Biomimetic
and
Nature-Inspired Surfaces:

Innovation in Chemistry
and Engineering

Biomimetics and Bio-Inspired Engineering

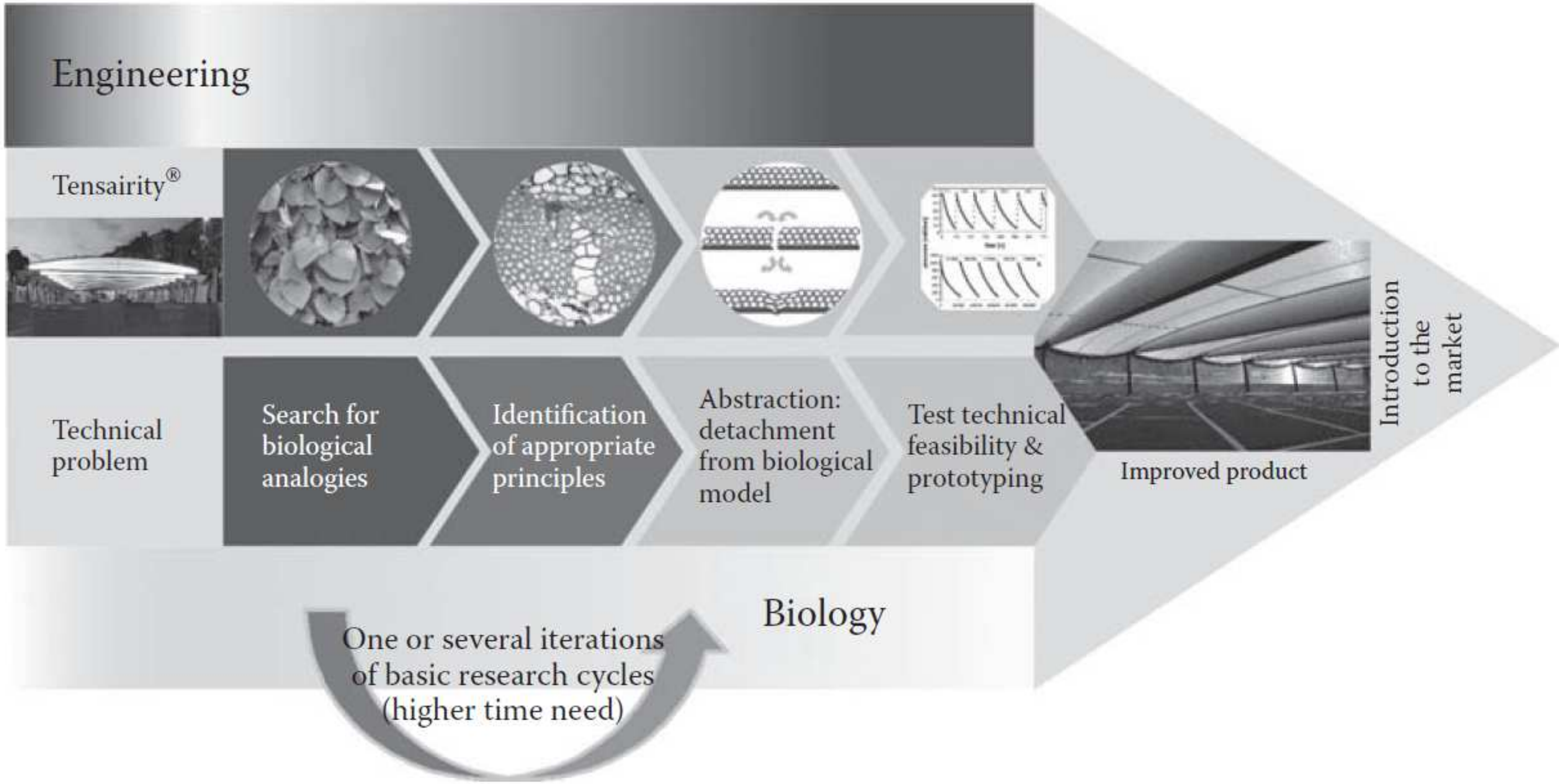


FIGURE 12.4
Development of self-repairing membranes in an extended top-down-process (see Section 12.1). (Copyright Plant Biomechanics Group University of Freiburg.)

Yoseph Bar-Cohen-Biomimetics_ Nature-Based Innovation-CRC Press (2011)

Biological vs. Synthetic Polymers and Materials

Table 14.1 Comparison between Biological and Nonbiological Polymer or Materials Synthesis and Assembly

Feature	Laboratory	Nature
Synthesis		
Monomer	Usually racemates	Stereochemically pure
Blocks or domains	Usually mono or diblocks	Mono to highly diverse blocks
Polymerization	Comparatively rapid — mostly polydisperse	Comparatively slow template control — monodisperse (proteins, nucleic acids); others polydisperse (polysaccharides)
Processing or assembly		
Plasticizers	Varied, mostly organic	Water
Polymer interactions	Chain entanglements, fringed micelle model	Less chain entanglements, extensive hydrogen bonding and other weak interactions
Higher order structures features	Varied, rare	Common, controlled by chain interactions
Organic–inorganic composites	Usually mixtures, composites	Molecular-level interfaces controlled by weak bonds
Fate		
Environmental stability	Wide range of temperature	Narrower range of temperature
Degradability	Varies with polymer, most nondegradable	Universally degradable, rate matches function

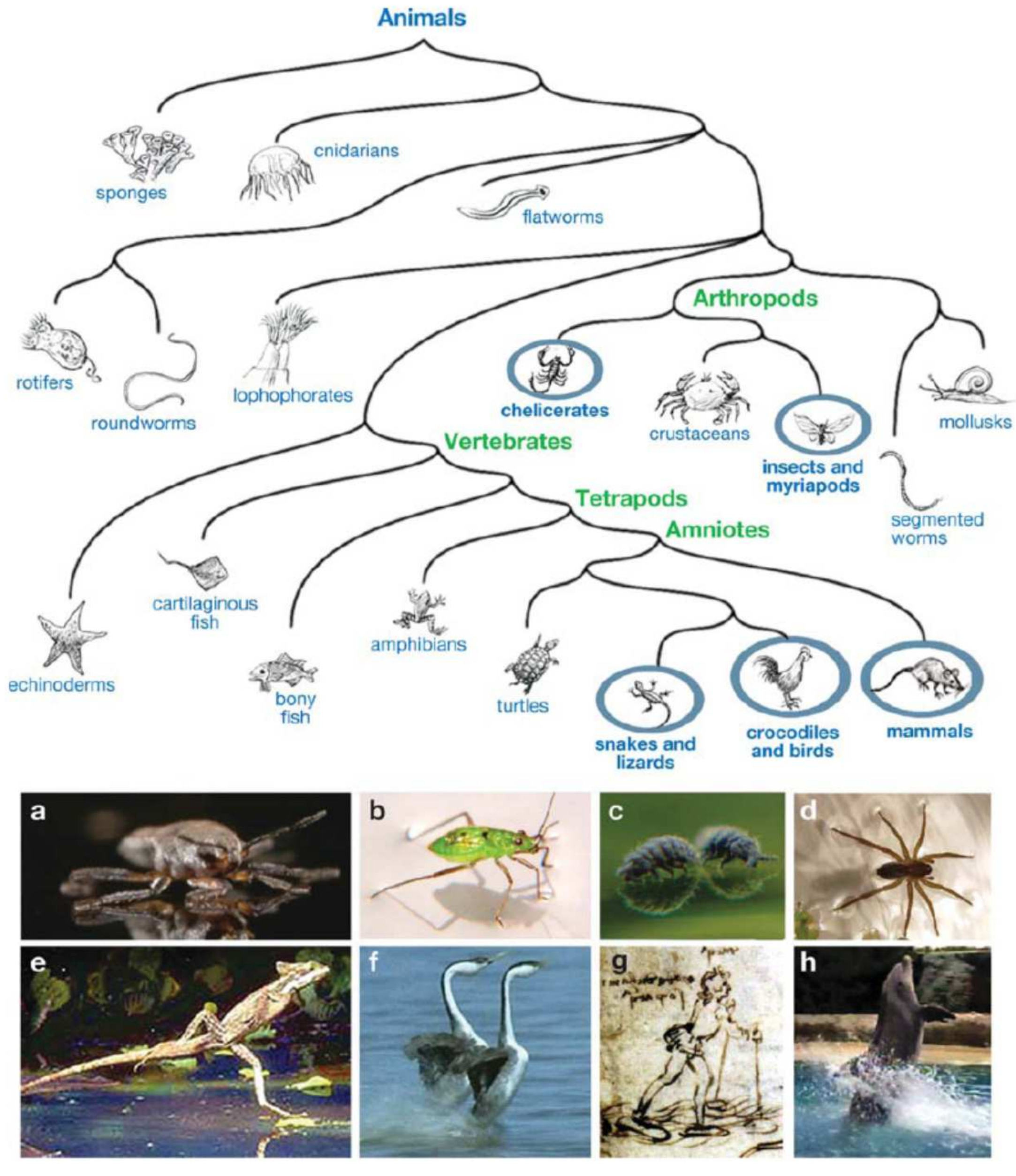
Yoseph Bar-Cohen-Biomimetics_ Biologically Inspired Technologies-CRC Press (2005)

Nature Uses Surface and Interfacial Tensions

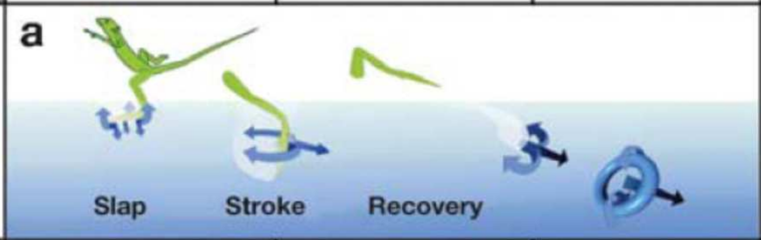
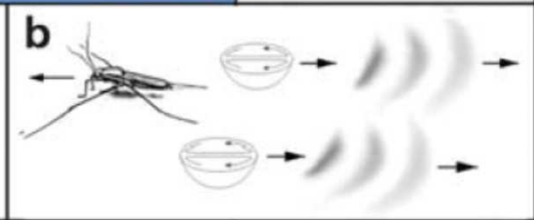
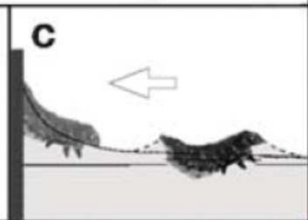
Walking on Water: Biolocomotion at the Interface

John W.M. Bush and David L. Hu

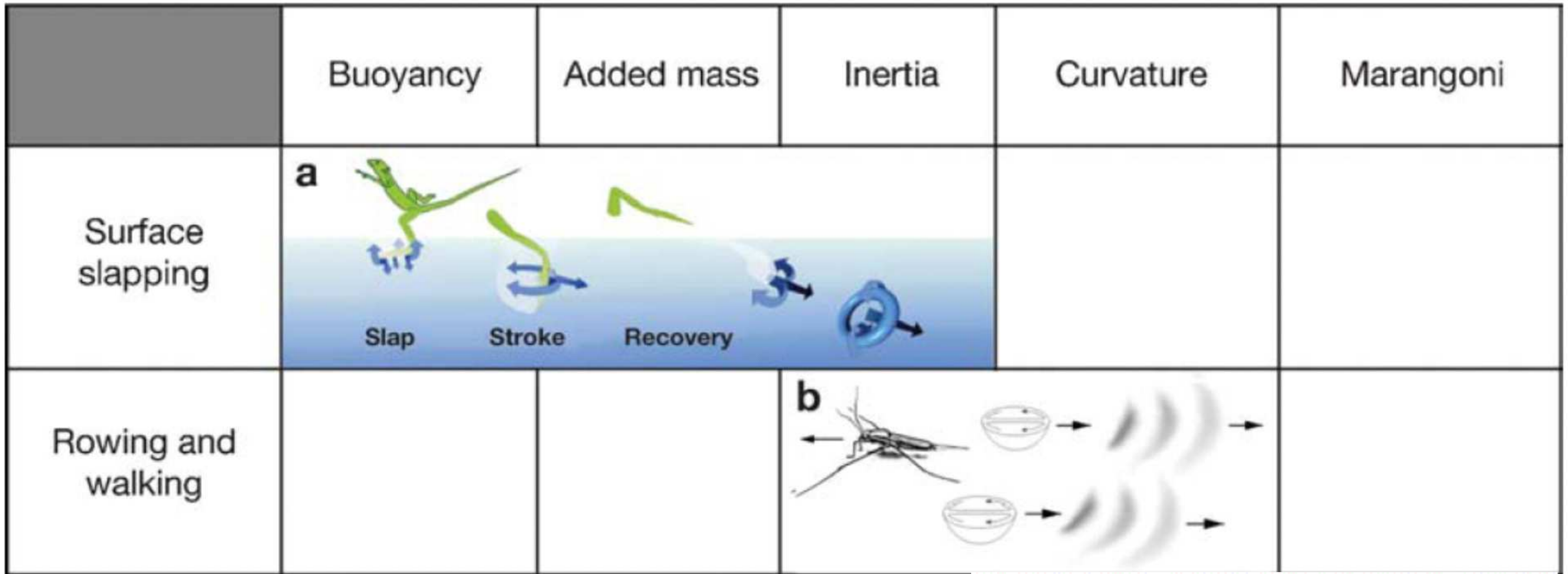
Annu. Rev. Fluid. Mech. 2006.*38*:339-369.

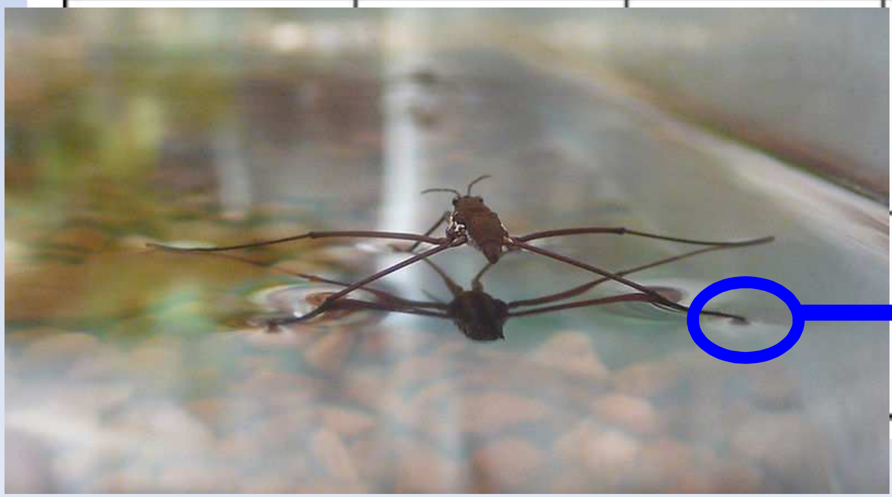


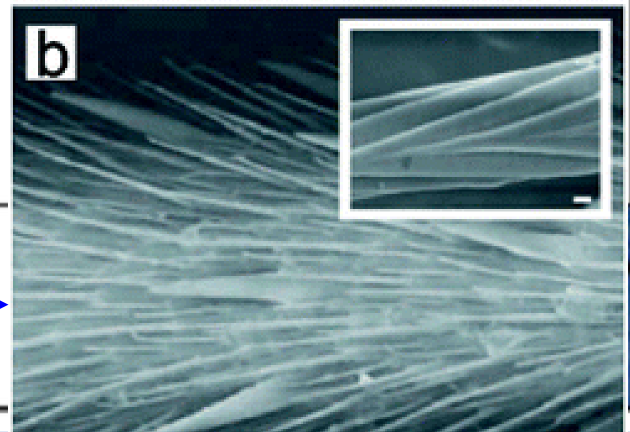
Nature Uses Surface and Interfacial Tensions

	Buoyancy	Added mass	Inertia	Curvature	Marangoni
Surface slapping					
Rowing and walking					
Meniscus climbing					
Marangoni propulsion					

Nature Uses Surface and Interfacial Tensions







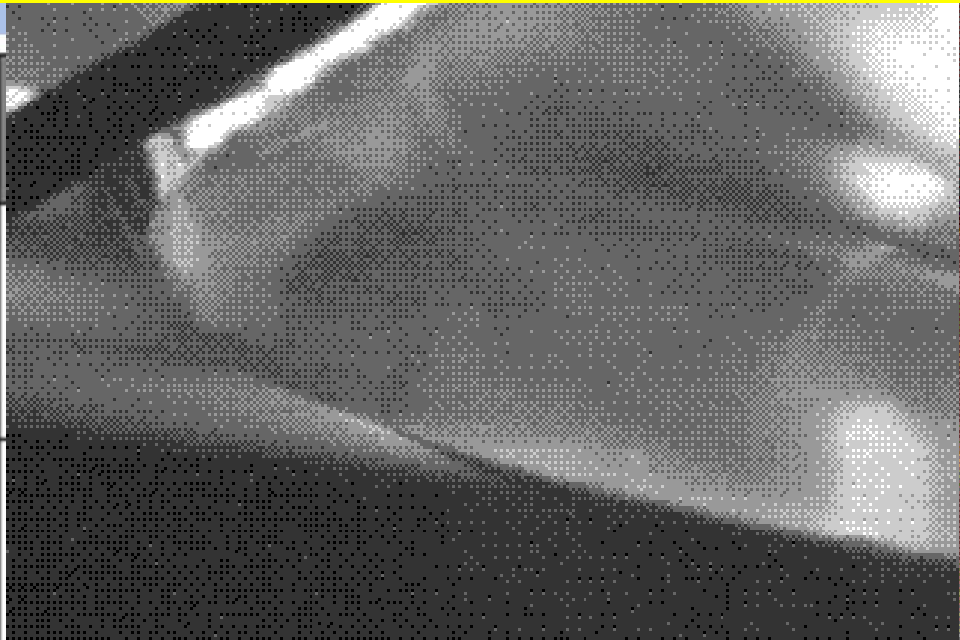
Nature, 2004, *432*, 36.

