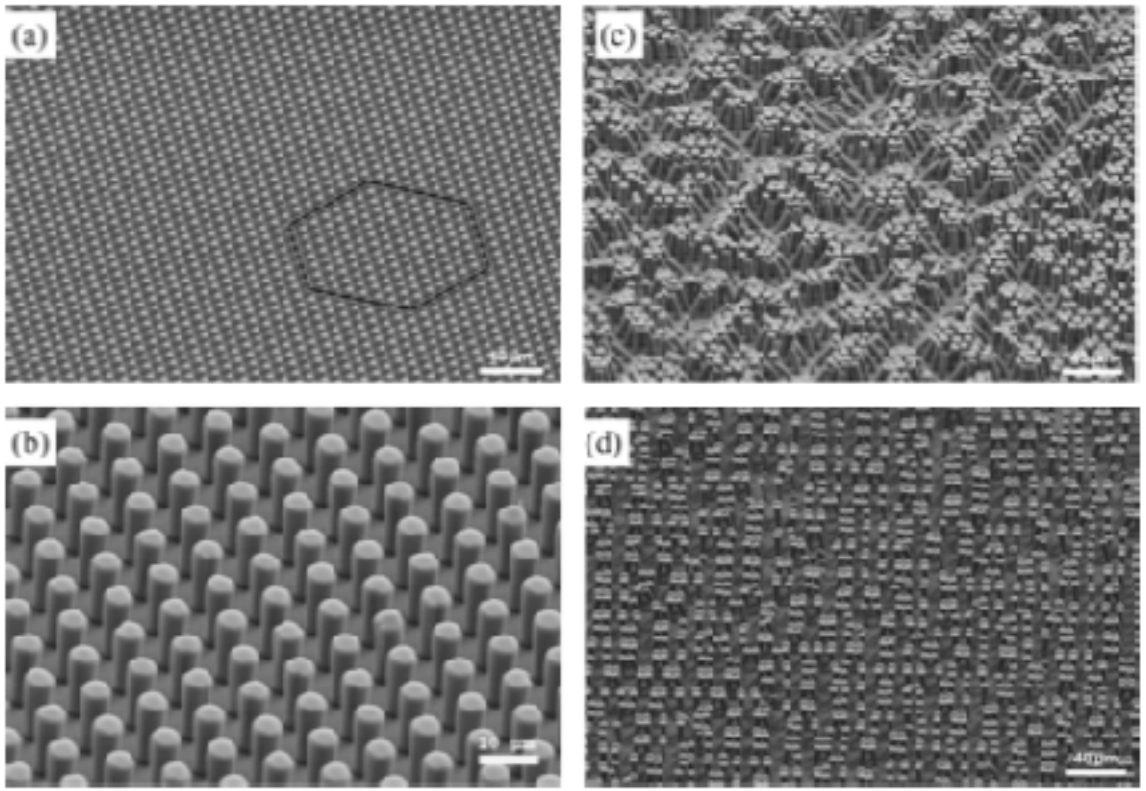
$\Delta\theta$ DECREASES

Water-repellency: requires the maintenance of a Cassie state

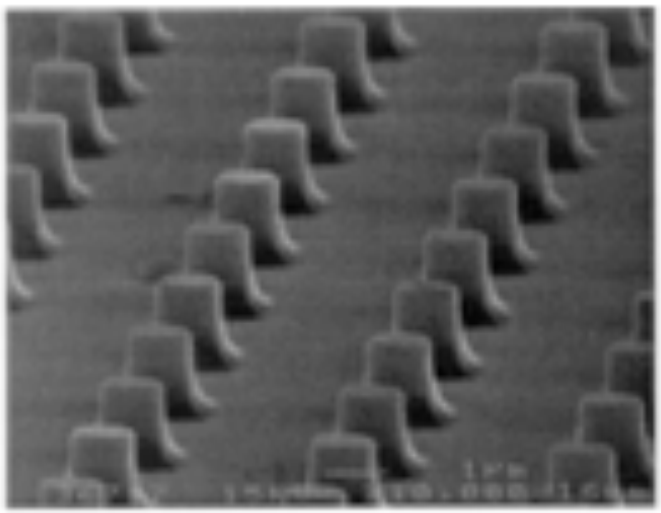
Biomimetic water-repellent surfaces: viable with new microfab techniques



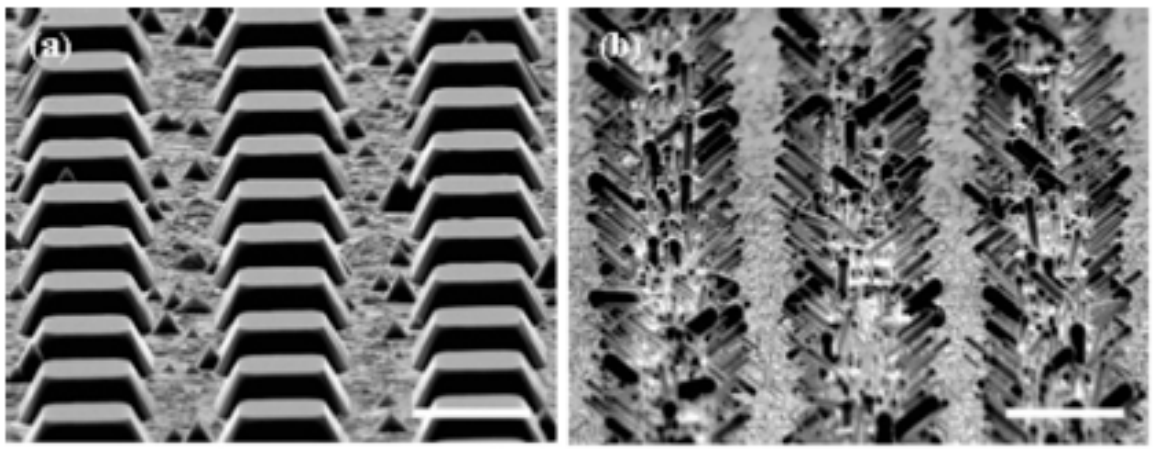
Lau et al. (2003)



Greiner et al. (2007)