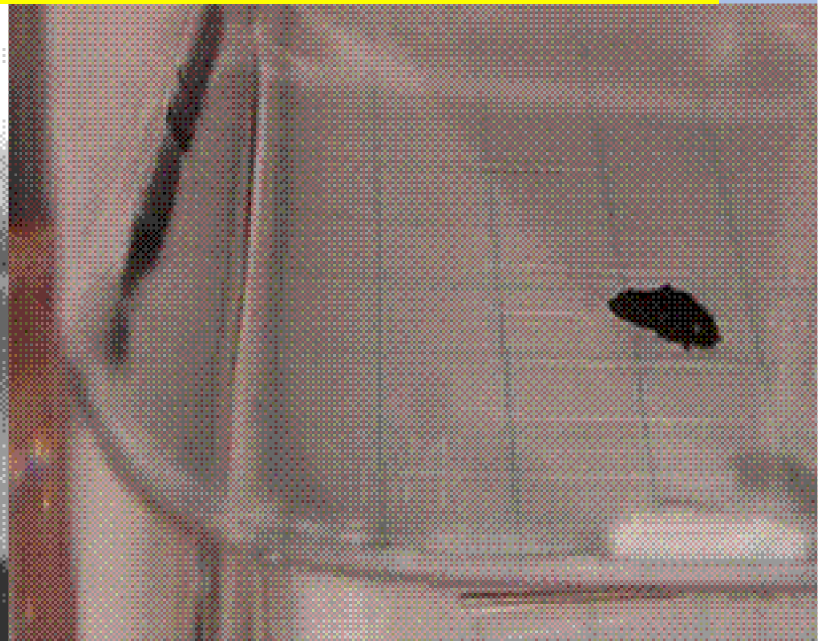
Nature Uses Surface and Interfacial Tensions

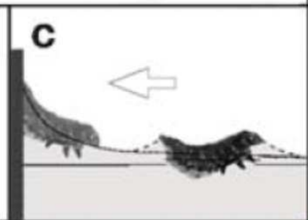
https://youtu.be/Z83l347rh6E?t=9

Nature, 2004, *432*, 36.

Nature Uses Surface and Interfacial Tensions





Meniscus climbing				c 	
Marangoni propulsion					d 

Nature Uses Surface and Interfacial Tensions

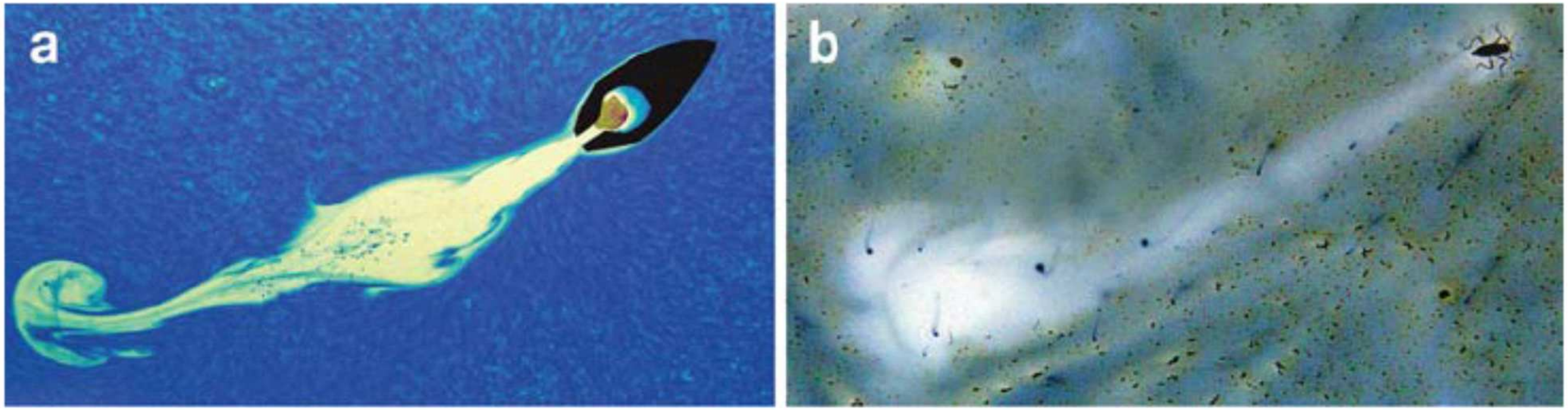
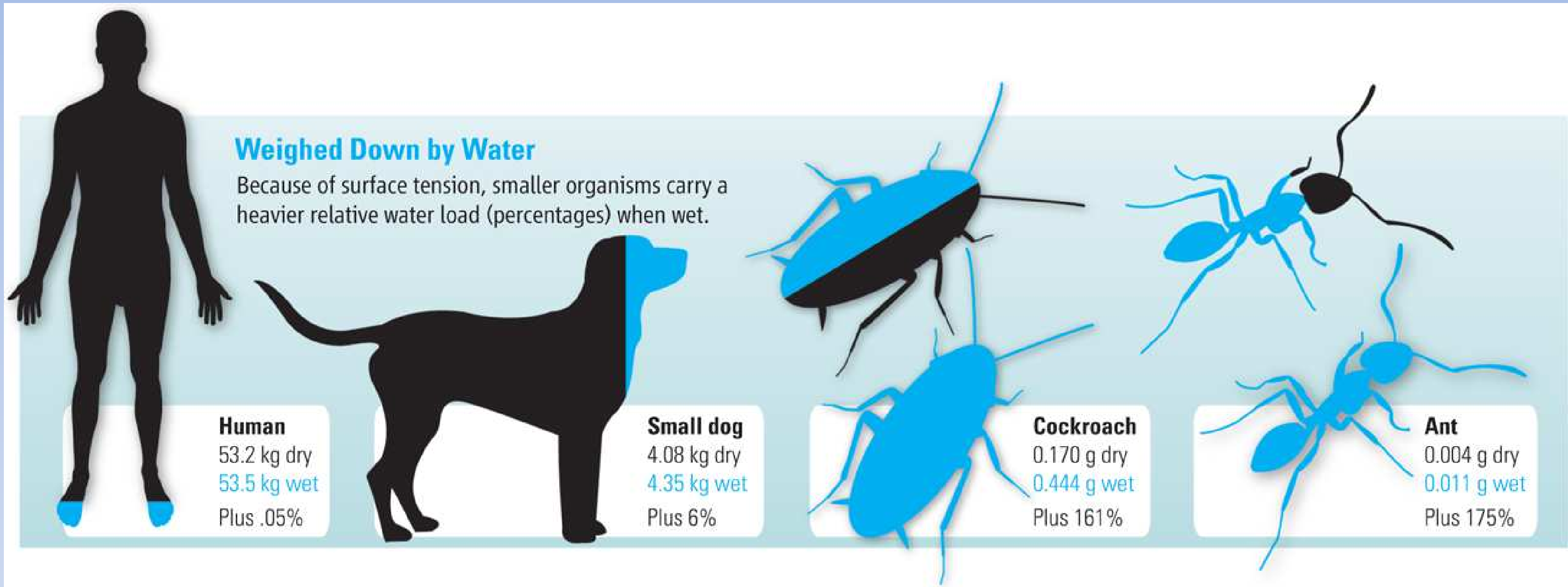


Figure 9

Marangoni propulsion for (*a*) a "soap boat," and (*b*) *Microvelia*. The latter releases a small volume of surfactant; the resulting surface tension gradient propels it forward. In both systems, the surface divergence generated by the surfactant is evident in the clearing of dye from the free surface.

					
Marangoni propulsion					



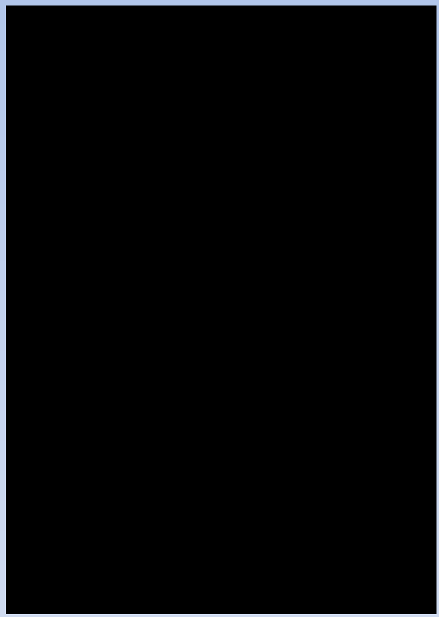
Elizabeth Pennisi Science 2014;343:1194-1197

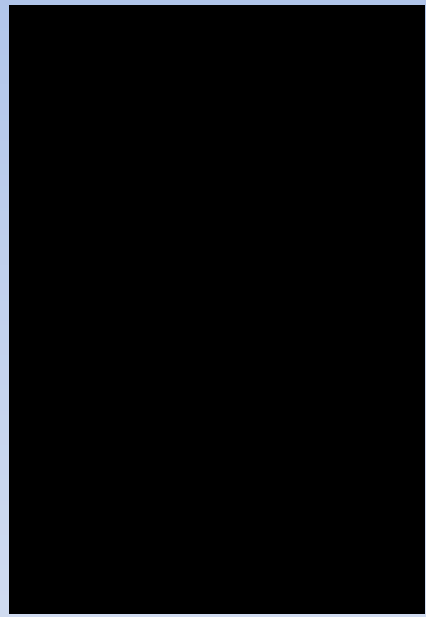
Published by AAAS

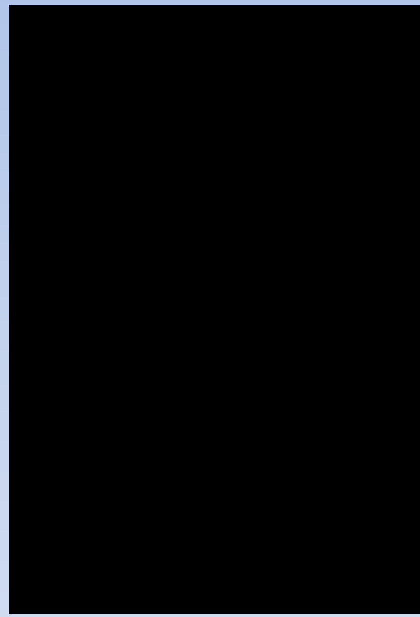
The Cheerio Effect

Cheerio Effect-NIcNrsTlbVU_x264

The Cheerio Effect

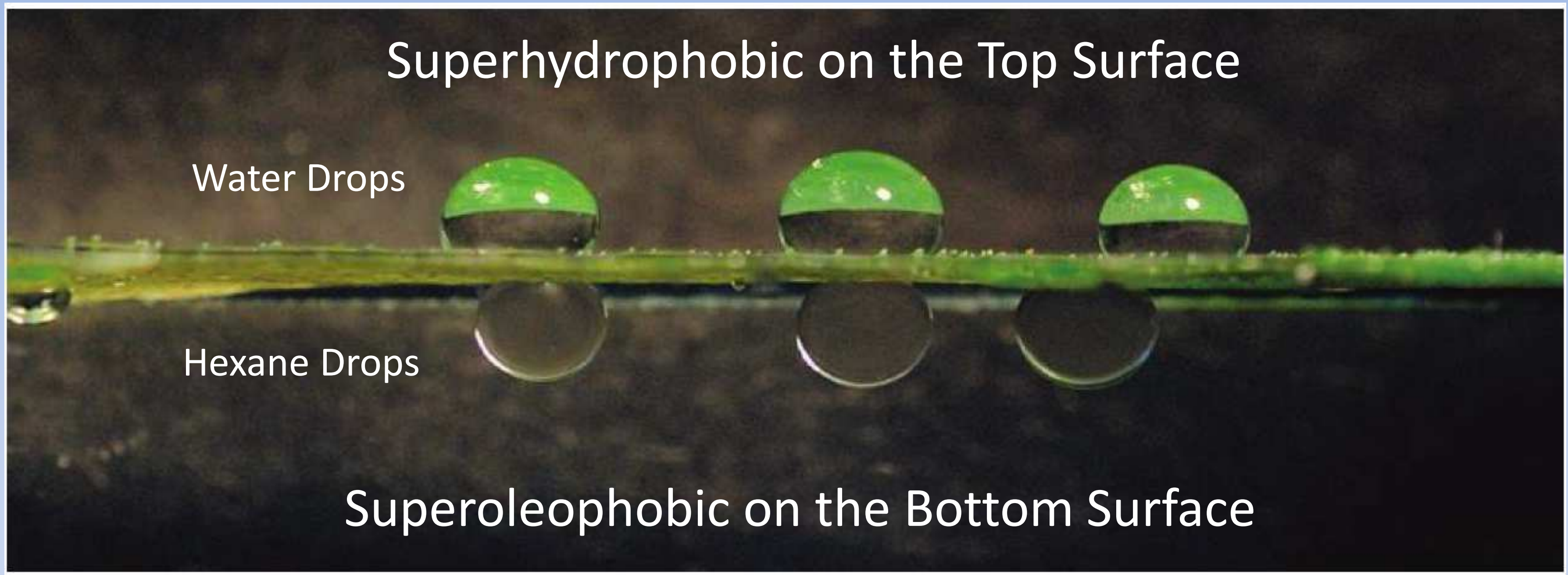


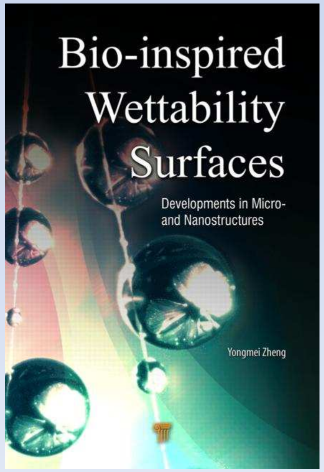




From: Karpitschka et al., Liquid drops attract or repel by the inverted Cheerios effect, *PNAS* **2016**, *113*, 7403–7407, doi: 10.1073/pnas.1601411113
See also: Anand Jagota, Role reversal: Liquid "Cheerios" on a solid sense each other, *PNAS*, **2016**, *113*, 7294–7295, doi: 10.1073/pnas.1607893113