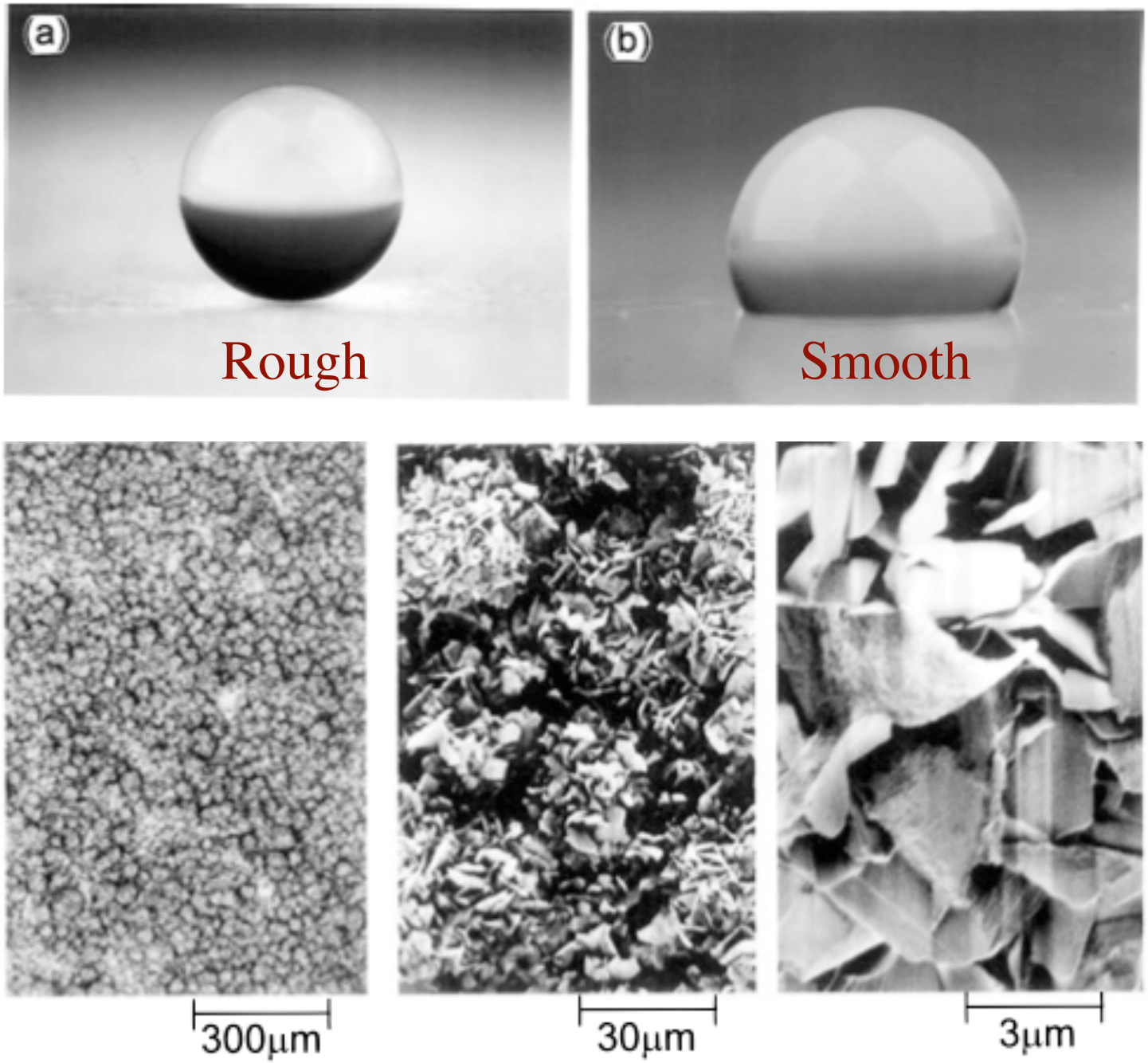
Bico et al. (1999)



Cao et al. (2007)

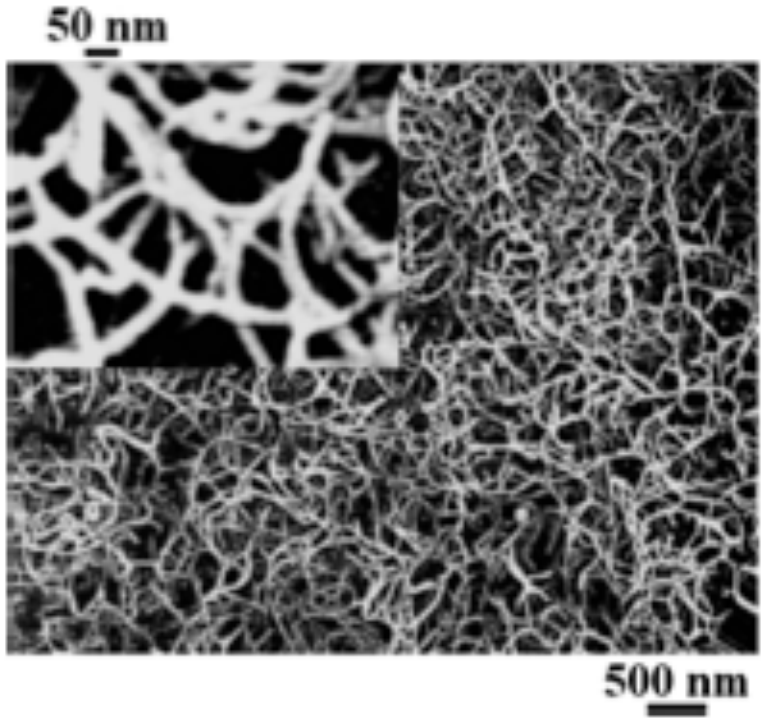
Superhydrophobic surfaces achieved with fractal texturing

Shibuichi et al. (1996), Onda et al. (1997), Herminghaus (2000)



A perfectly hydrophobic surface

Gao & McCarthy (2006)

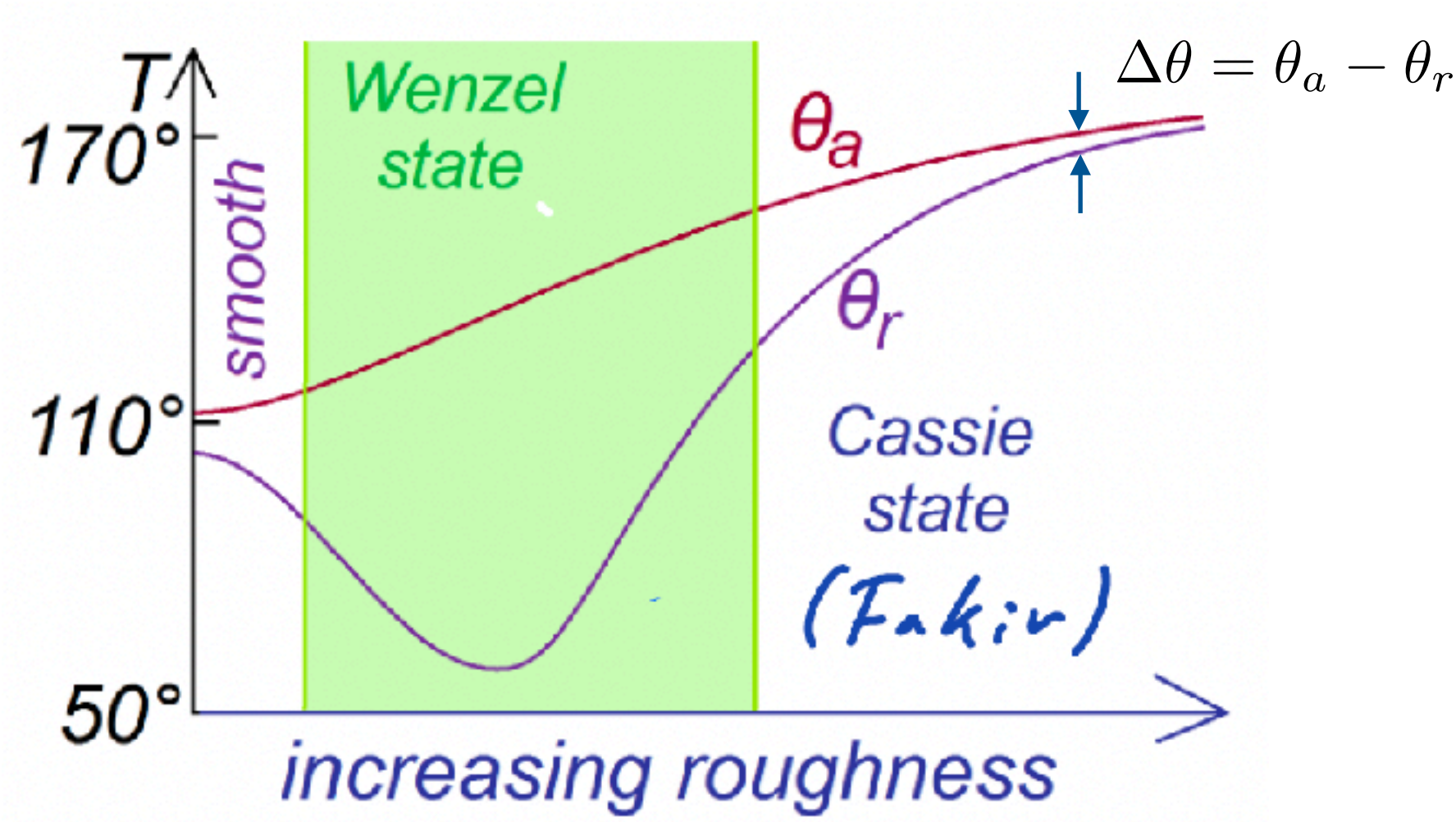


"The Lichao surface"

$$\theta = \theta_A = \theta_R = 180^\circ$$

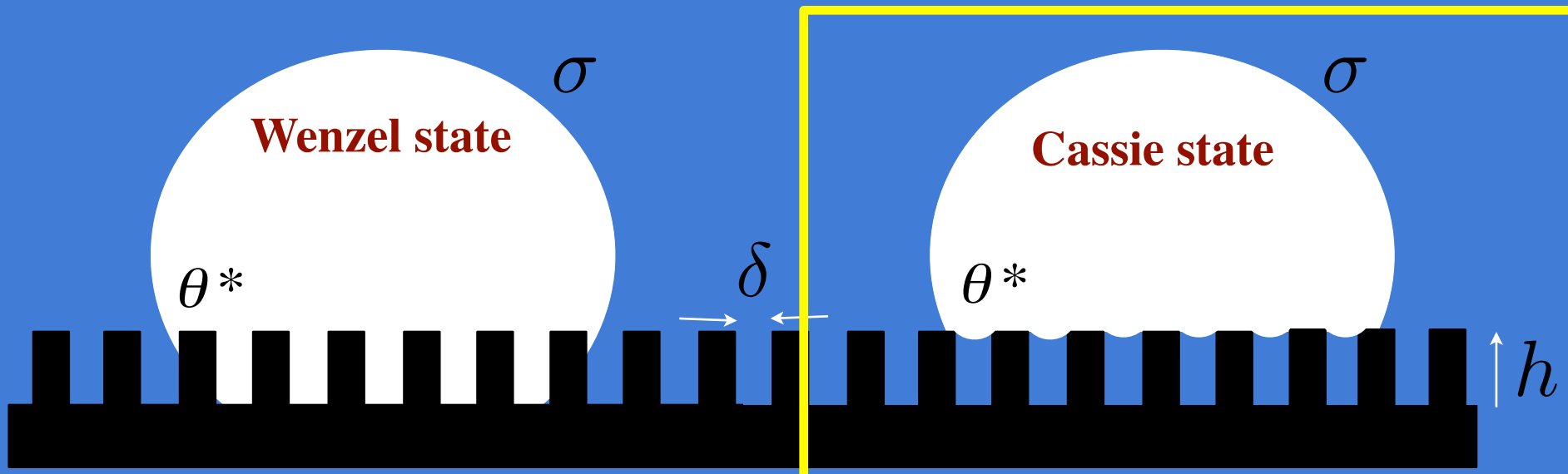
Water drops on wax Johnson & Dettre (1964)

- examined dependence of contact angle hysteresis on roughness, temperature



- showed increase, then decrease of $\Delta\theta$ with increasing roughness
- Cassie state required for water repellency