The Lotus Leaf





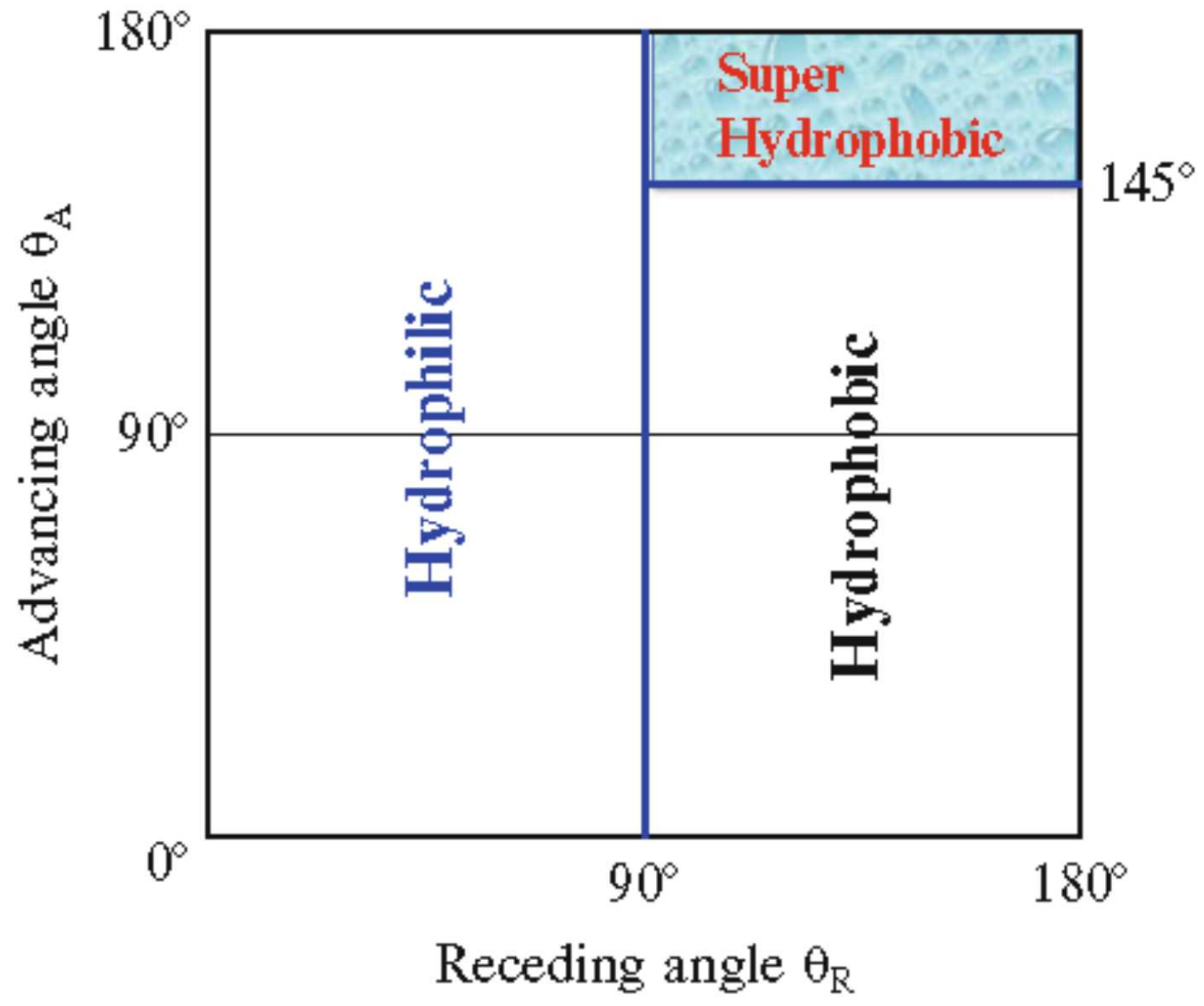
The Lotus Leaf and Rose Petal Effects

lotus leaf and rose petal effect

Zoom Into the Upper Side of a Lotus Leaf

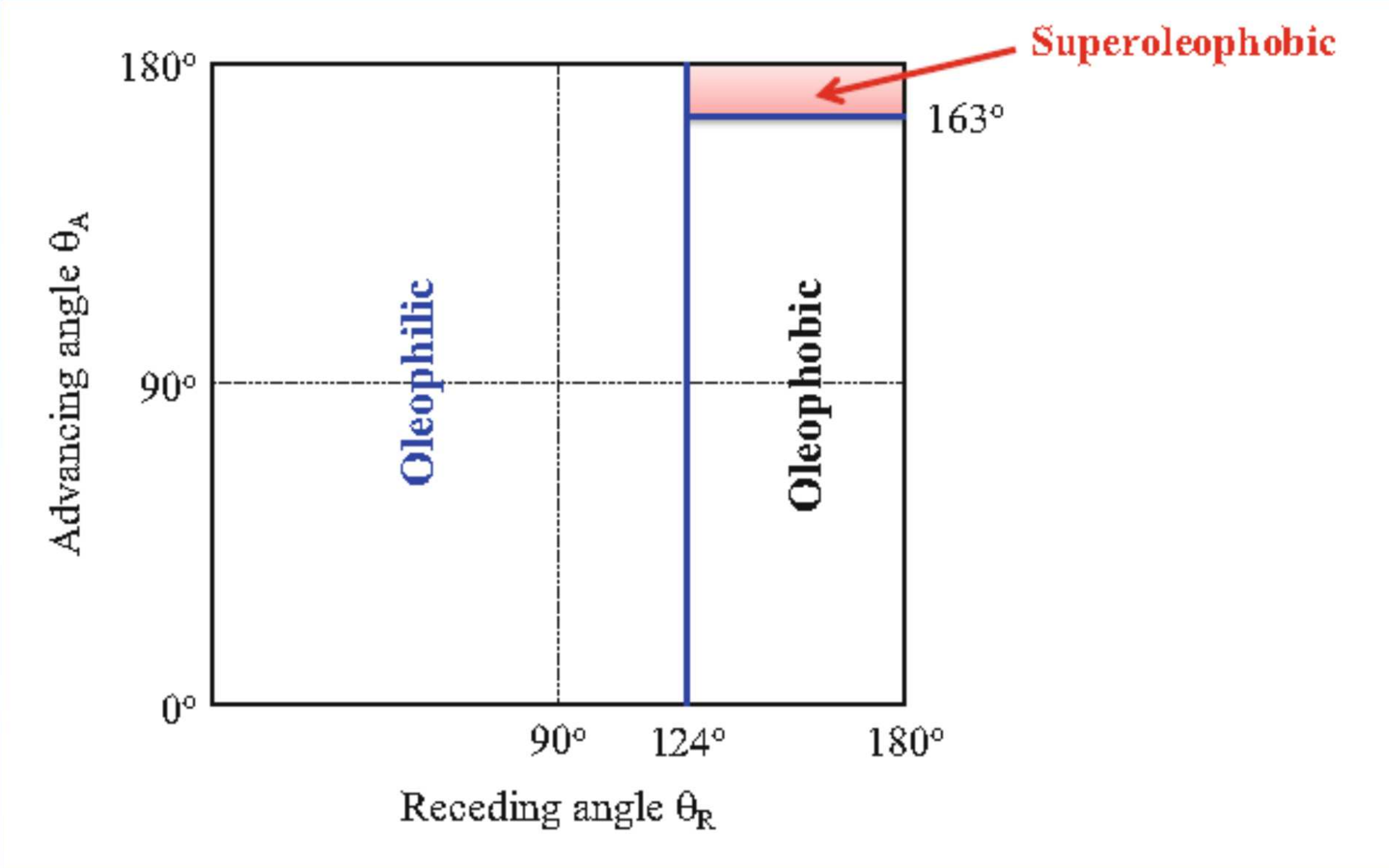
Zoom Into a Lotus Leaf (Narrated)

Defining Hydrophilic and Hydrophobic Surfaces from Contact Angle



Law KY (2014) Definitions for hydrophilicity, hydrophobicity and superhydrophobicity getting the basics right. J Phys Chem Lett 5:686–688

Defining Oleophilic and Oleophobic Surfaces from Contact Angle

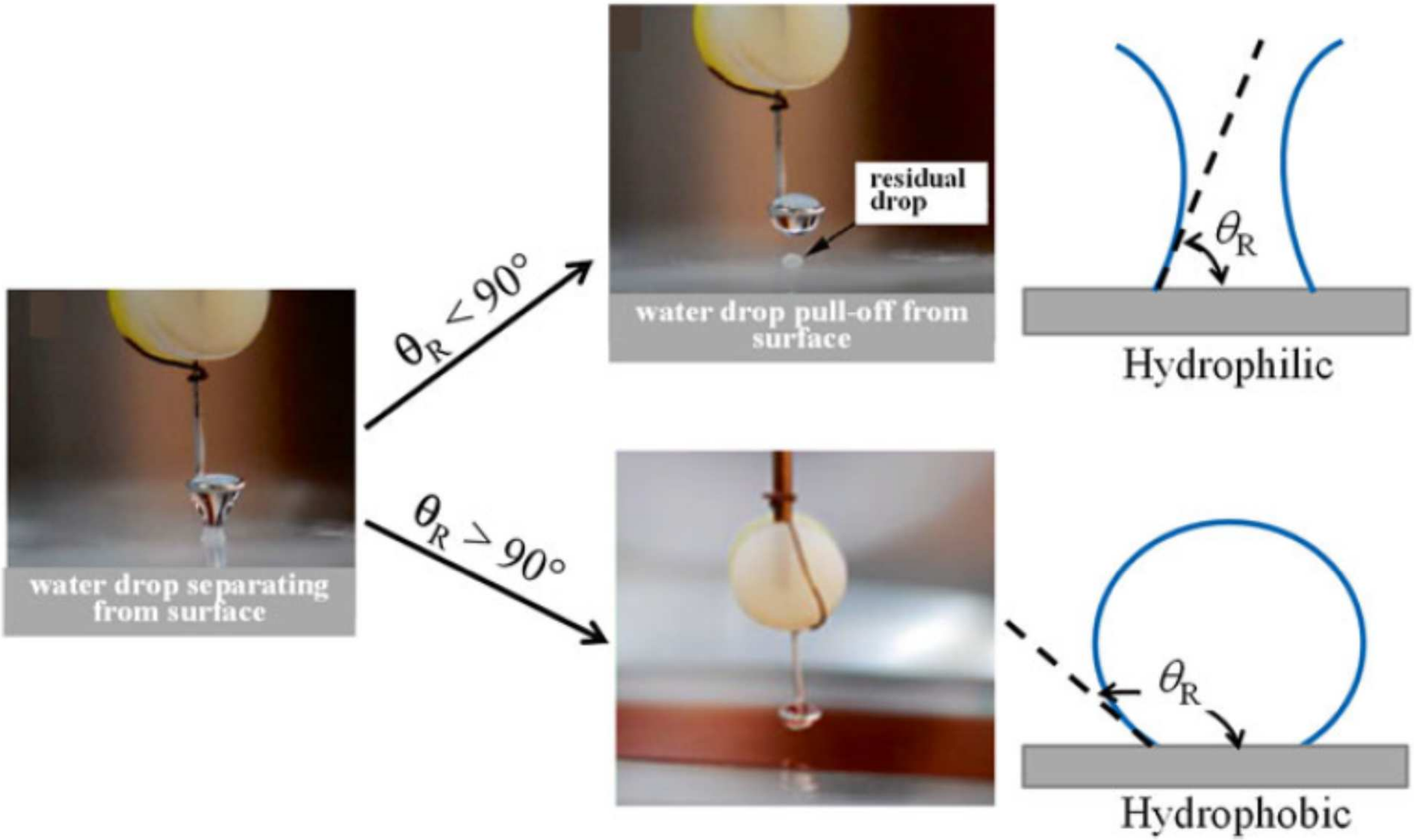


Law KY (2015) Water-surface interactions and definitions for hydrophilicity, hydrophobicity and superhydrophobicity. Pure Appl Chem 87(8):759–765

Water Drop Bouncing on a Superhydrophobic Surface

Bouncing Water Droplet Falling onto Super-Hydrophobic Surface-riXp_Q-fDv8_x264

Removing Water Drops from Hydrophilic and Hydrophobic Surfaces

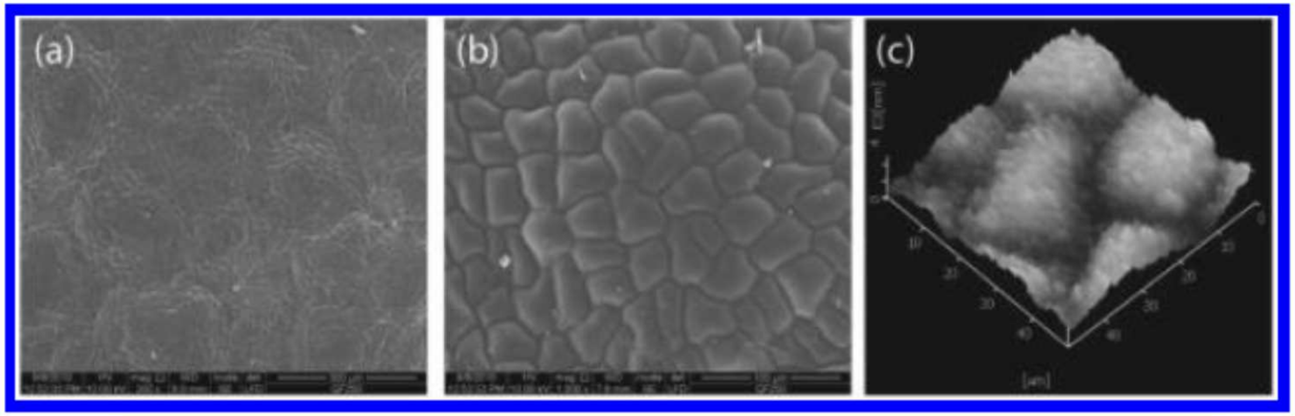


Law KY (2014) Definitions for hydrophilicity, hydrophobicity and superhydrophobicity getting the basics right. J Phys Chem Lett 5:686–688

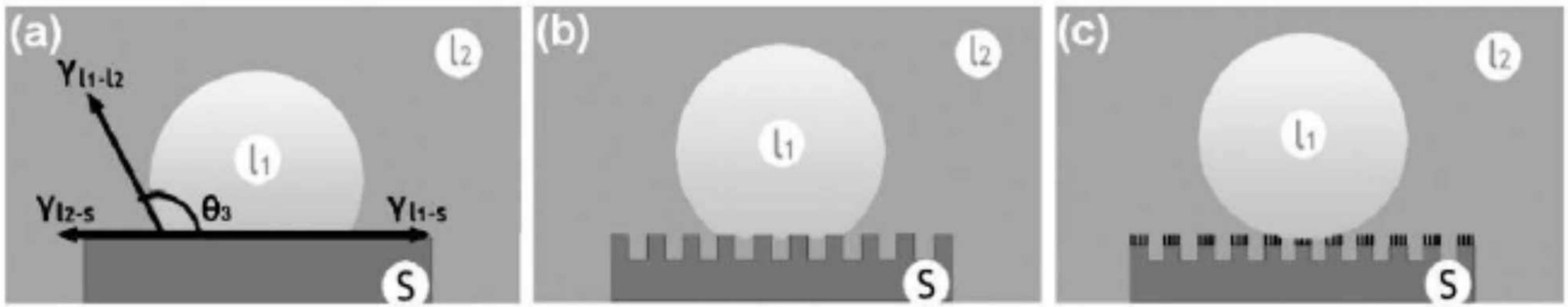
Practical Applications of Superhydrophobic Surfaces

The SECOND Official Ultra-Ever Dry Video - Superhydrophobic coating - Repels almost any liquid!-BvTkefJHfC0_x264

The Underside of the Lotus Leaf

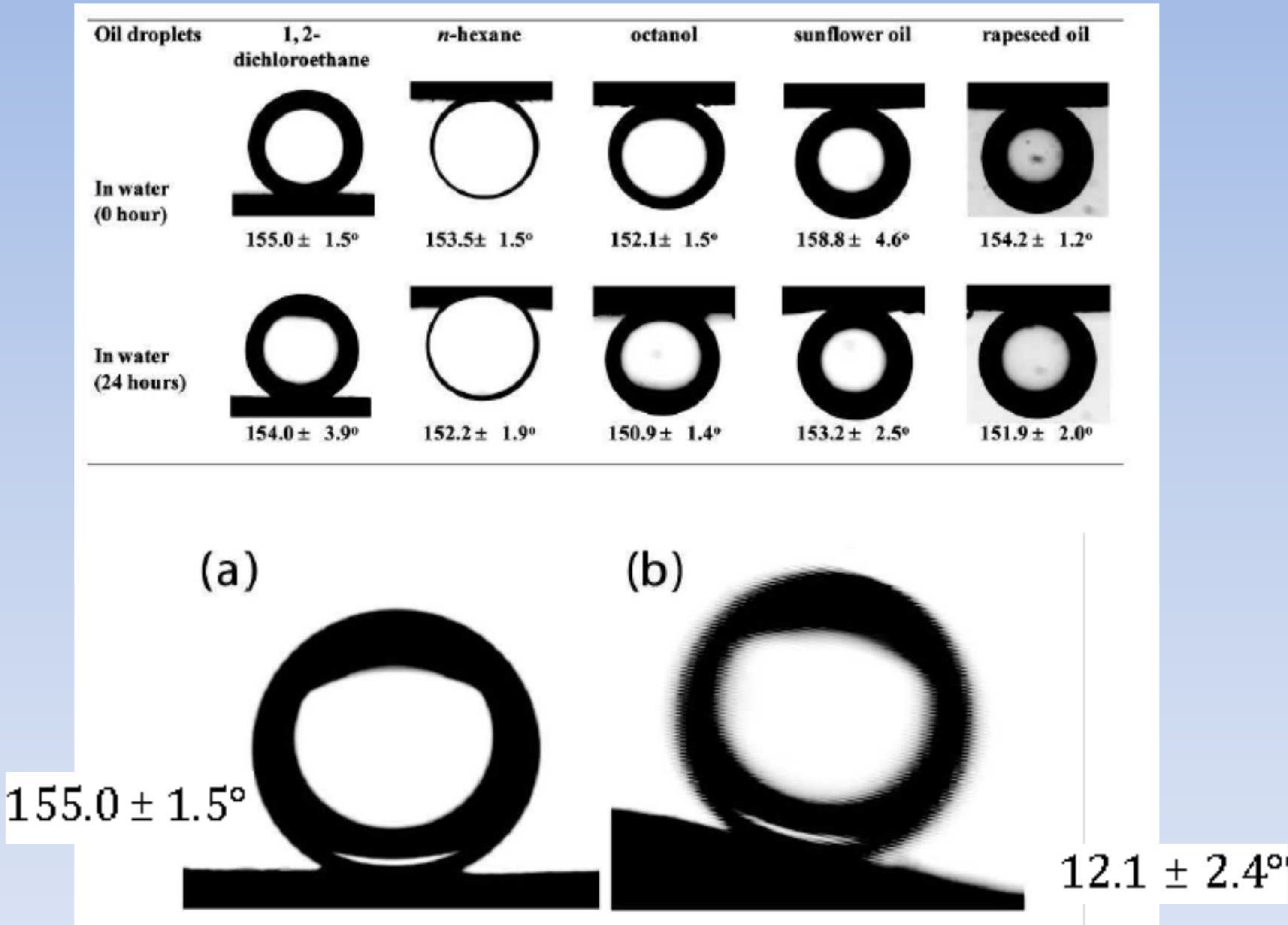


Environment SEM (ESEM) images (a & b) show its lower side is made of many cells, and every cell consists of numerous tabular and slightly convex papillae with 30–50 μm in length and 10–30 μm in width. (c) Atomic force microscope (AFM) image further shows the tabular papillae are covered with nanogrooves structure with a size of 200–500 nm and the height of single papilla is around 4 μm.