Wetting of a rough hydrophobic surface: Wenzel vs. Cassie



$$dW = r\, dx\, (\sigma_{SG} - \sigma_{SL}) - dx\, \sigma\, cos\theta^*$$

$$\cos\theta^* = r\, \cos\theta$$

where r is total/planar area

θ^* INCREASES, but $\Delta\theta$ INCREASES

$$\cos\theta^* = -1 + f_s + f_s \cos\theta$$

where f_s is exposed/planar area

θ^* INCREASES

$\Delta\theta$ DECREASES

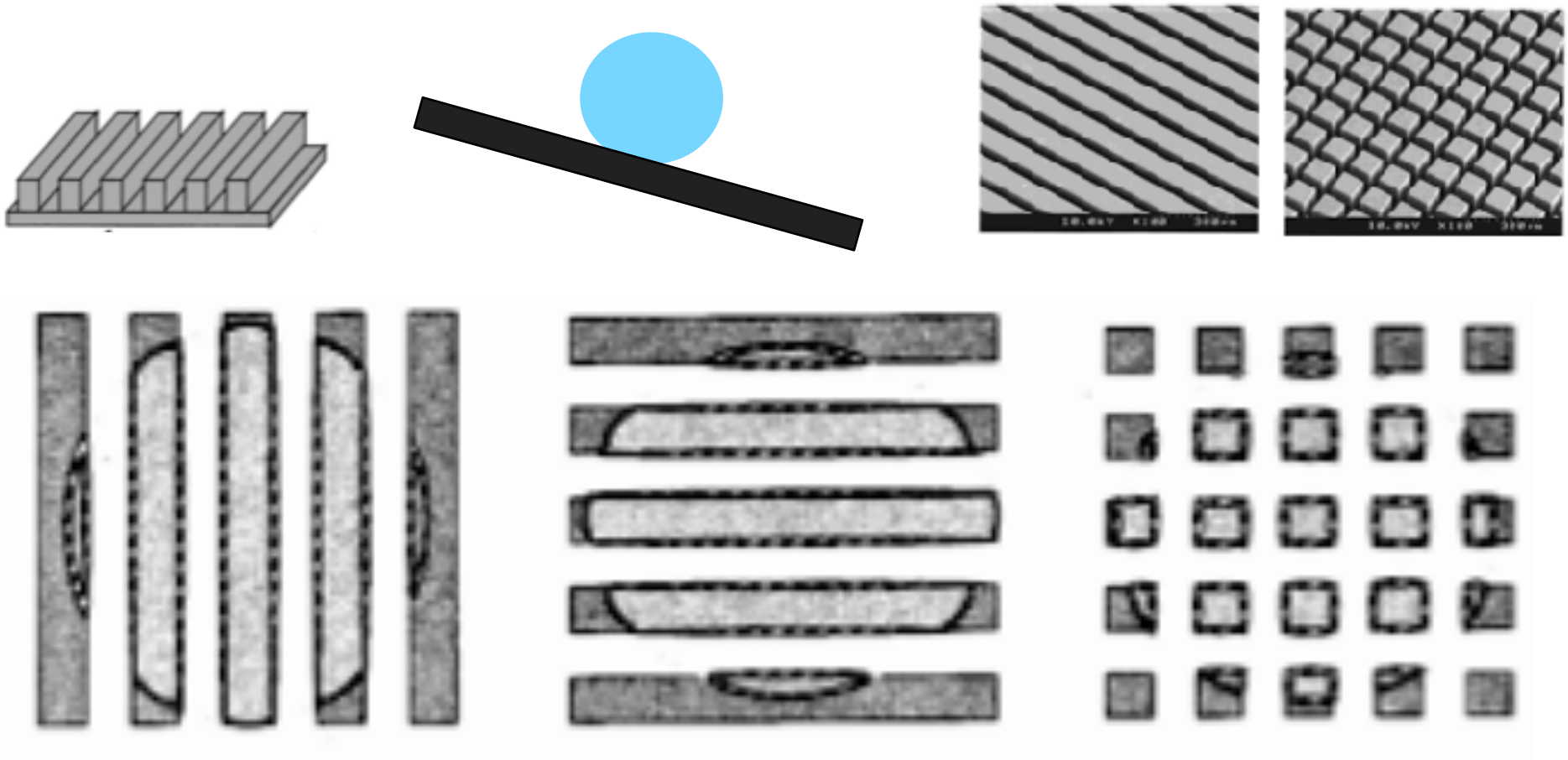
Water-repellency: requires the maintenance of a Cassie state

$$\rightarrow \quad P_{applied} < \sigma \left(\frac{1}{\delta}, \frac{h}{\delta^2} \right)$$

Bartolo et al. (2006)
Reyssat et al. (2007)

Surface texturing and directional adhesion

Yoshimitsu et al. (2002)

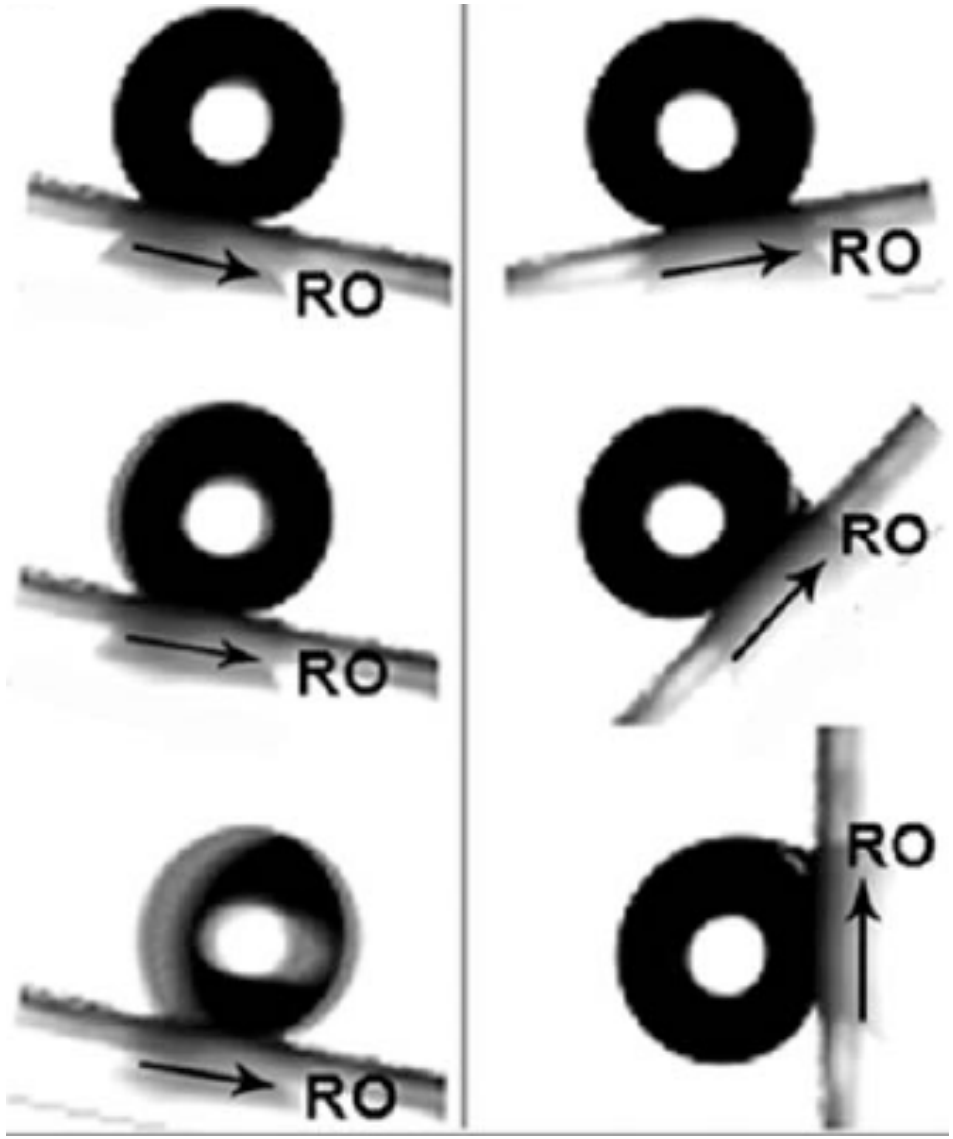


- drops move most easily along nanogrooves
- greatest resistance to motion perpendicular to grooves
- texturing introduces anisotropy in contact line resistance