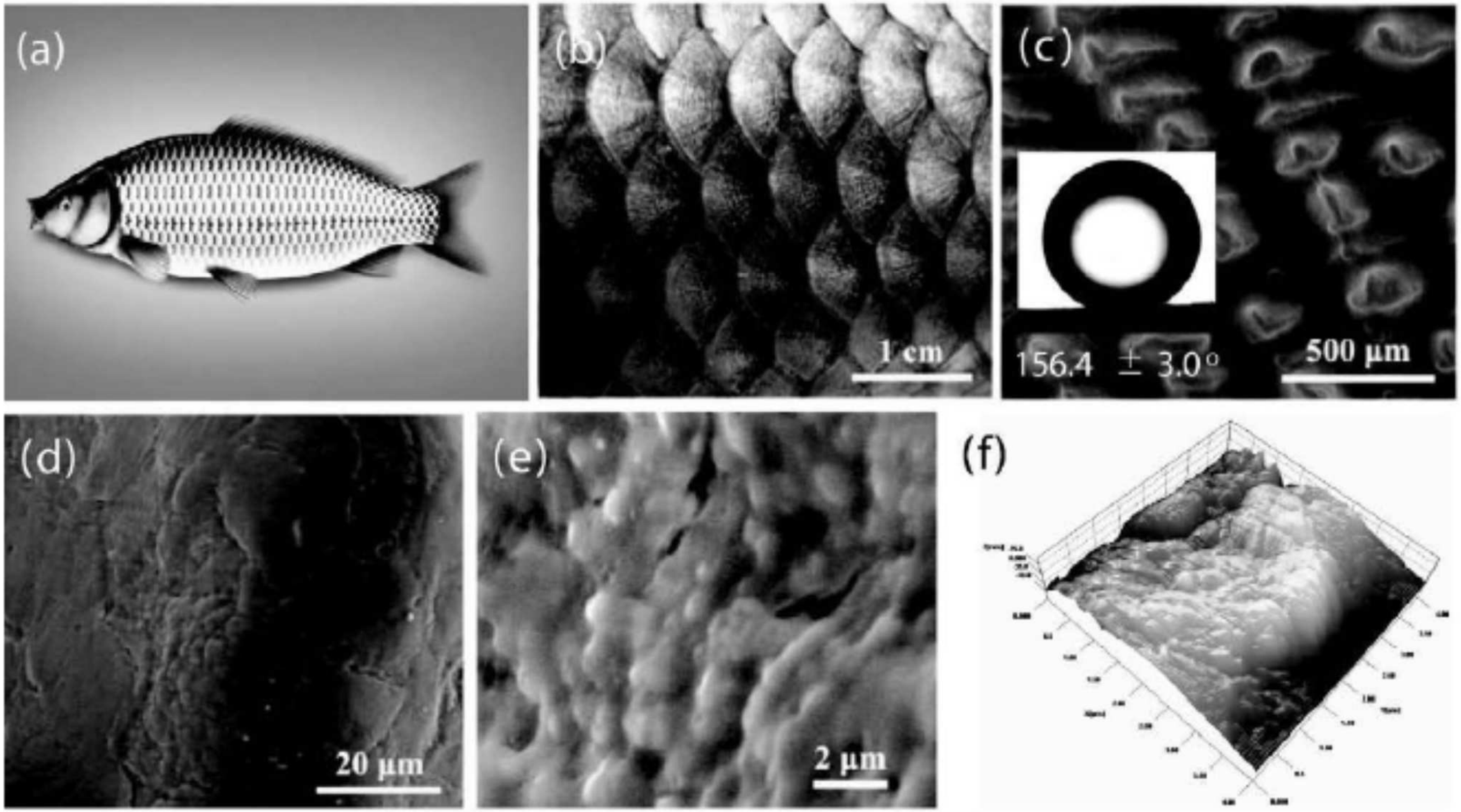
Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

The Underside of the Lotus Leaf



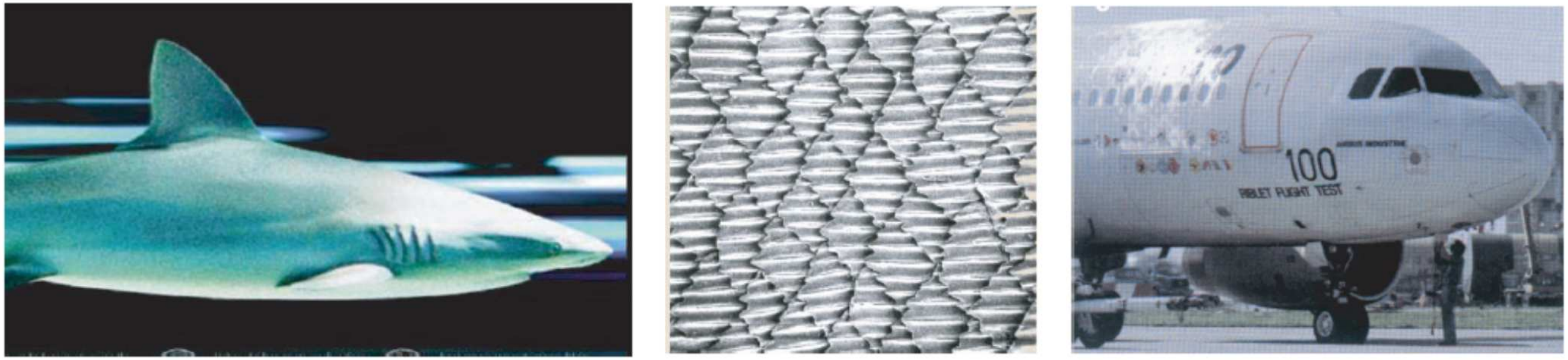
Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

Similarly Patterned Superoleophobic Fish Scales



Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

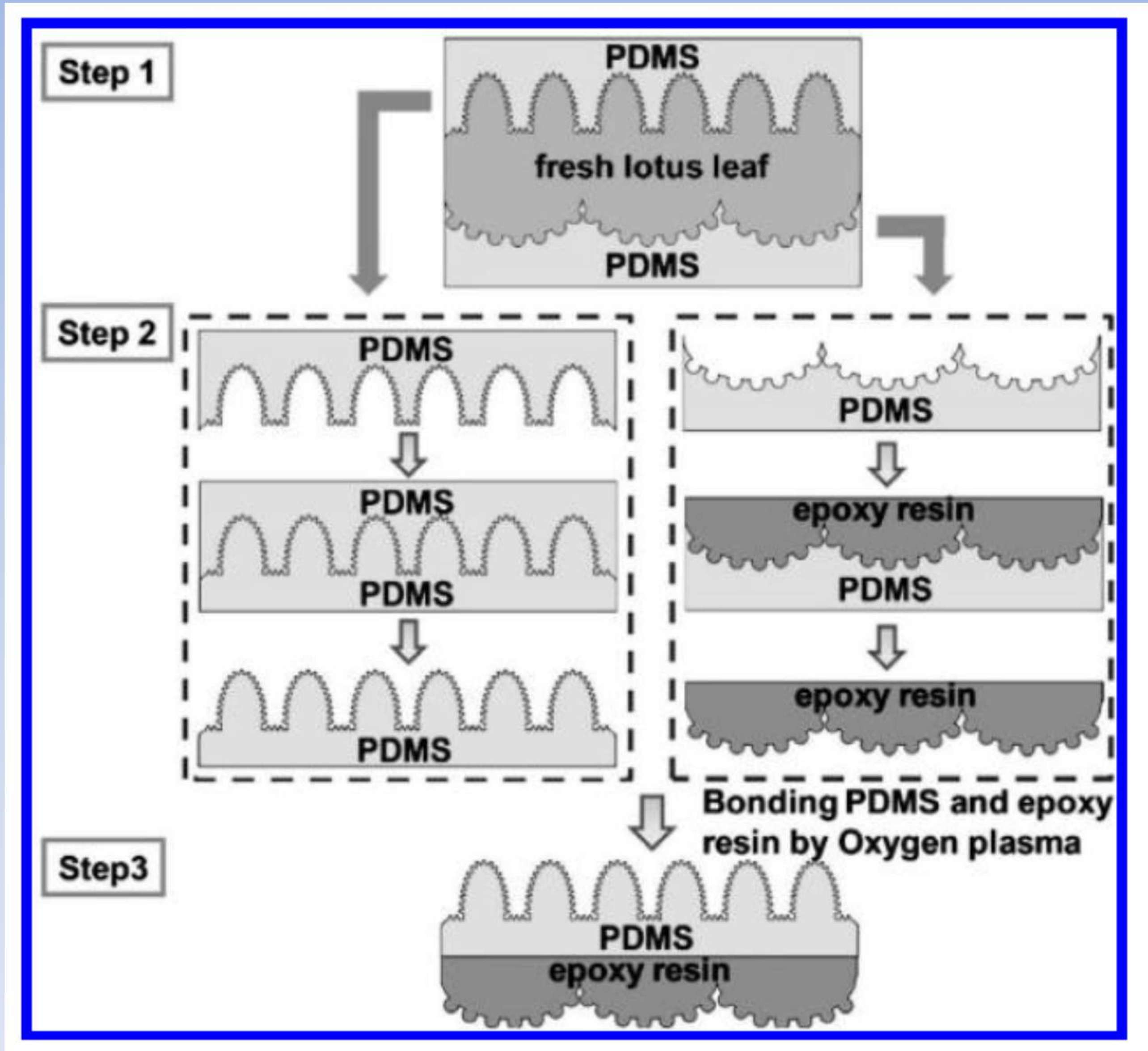
Shark Skin and Sharkskin-Mimetic Surfaces



(a) (b) (c)

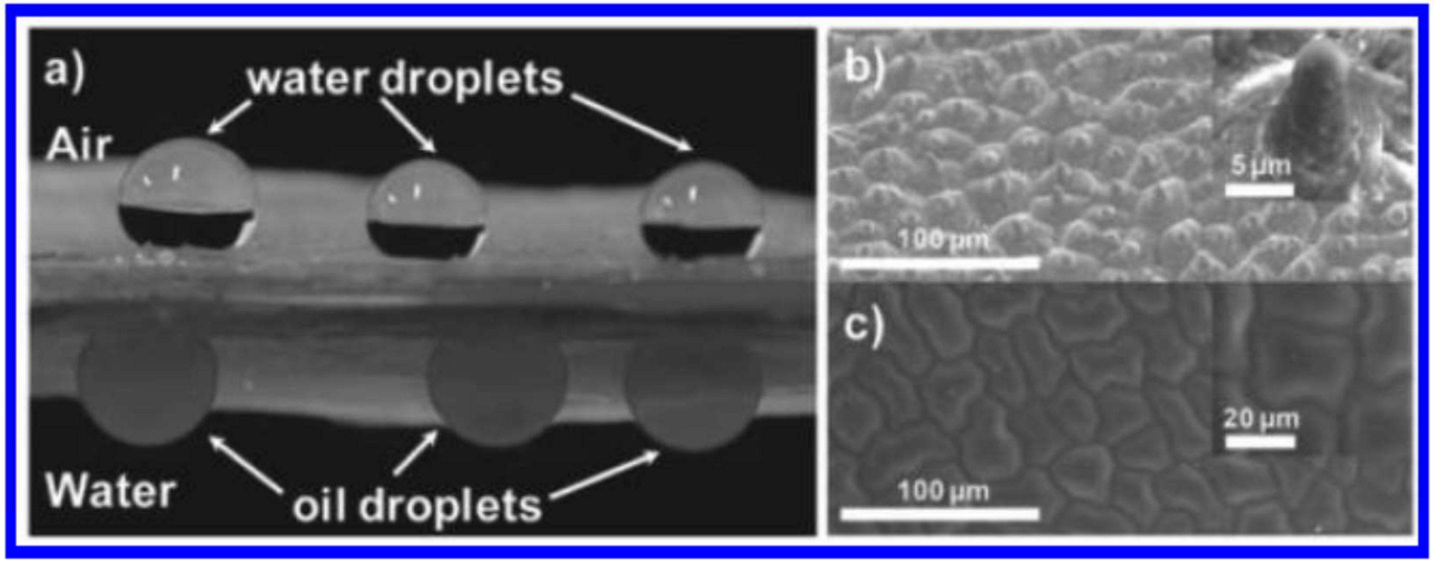
Fig. 1.7 (a) and (b): The riblets on shark skin provided inspiration for modeling studies of the drag reduction they confer. (c) Trials on an aircraft coated with a plastic film with this same microscopic texture.[60] (Reprinted by permission from Macmillan Publishers Ltd: *Nature*, copyright 1999.)

Lotus Leaf Mimetics of Both Surfaces



Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

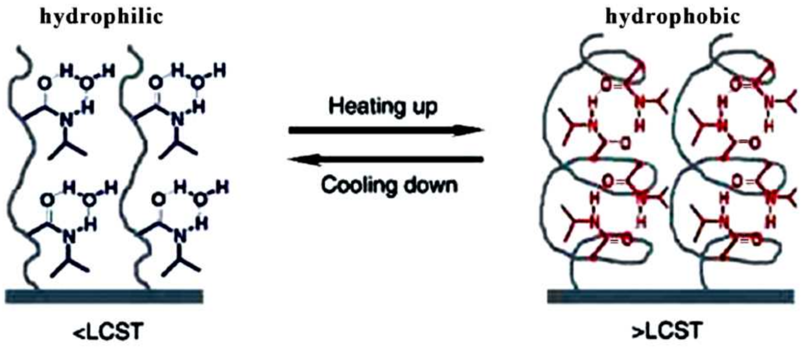
Lotus Leaf Mimetics of Both Surfaces



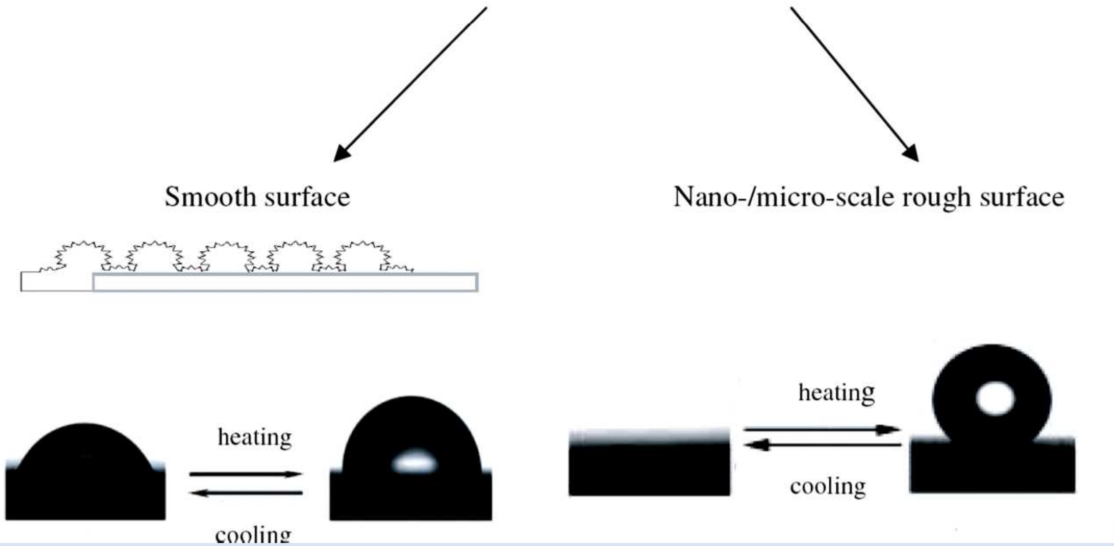
(a) The Janus interface materials is floating on the water surface, and the water droplets can stay on its upper side in the shape of sphere in air and the oil (*n*-hexane dyed red) droplets are on its lower side in the shape of sphere in water. (b) SEM images show the micro-/nanoscale hierarchical structure on the upper side of lotus leaf is replicated by PDMS. (c) The tabular and slightly convex papillae on lower side of lotus leaf are also replicated by epoxy resin.

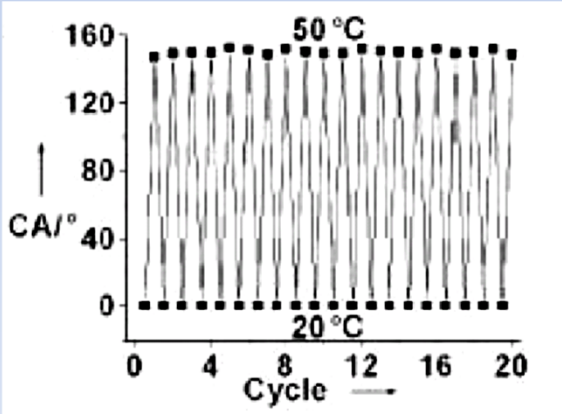
Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

Switchable Wetting of Surfaces



Structural transformation of polymer film with binary states induced by multiple intermolecular interactions and intramolecular interactions



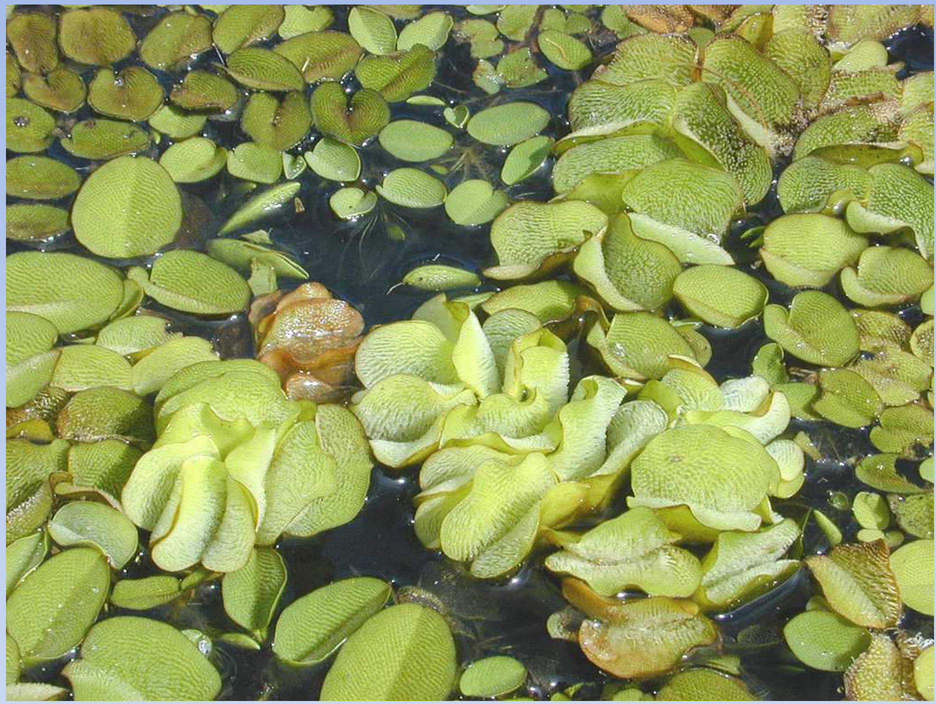


Sun T L, Wang G J, Feng L, Liu B Q, Ma Y M, Jiang L, Zhu D B. *Angew. Chem. Int. Ed.*, 2004, **43**: 357.

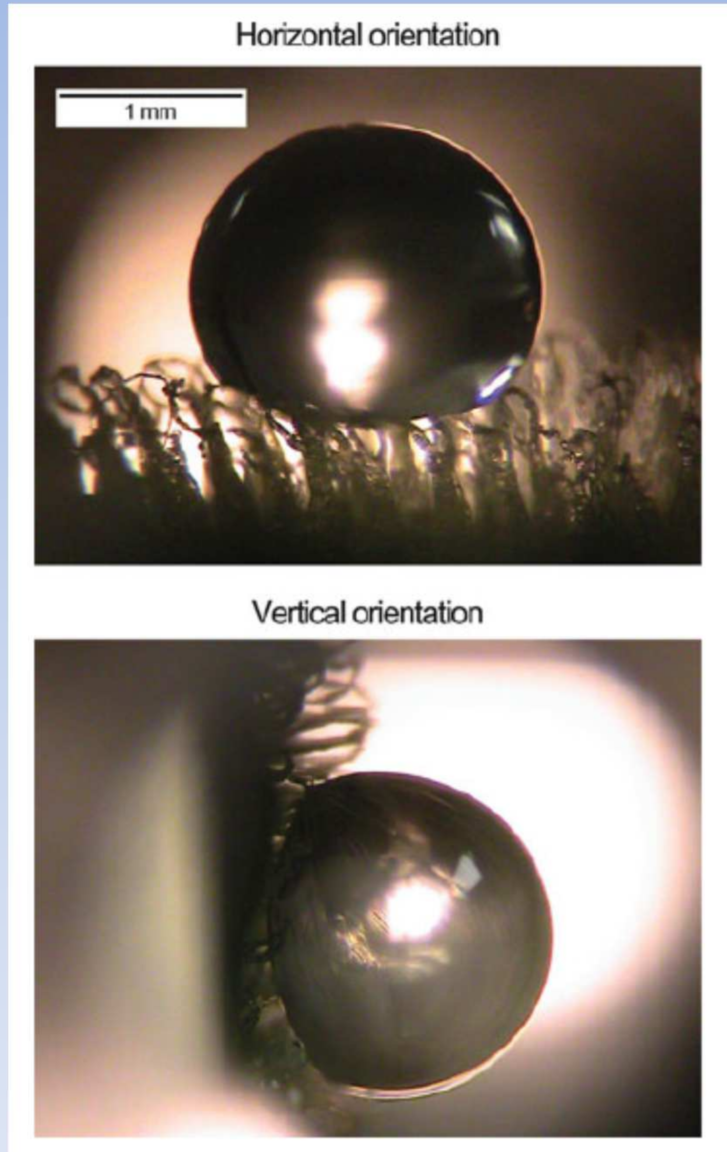
The Aquatic Plant *Salvinia molesta*

Giant Salvinia - A Very Wicked Plant-CWsq7cX3tWg_x264

The Aquatic Plant *Salvinia molesta*



Hairs with Hydrophilic Tips that secure the water drops



Bharat Bhushan-Biomimetics_ *Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology,* Springer-Verlag, 2012.

Scanning Electron Microscope Zoom of the Mosquito Eye

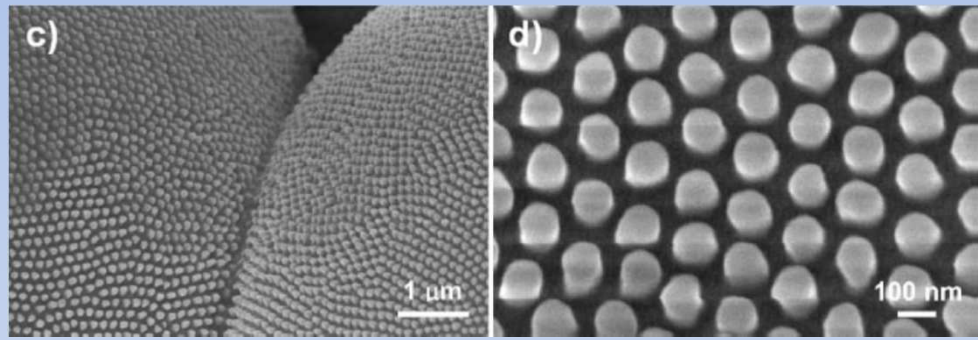
Mosquito Eye (2005) Scanning Electron Microscope Zoom

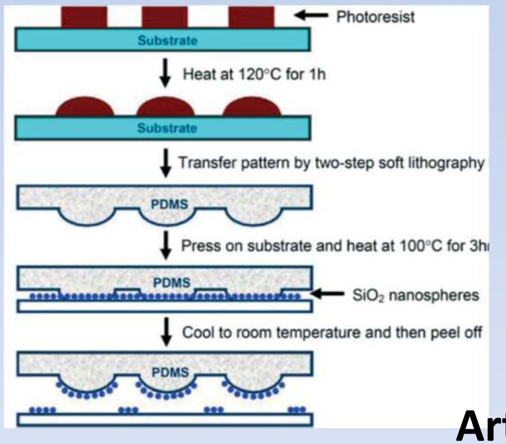
Anti-Fogging Mosquito Eyes

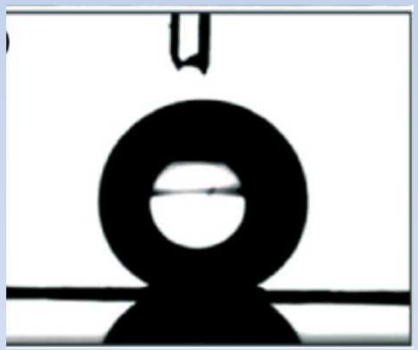
http://www.photomacrography.net/forum/viewtopic.php?t=8547

Xuefeng Gao, Xin Yan, Xi Yao, Liang Xu, Kai Zhang, Junhu Zhang, Bai Yang, and Lei Jiang, "The Dry-Style Antifogging Properties of Mosquito Compound Eyes and Artificial Analogues Prepared by Soft Lithography", *Adv. Mater.* **2007**, *19*, 2213–2217.

Two Adjacent Omatidia **Nano-Nipples on the Omatidia**







A Water Drop on the Artificial Biomimetic Surface

Insect Capture by the Insectivorous Plant *Nepenthes*

Holger F. Bohn and Walter Federle, "Insect aquaplaning: *Nepenthes* pitcher plants capture prey with the peristome, a fully wettable water-lubricated anisotropic surface", *PNAS*, 101, 14138–14143 (2004).

Ulrike Bauer and Walter Federle, "The insect-trapping rim of *Nepenthes* pitchers. Surface structure and function", *Plant Signaling & Behavior,* 4, 1019-1023 (2009).

Tak-Sing Wong, Sung Hoon Kang, Sindy K. Y. Tang, Elizabeth J. Smythe, Benjamin D. Hatton, Alison Grinthal & Joanna Aizenberg. "Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity", *Nature*, 477, 443-447 (2011).

The Insectivorous Pitcher Plant *Nepenthes*

How flesh-eating pitcher plants trap insects-ya2ndp1OrPQ_x264

MythBusters - Banana Peel Slip

MythBusters - Banana Peel Slip

Instant Banana Peel or Riotrol

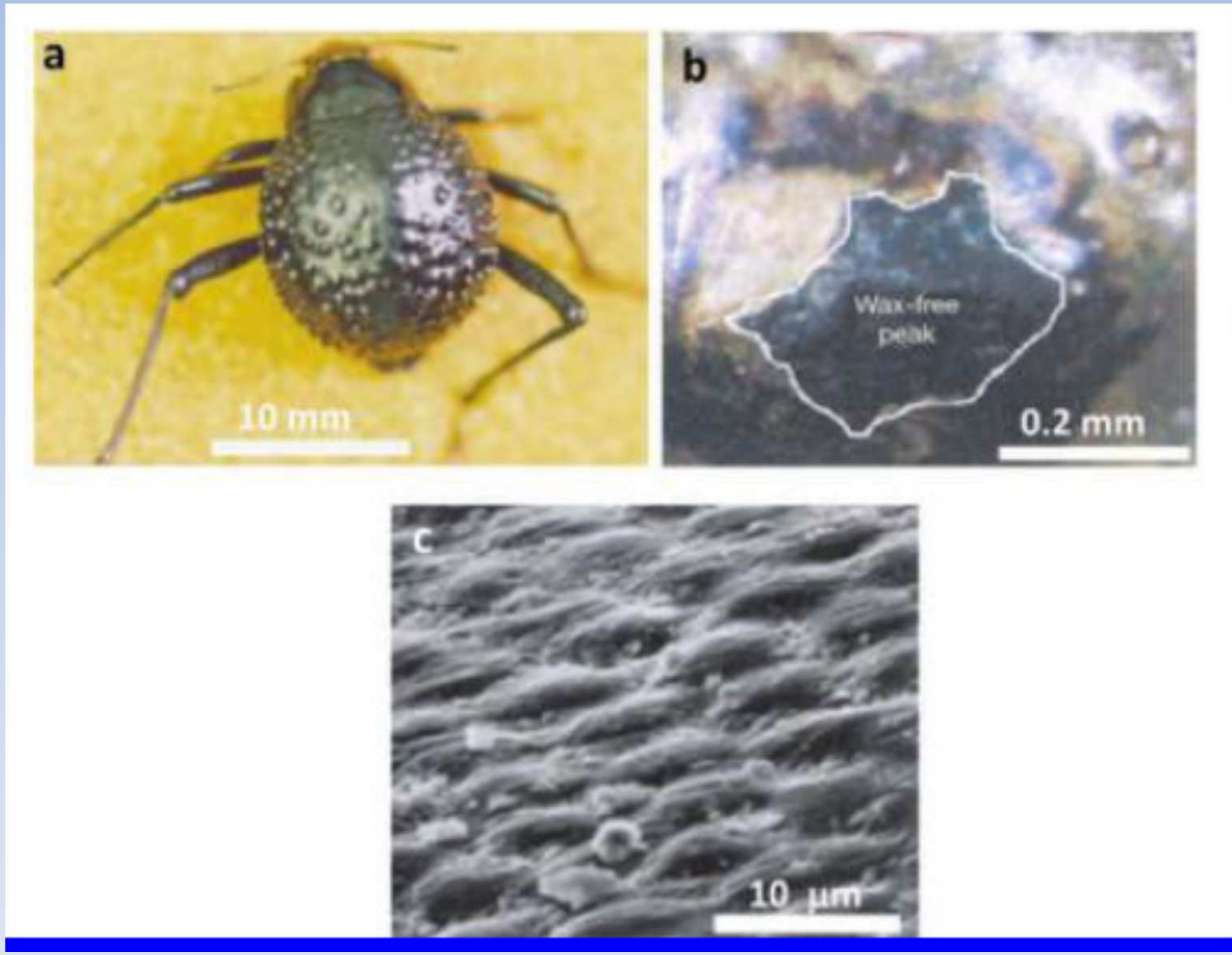
Police demonstrate the effectiveness of 'instant banana peel' as a tool to curb ...HD Stock Footage

Sliding Angle Permits Skiing in Tropical Brazil

Pista de ski em São Roque-SP

Functional Biomimetic Surfaces - Durham University

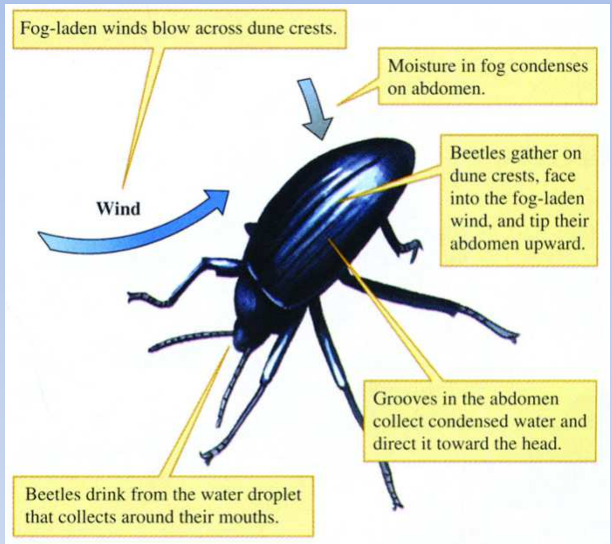
Namib Desert Beetle Wing Cover Surface



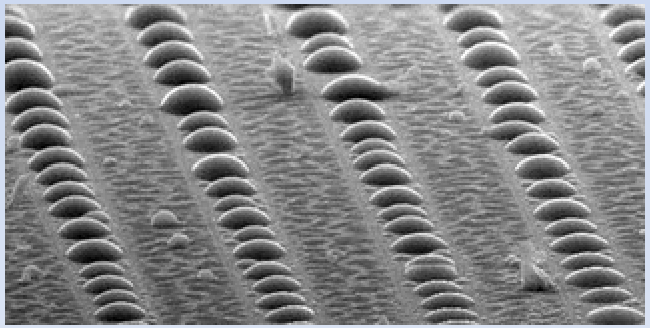
Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