Unidirectional adhesion

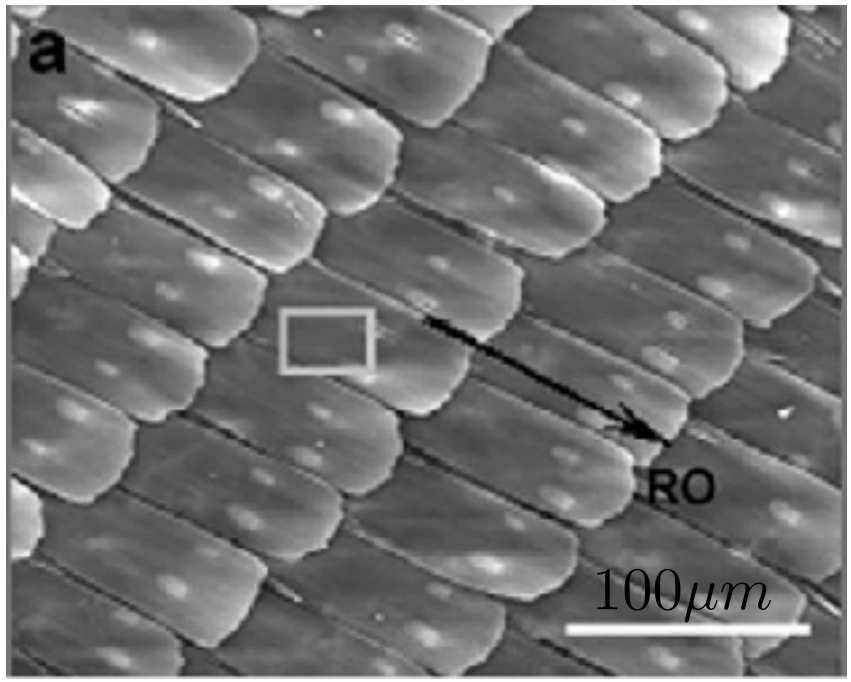
on the butterfly wing

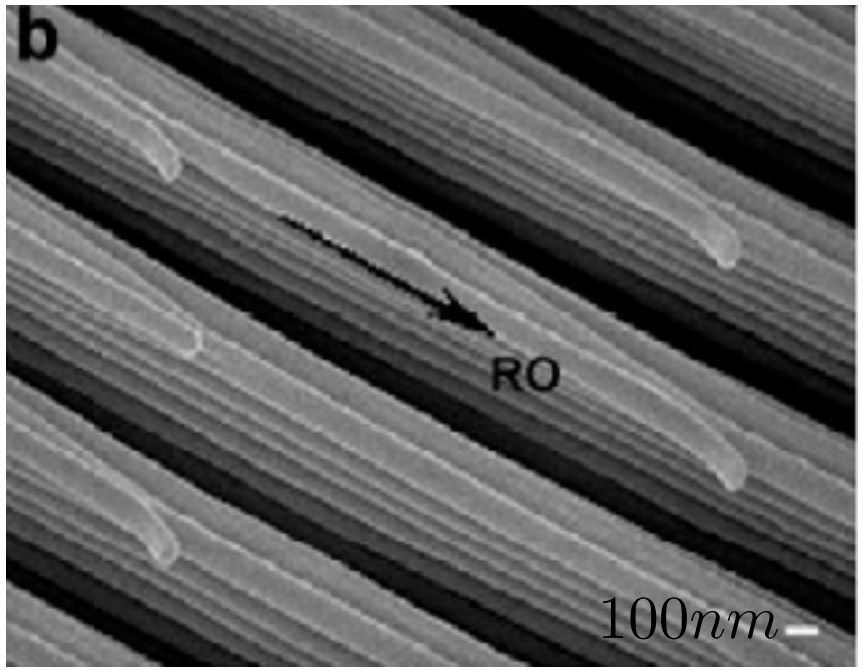
Zheng et al. (2007)

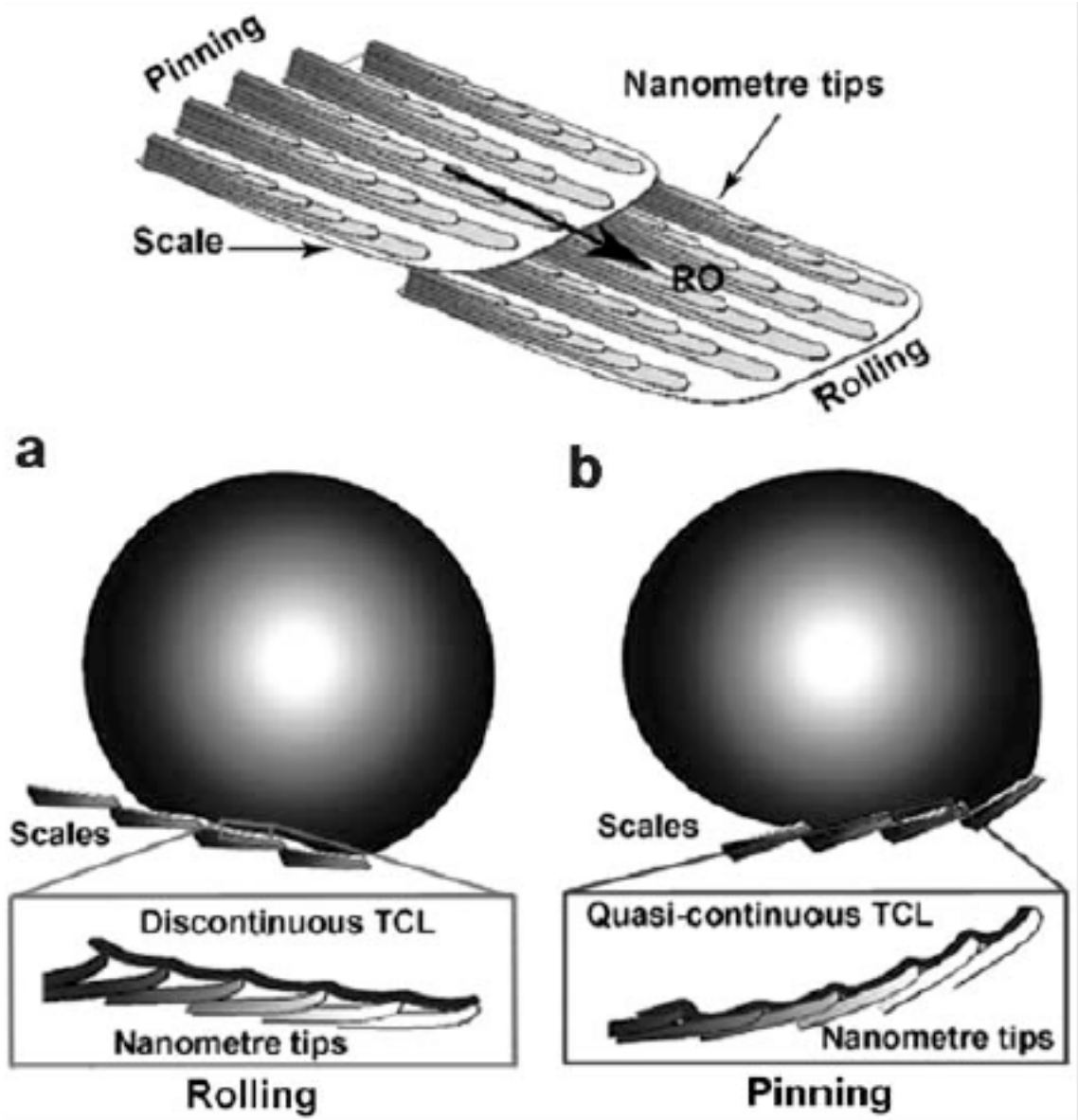


Unidirectional adhesion

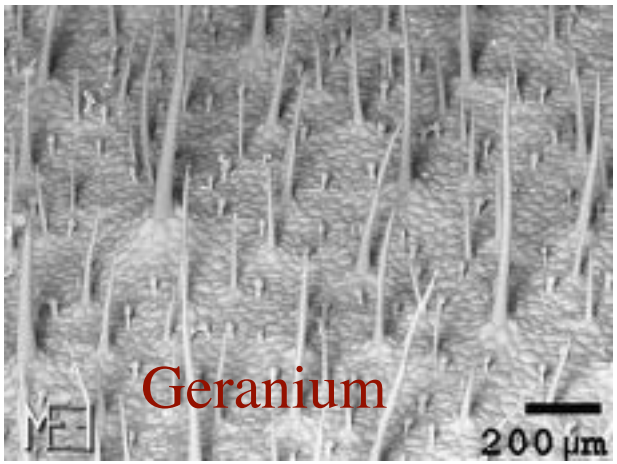
Zheng et al. (2007)