Nature Using Surface and Interfacial Tensions

Namib Desert Beetle



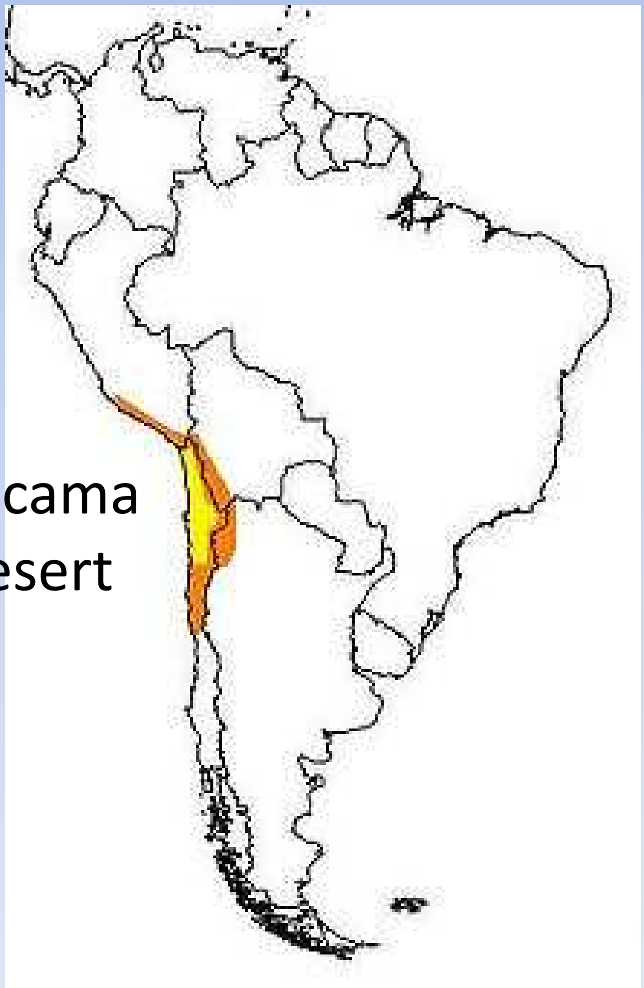
Hydrophilic bumps/Hydrophobic channels

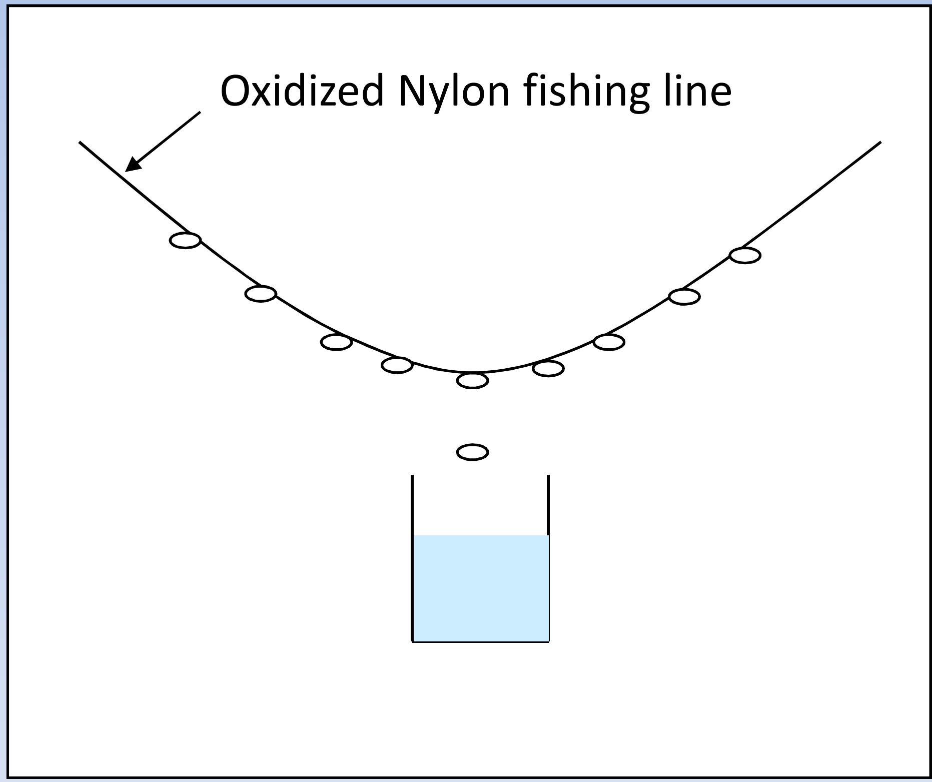


http://thireaultdesign.blogspot.com.br/2011/09/namib-desert-beetles.html

http://www.yankodesign.com/2010/07/05/beetle-juice-inspired/

Primitive Man Watching Nature Use Surface and Interfacial Tensions





L. Sepúlveda, Univ. Chile (1983)

Bio-Inspired Fog Harvesting – Durham University

Superhydrophobic Surfaces – Durham University

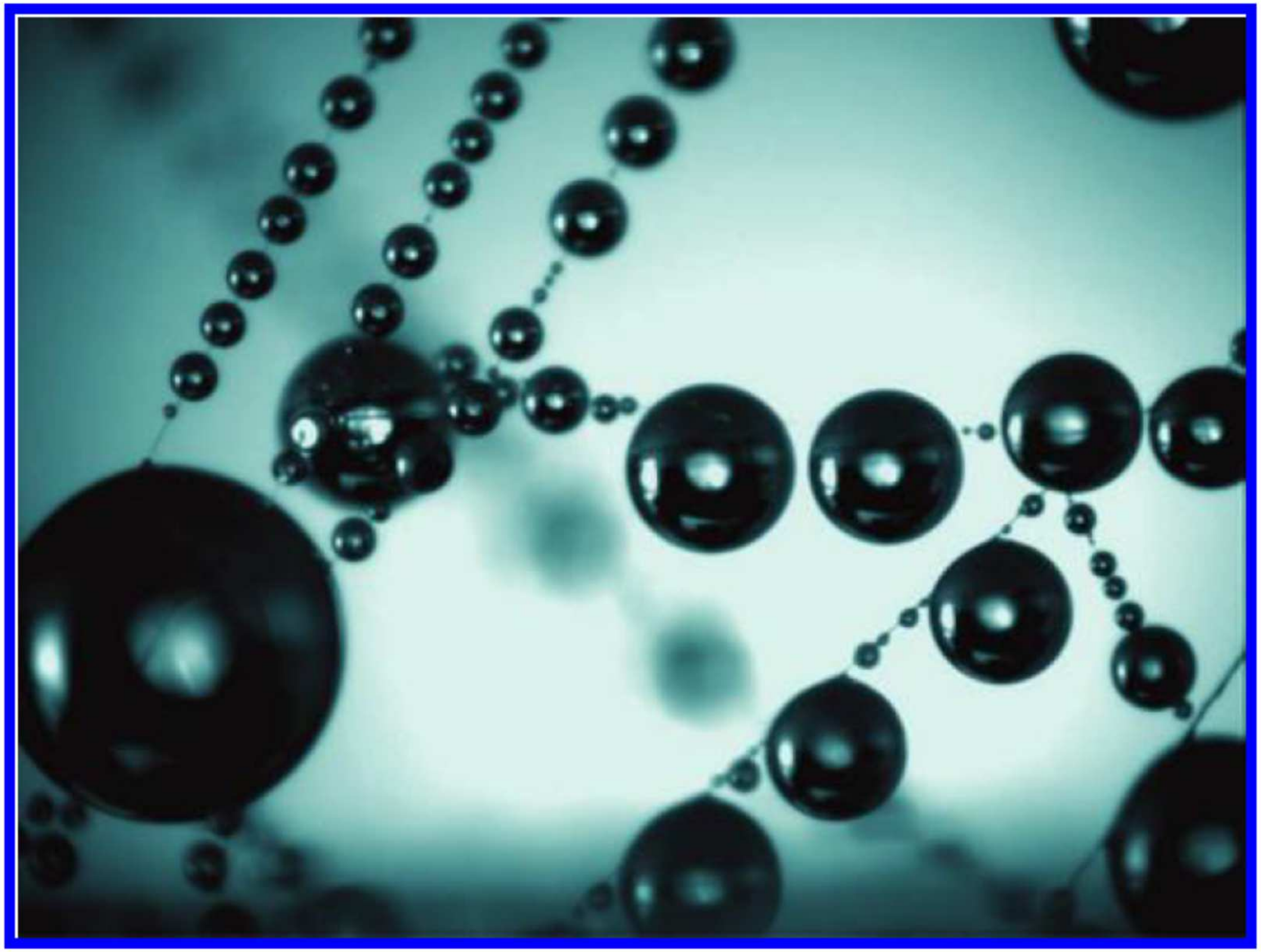
Superhydrophilicity

Applications ~superhydrophilicity ~

performance	applications
drip-proofing	・automotive door mirrors ・window glass for house
antifogging	・window glass for house ・glasses, goggles ・bathroom mirrors ・refrigeration showcases
self-cleaning	・traffic sign boards ・exterior building materials
easy cleaning	・window glass for building ・automotive bodyshell

http://www.iskweb.co.jp/eng/products/functional05.html

Water Drops on a Spider Web



Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

Spider Silk

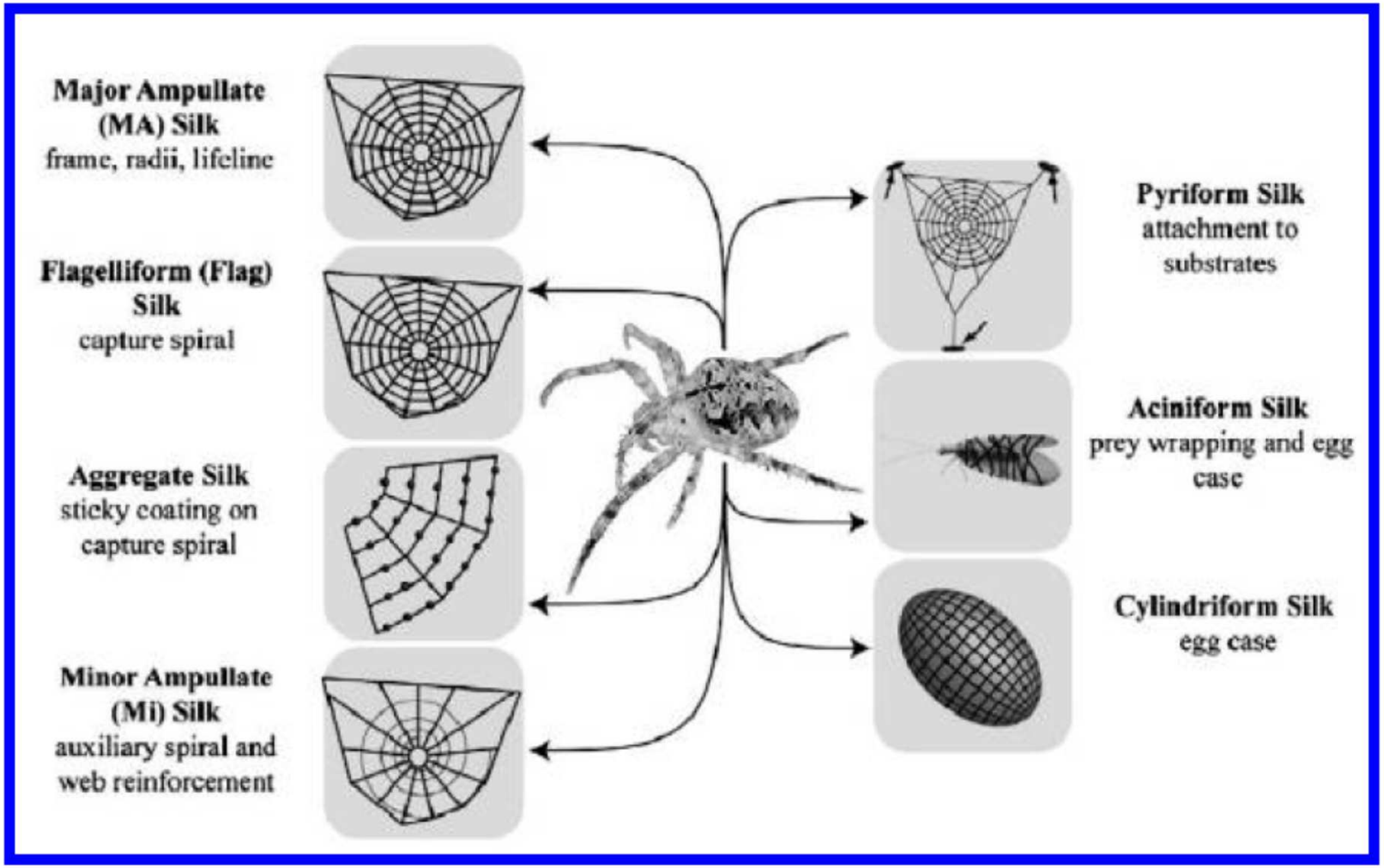
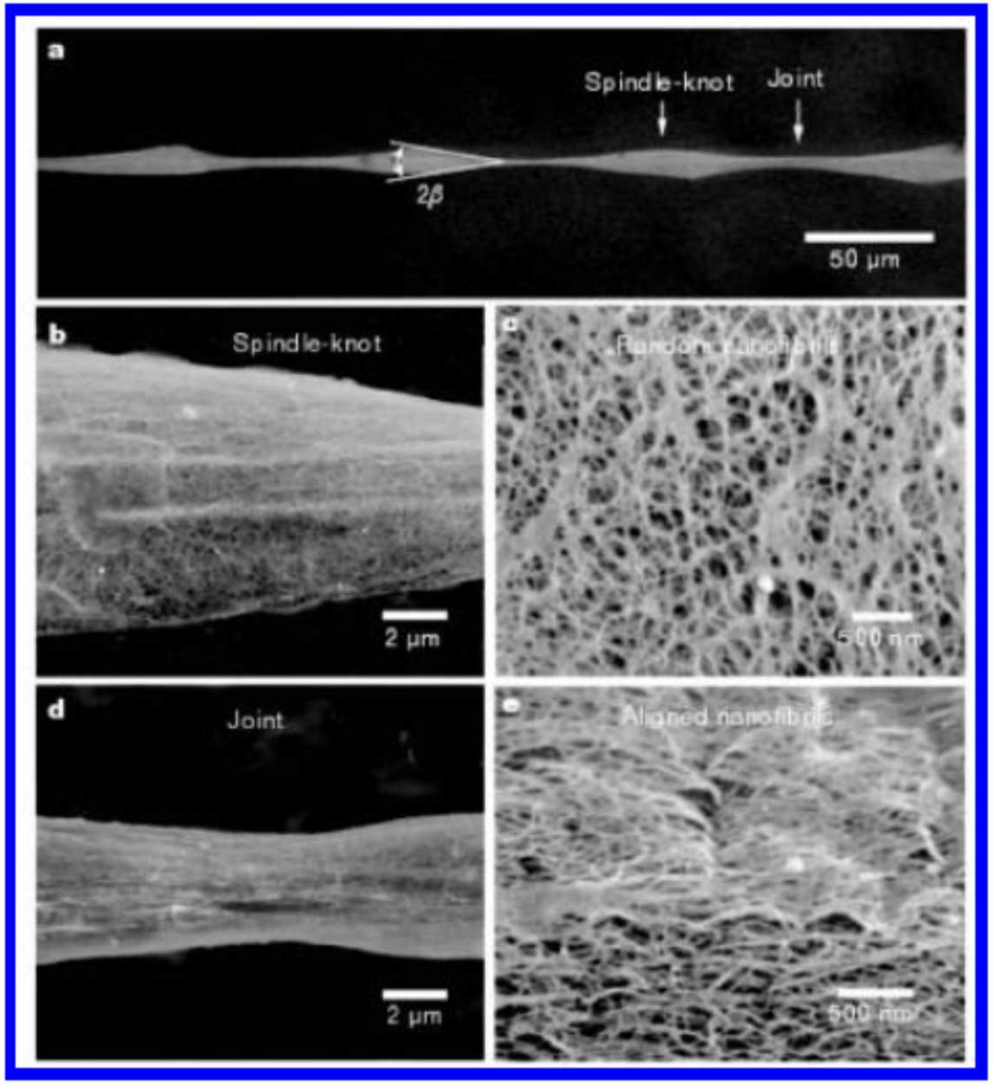


Figure 3.2 Schematic overview of different silk types produced by female orb weaving spiders (Araneae).

Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

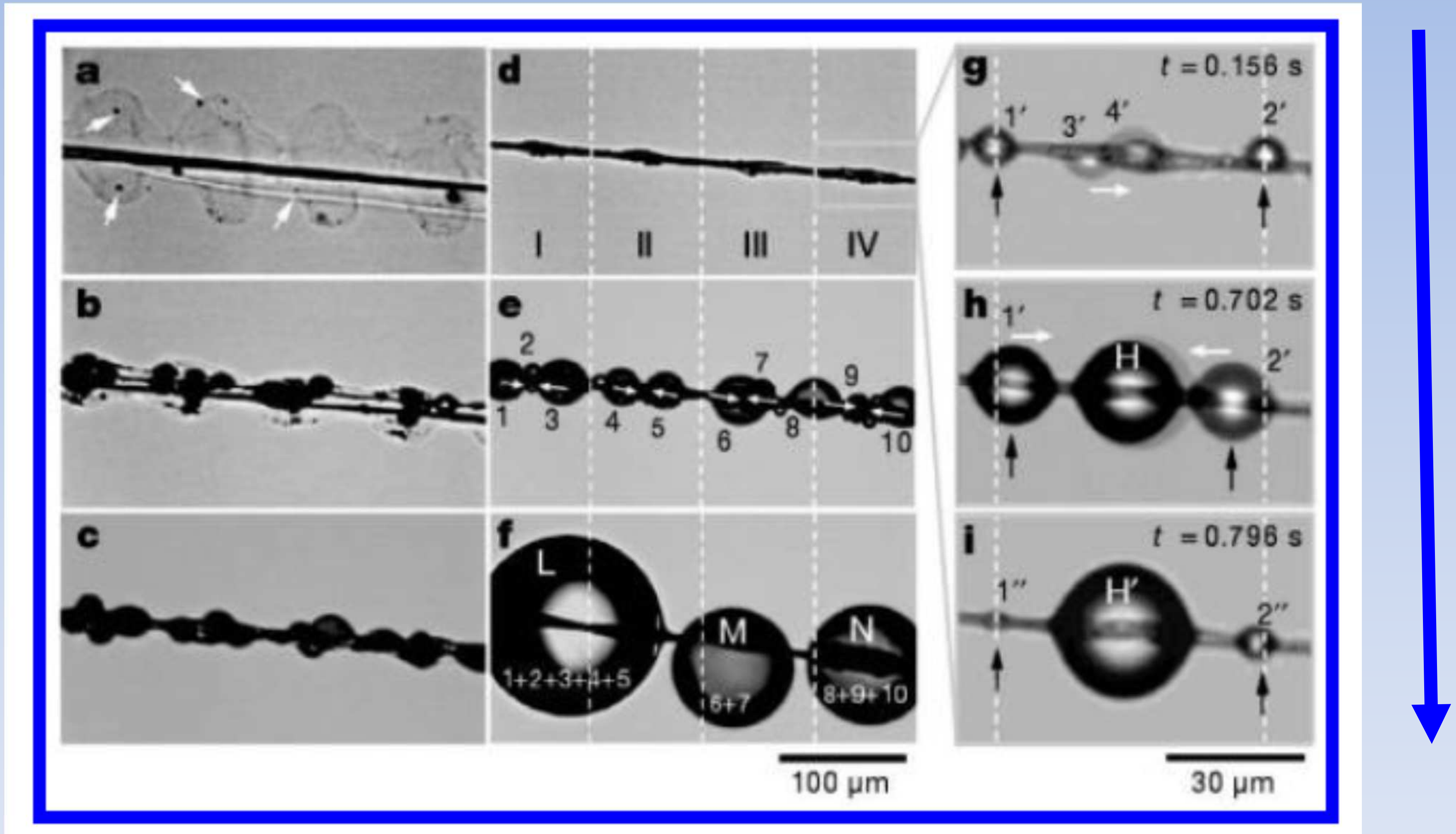
Spindles on Spider Silk



Structure of wet-rebuilt spider silk.