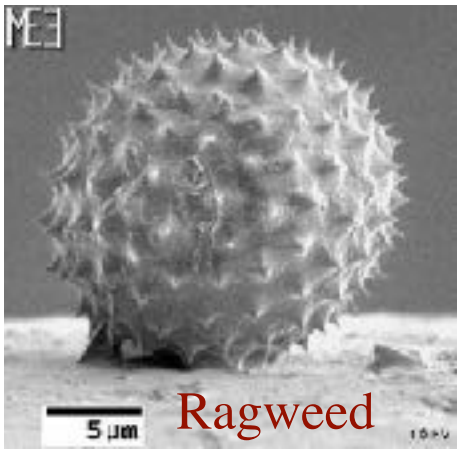






Plants are bumpy: isotropic roughness provides water-repellency

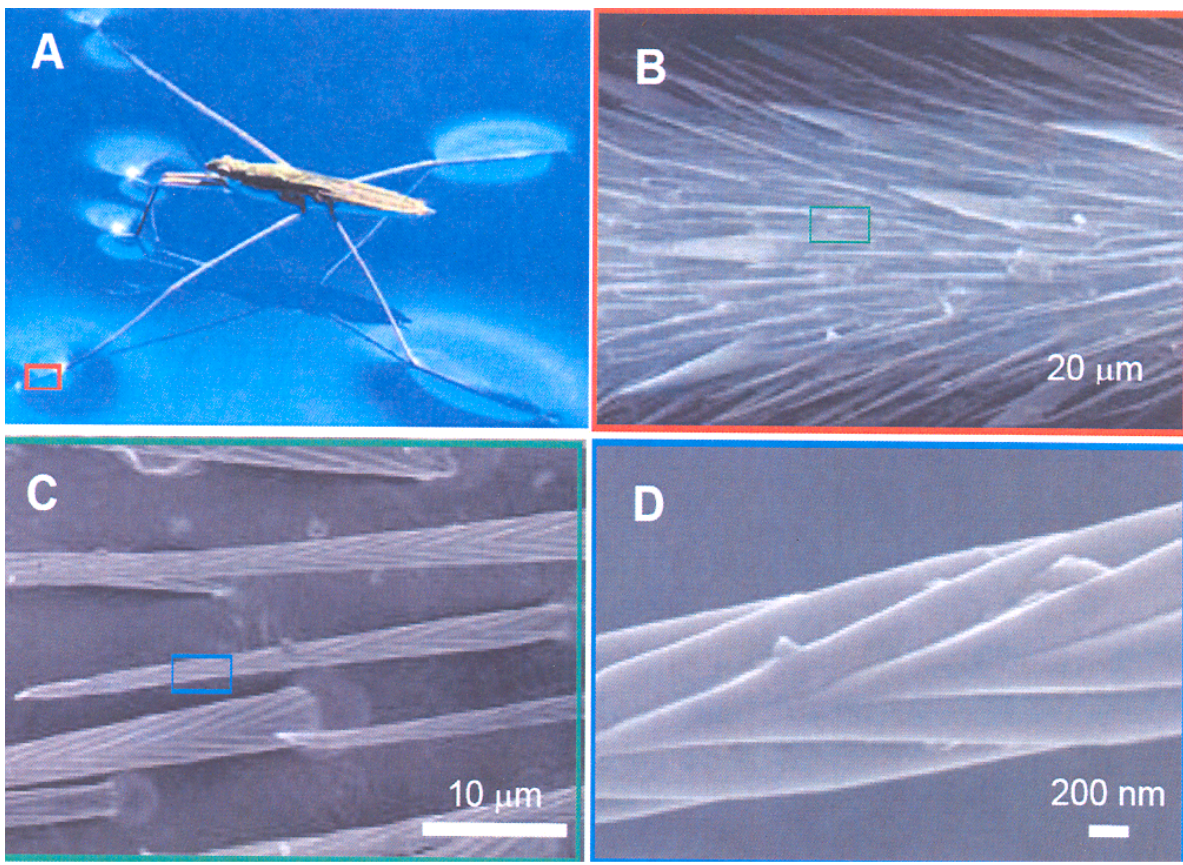




Water-walking bugs are hairy

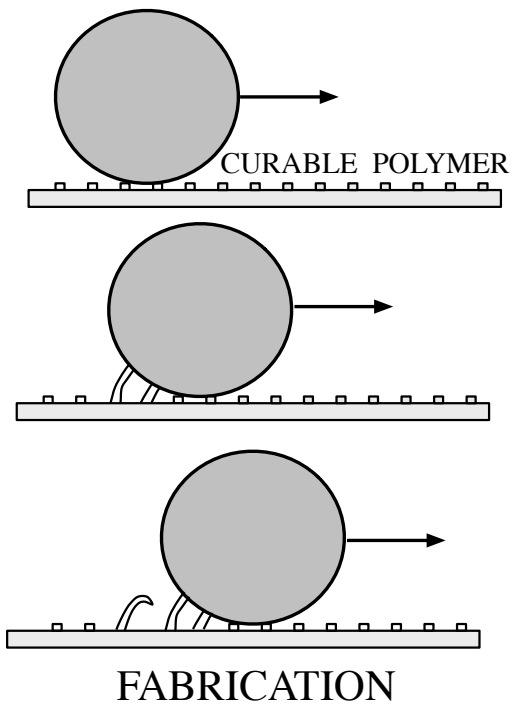
- roughness provides water-repellency
- driving leg exhibits *unidirectional adhesion*
- anisotropic roughness facilitates *propulsion*

(Prakash & Bush 2011)

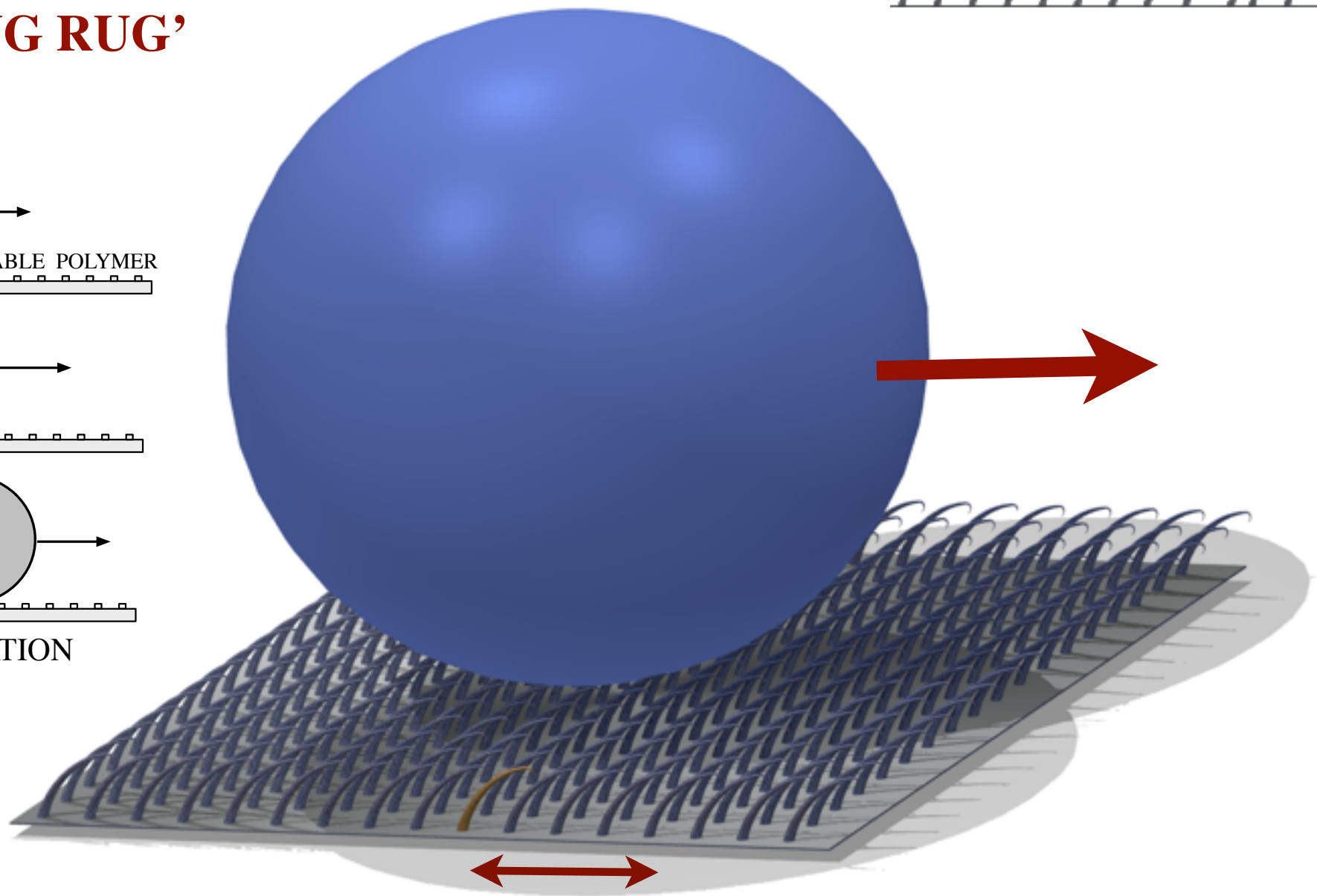


Biomimetic unidirectional surface

`THE BUG RUG'