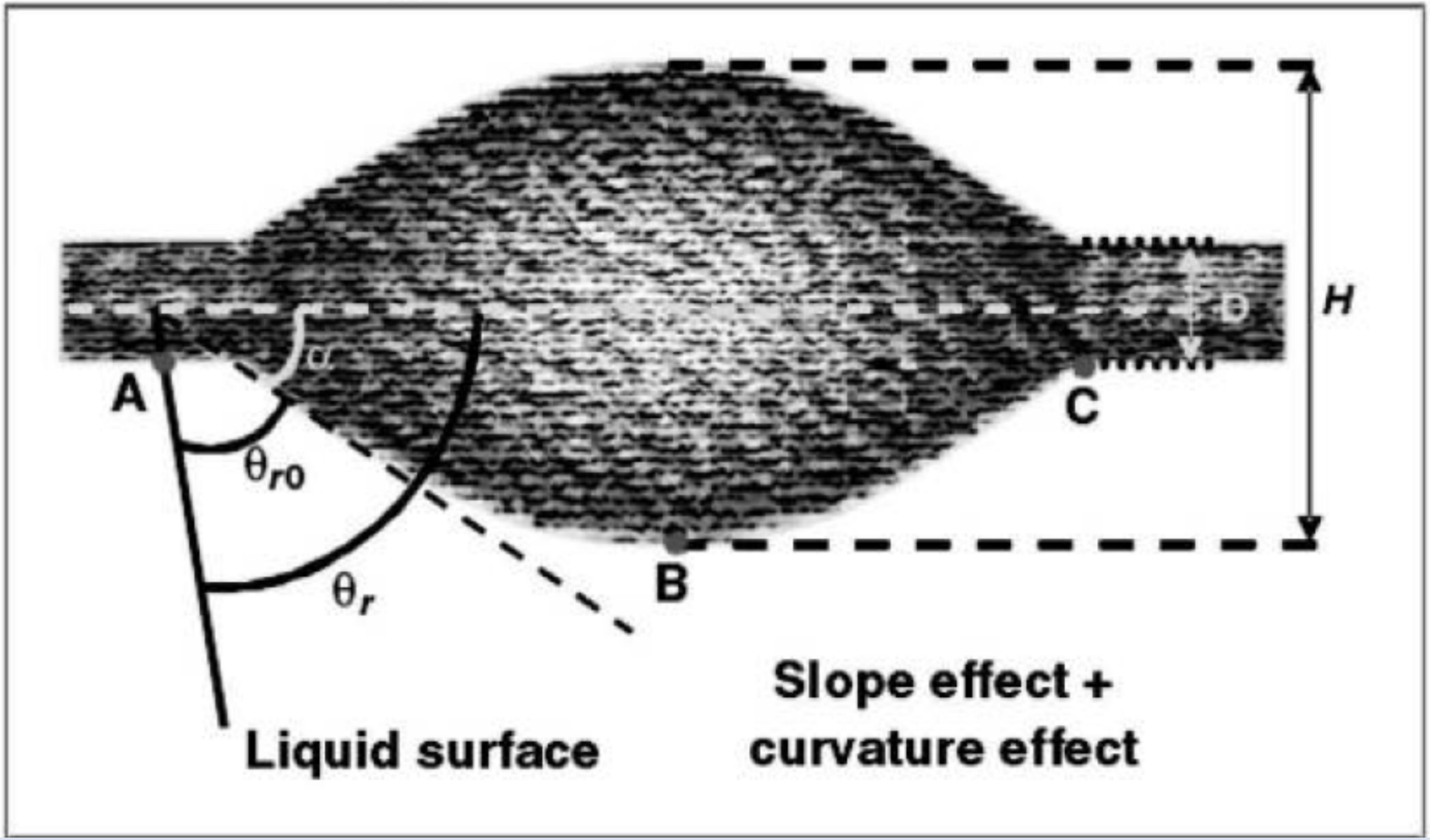
Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

Time-Dependence of Directional Water Collection by a Spider Web



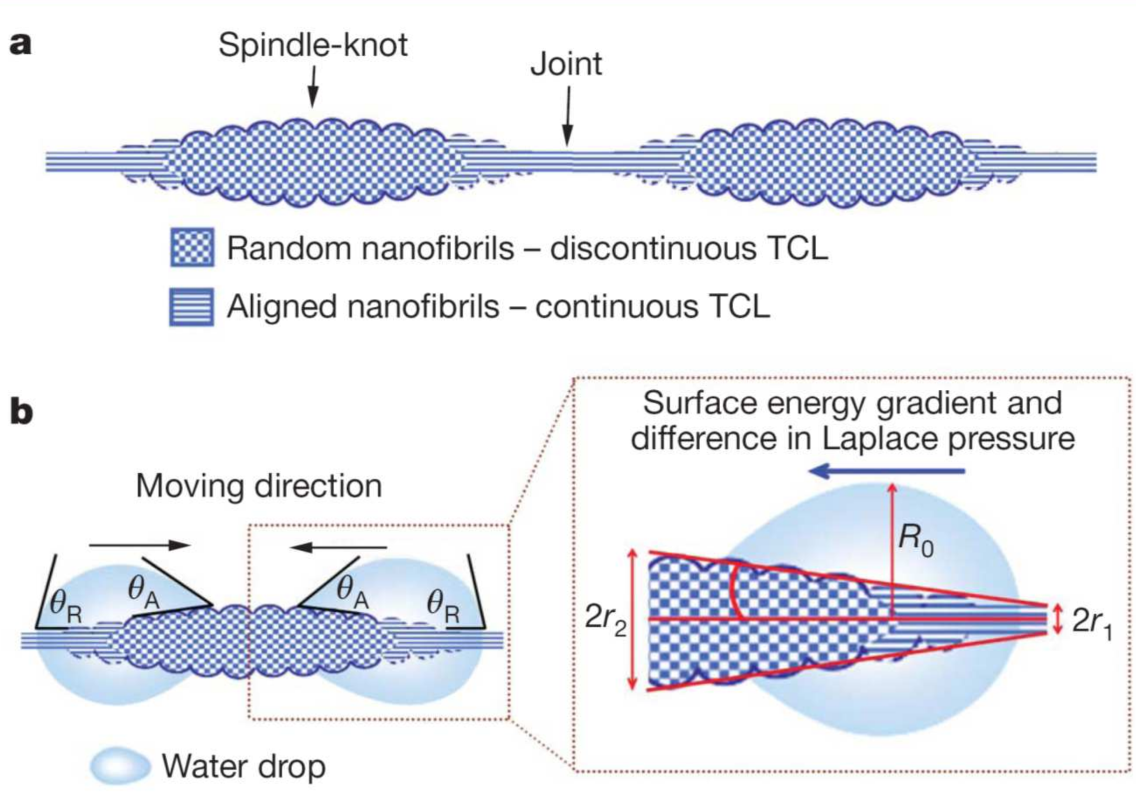
Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

Nature Uses Surface and Interfacial Tensions



Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

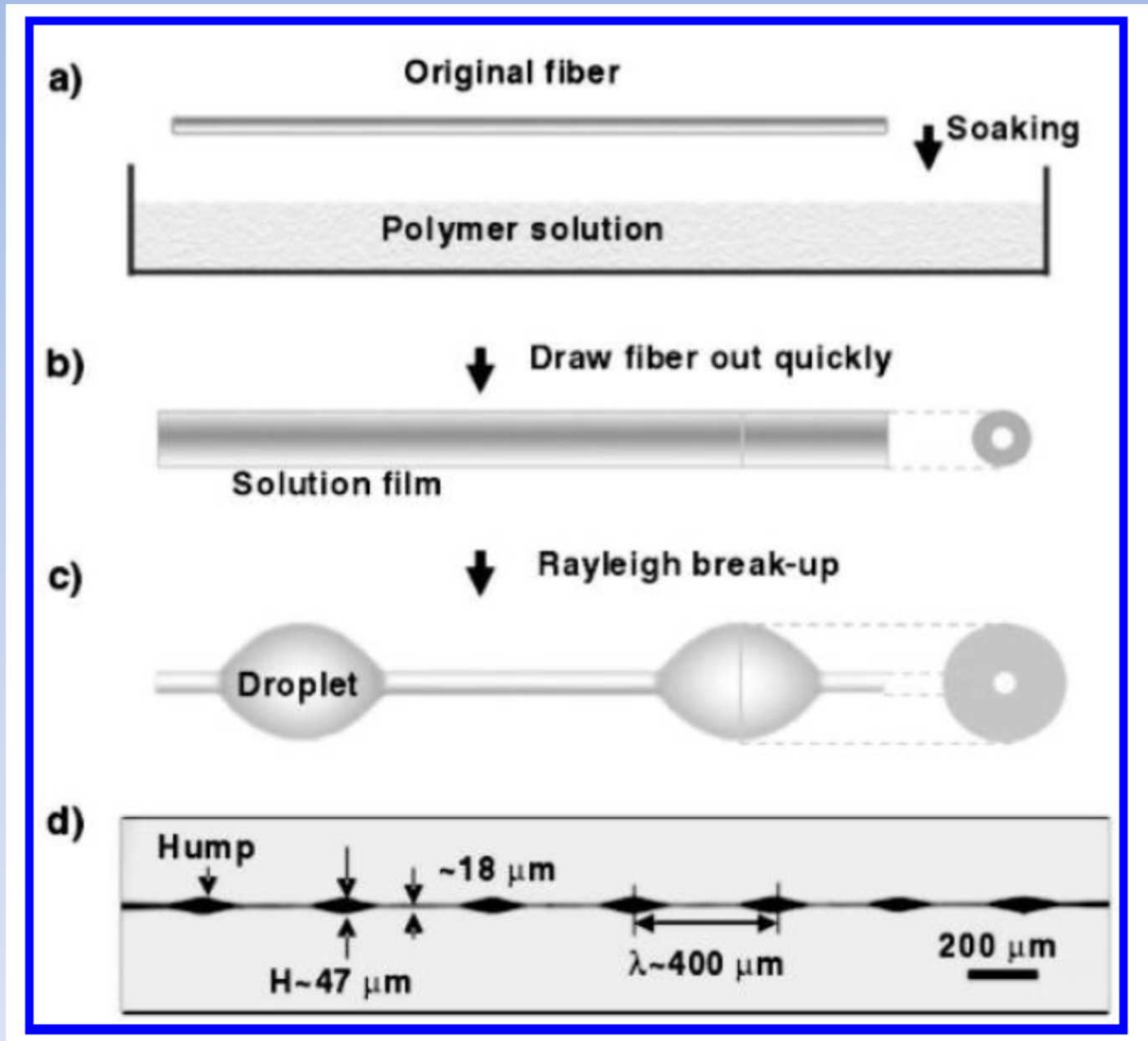
Nature Uses Surface and Interfacial Tensions



Mechanism of directional water collection on wet-rebuilt spider silk.

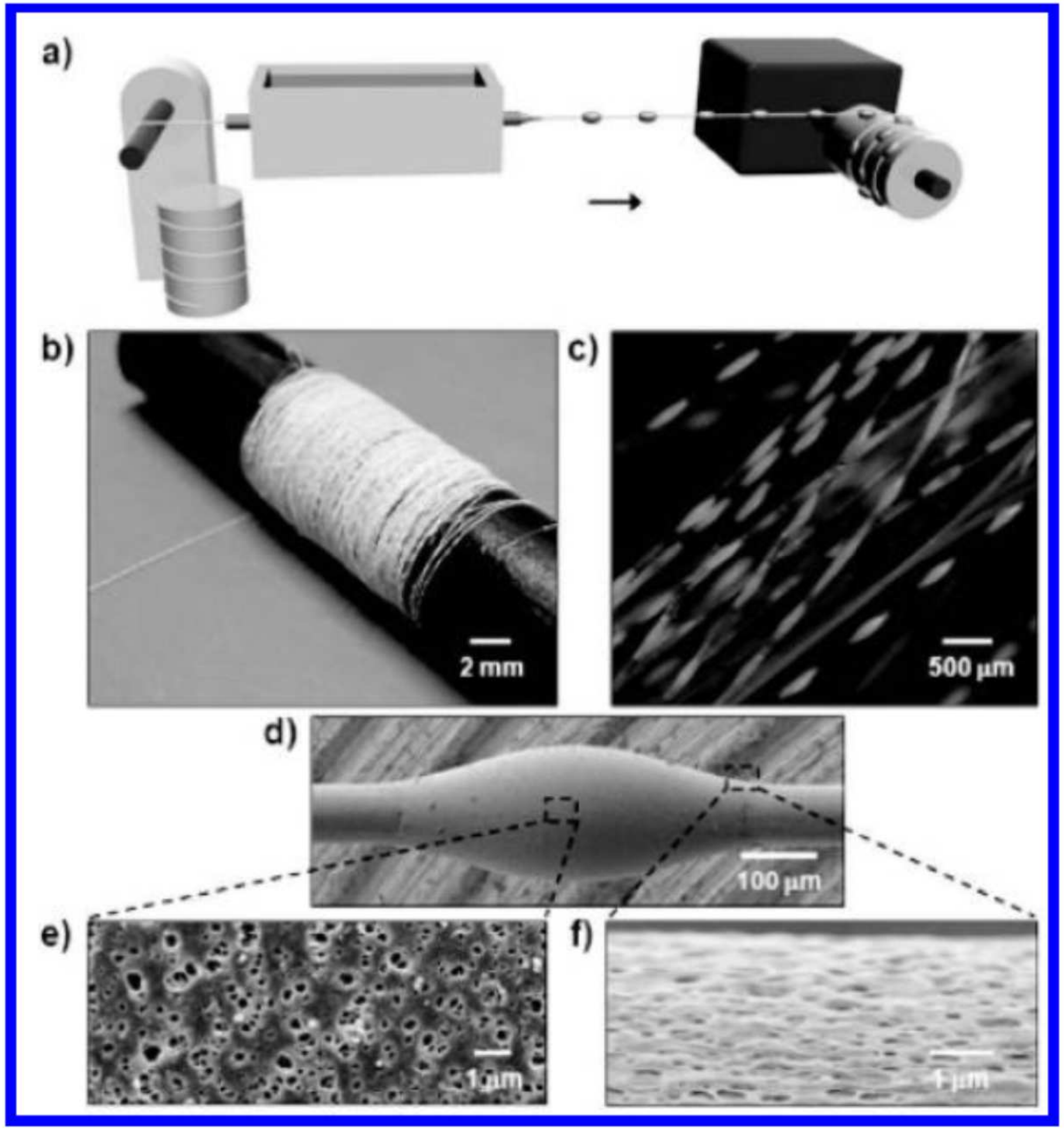
Nature, 2010, *463*, 640-643.

Making Fibers with Artificial Spindles



Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

Fluid-Coating Method for Making Fibers with Artificial Spindles



Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

Applications:

Controlling the Motion of Liquid Drops

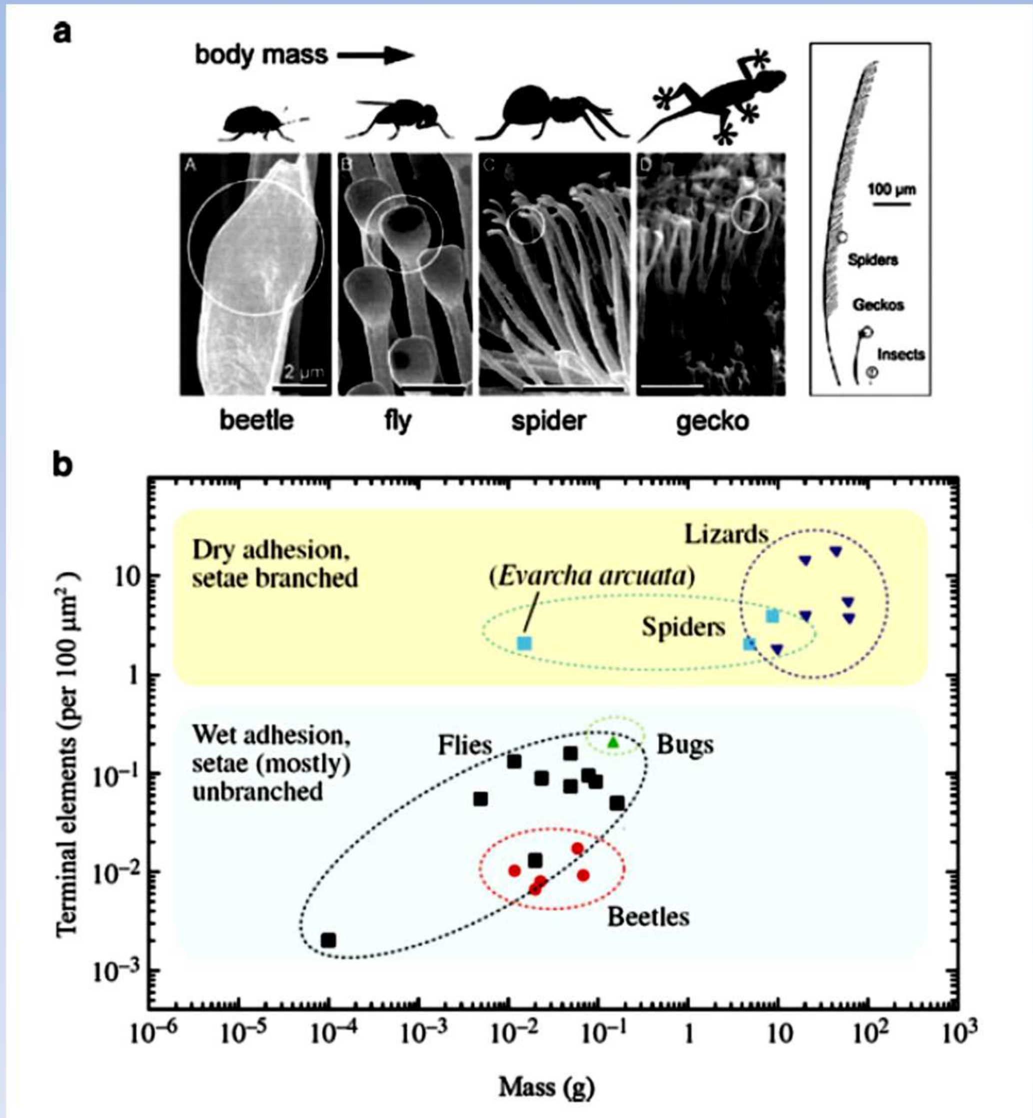
High Efficiency Water Collection

Enhanced Solid-Liquid Adhesion

Fibers Responsive to their Environment

Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

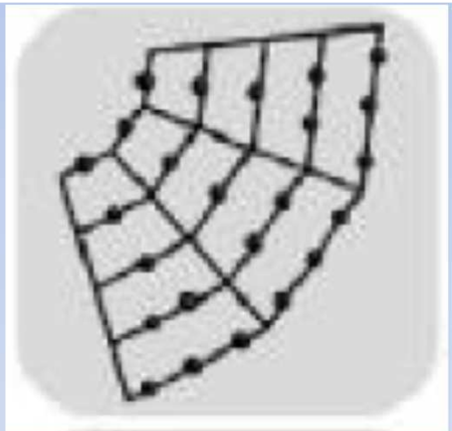
Bio-Inspired and Biomimetic Adhesion



Bharat Bhushan-Biomimetics_ *Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology,* Springer-Verlag, 2012.