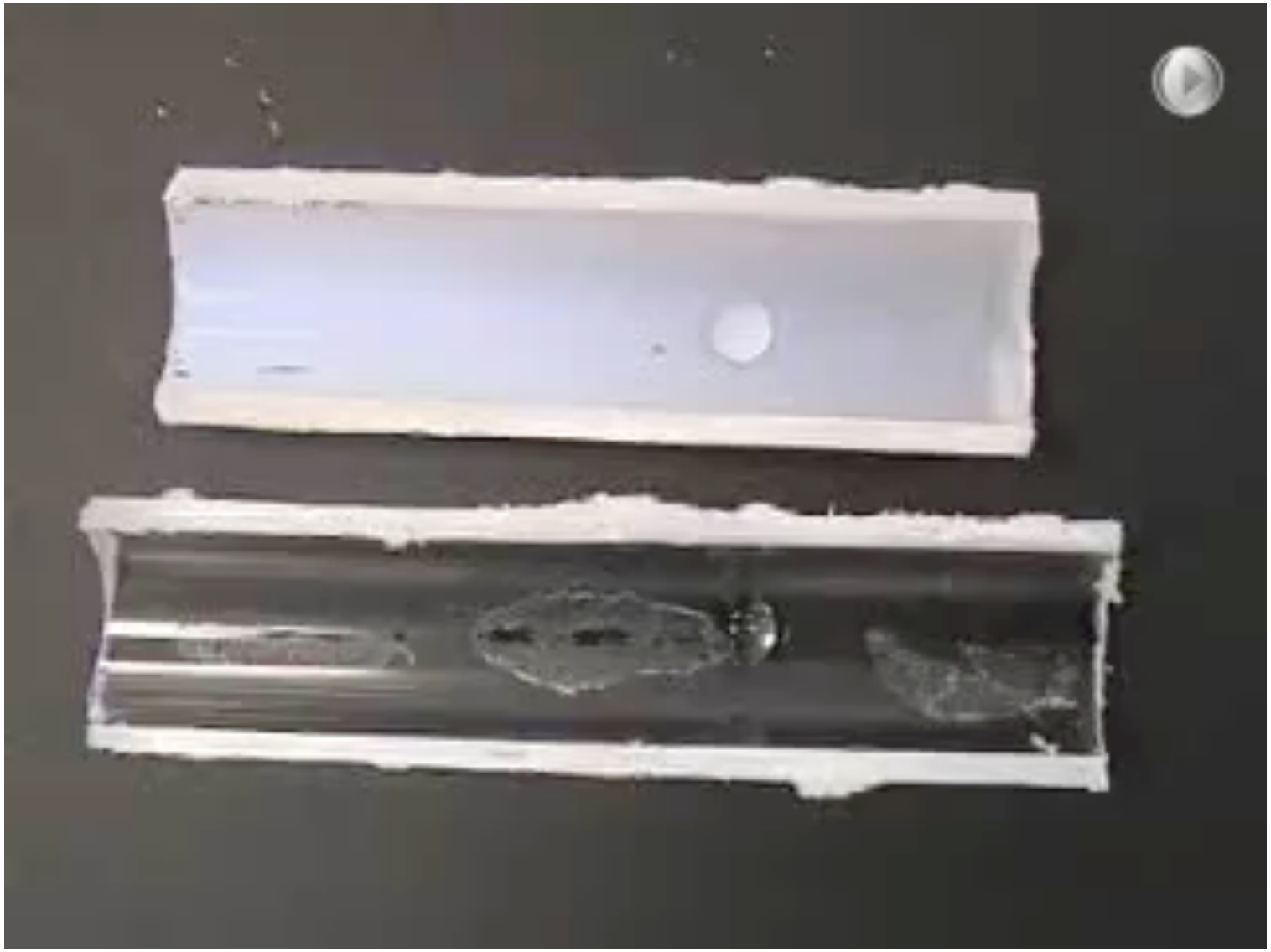


FABRICATION

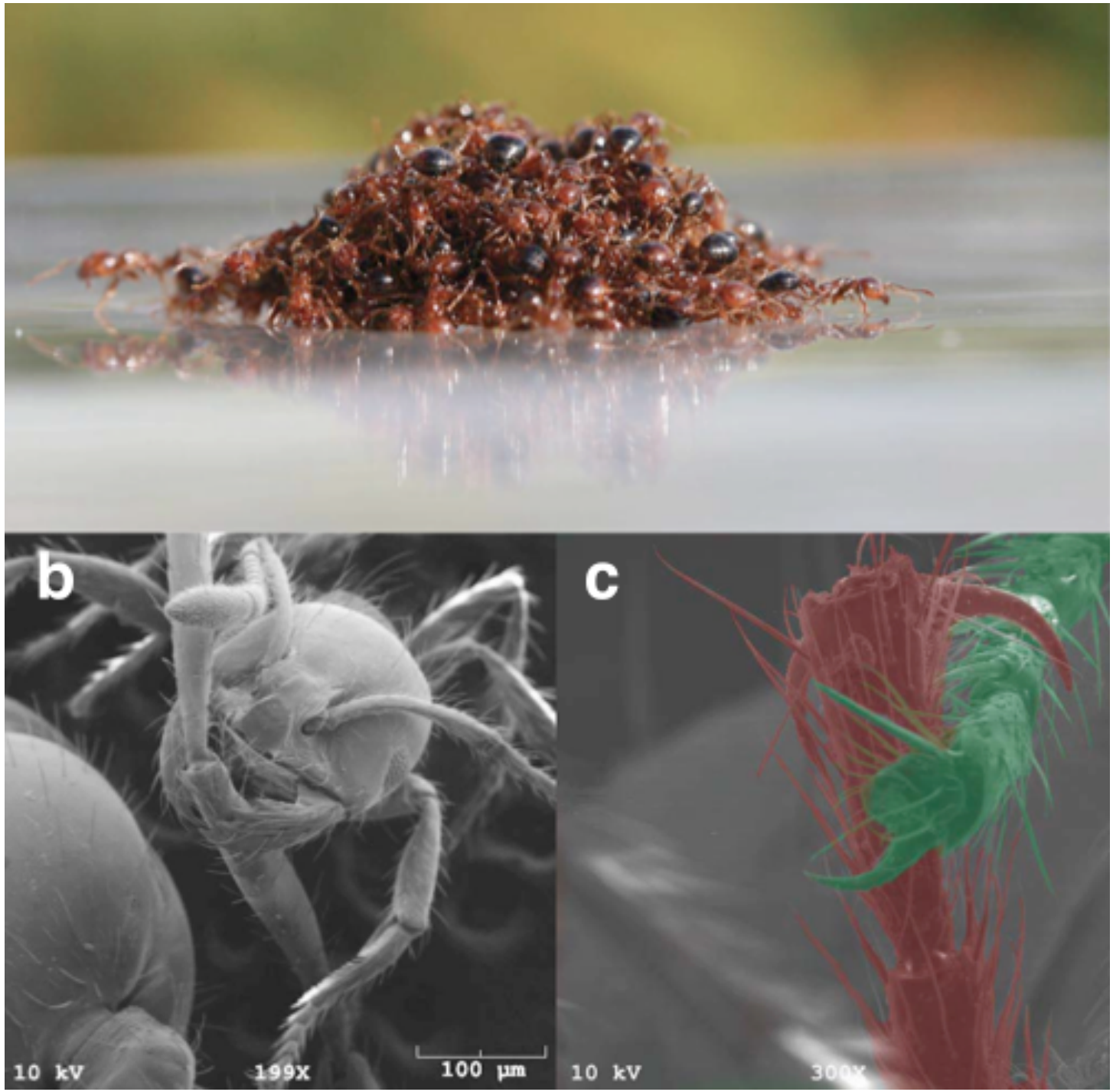


- permits drop motion in only one direction
- applications in directional draining, microfluidics

Vibration-induced motion on a directional surface



The ant raft: a self-assembling superhydrophobic surface



Mlot et al. (2011)