Spider Capture Silk

Aggregate Silk
sticky coating on
capture spiral



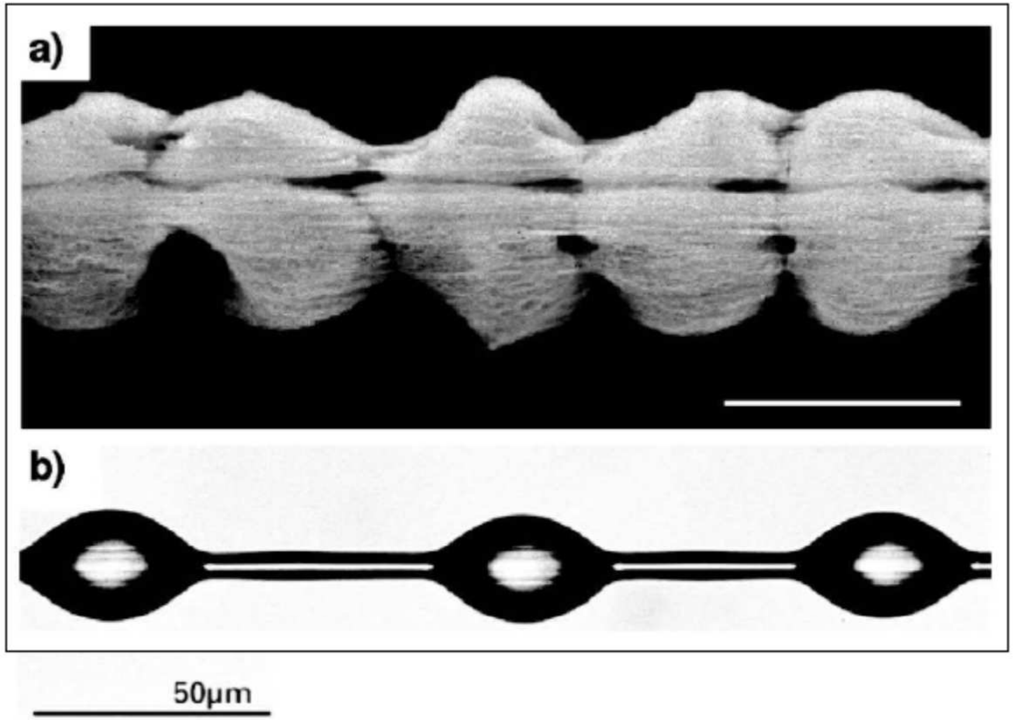


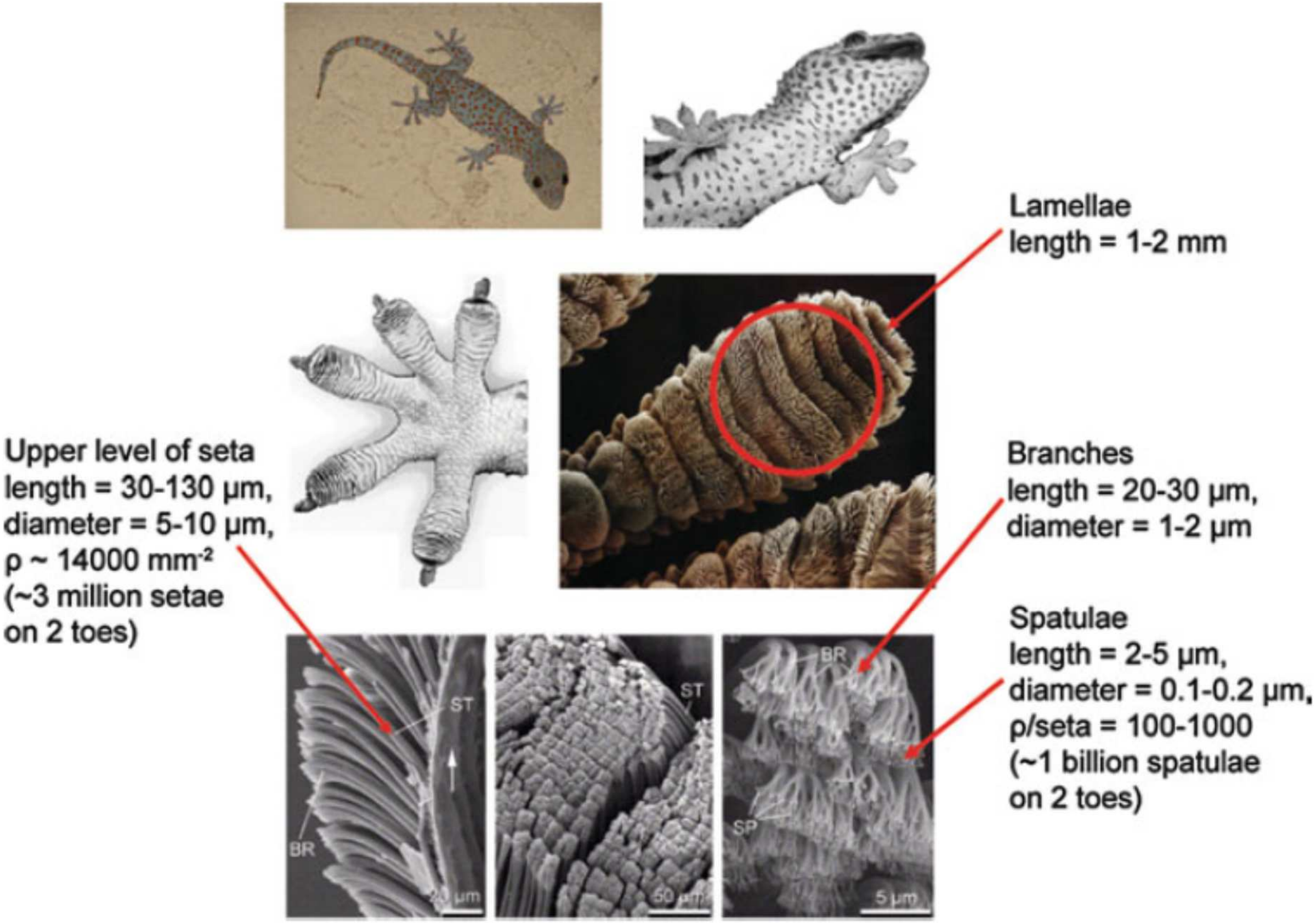
Figure 3.4 Two kinds of spider's capture silk: (a) scanning electron microscopic image of cribellar capture silk with periodic "puff." (b) Optical image of adhesive ecribellar capture silk with flue droplets. Scale bars are 50 μm.

Yongmei, Zheng-Bio-inspired wettability surfaces _ developments in micro- and nanostructures-Pan Stanford Publishing (2016)

The Insectivorous Sundew Plant *Drosera*

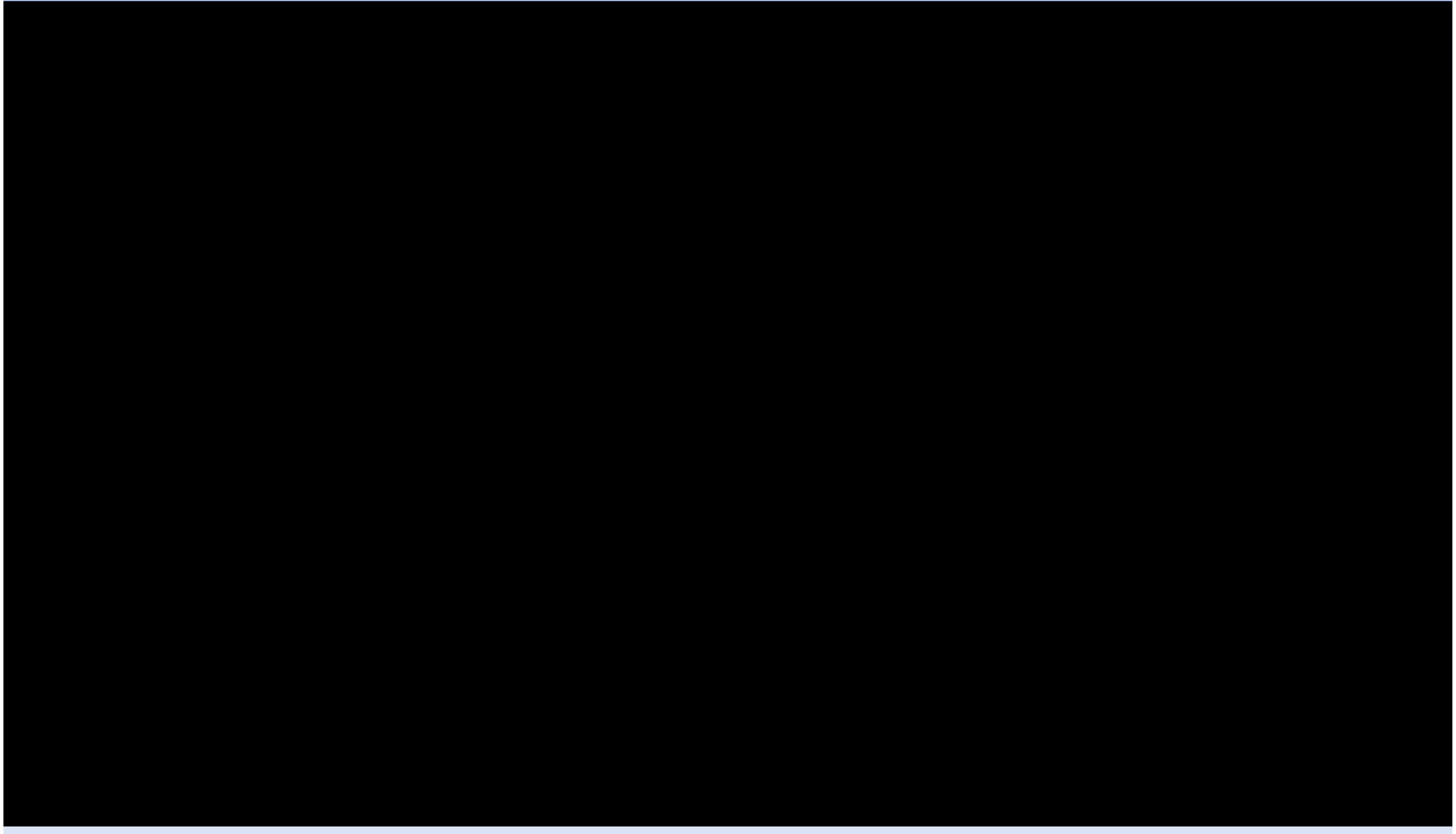
Drosera hunting insect-_ebJ6Fgr0Vg_x264

The Tokay Gecko Foot



Bharat Bhushan-Biomimetics_ *Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology,* Springer-Verlag, 2012.

The Gecko Foot



Smart materials (1 of 5)_ Gecko Adhesive fit for Spiderman-gzm7yD-JuyM_x264

A Tokay Gecko Foot Mimic

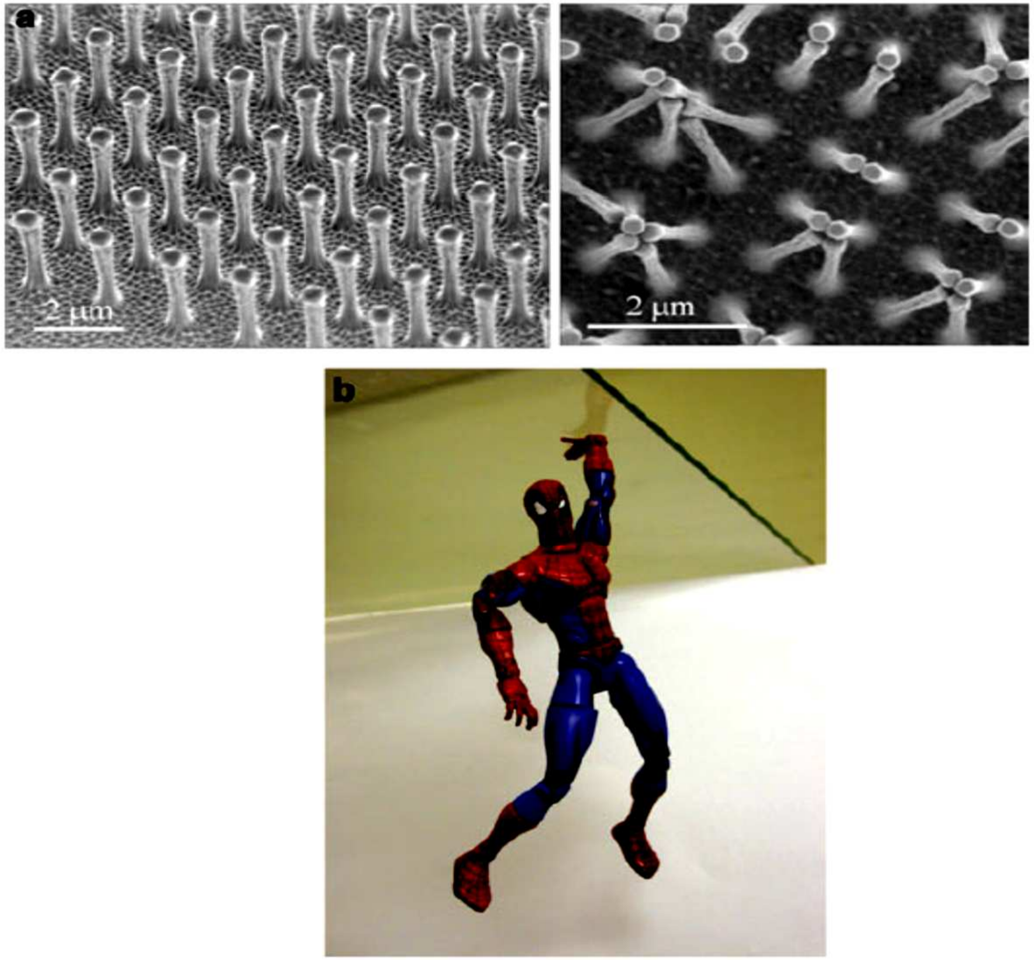


Fig. 11.29 (**a**) (*left*) An array of polyimide nanohairs and (*right*) bunching of the nanohairs, which leads to a reduction in adhesive force. (**b**) A Spiderman toy (about 0.4 N) with a hand covered with the molded polymer nanohairs, clinging to a glass plate (Geim et al., 2003)

Bharat Bhushan-Biomimetics_ *Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology,* Springer-Verlag, 2012.

Gecko Foot Peeling Off Surfaces

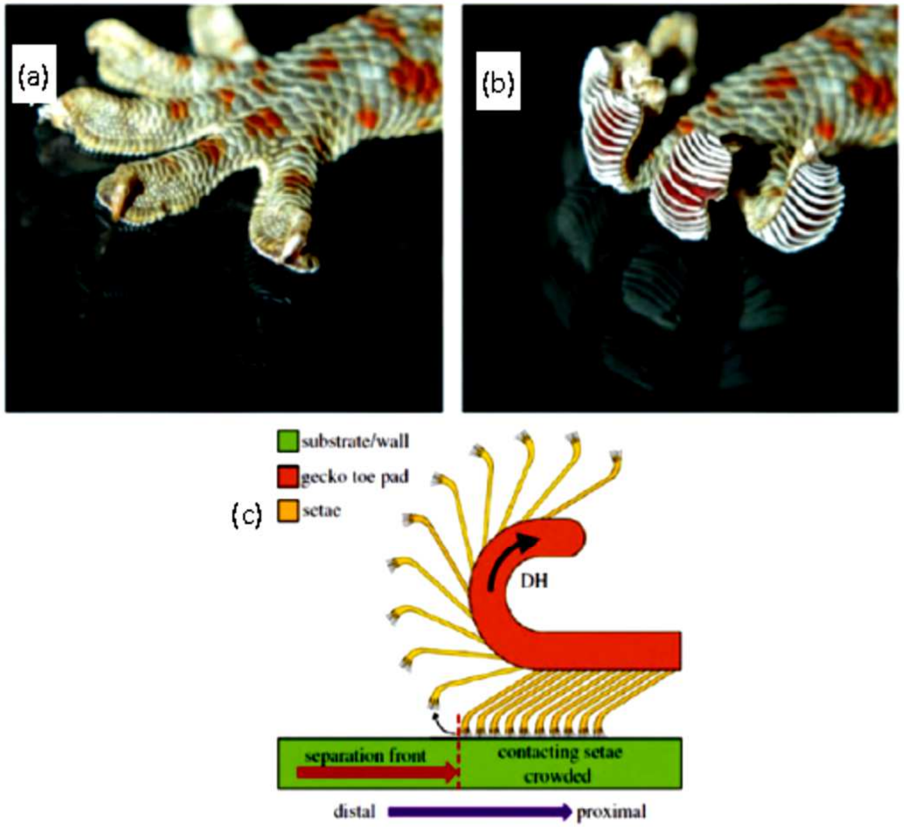


Figure 4.4 (a) Optical image showing a gecko's foot attached to a substrate. (b) Optical image showing a gecko's foot with the digits hyperextended. (c) Schematic illustration of how the hyperextension motion introduces a mechanism by which the setae "roll" off the surface and create large peel angles [18].

Cremaldi et al. In: Havazelet Bianco-Peled_ Maya Davidovich-Pinhas-Bioadhesion and biomimetics _ from nature to applications-Pan Stanford Publishing (2015), pp. 85ff

Gecko Foot Inspired Adhesive Patch

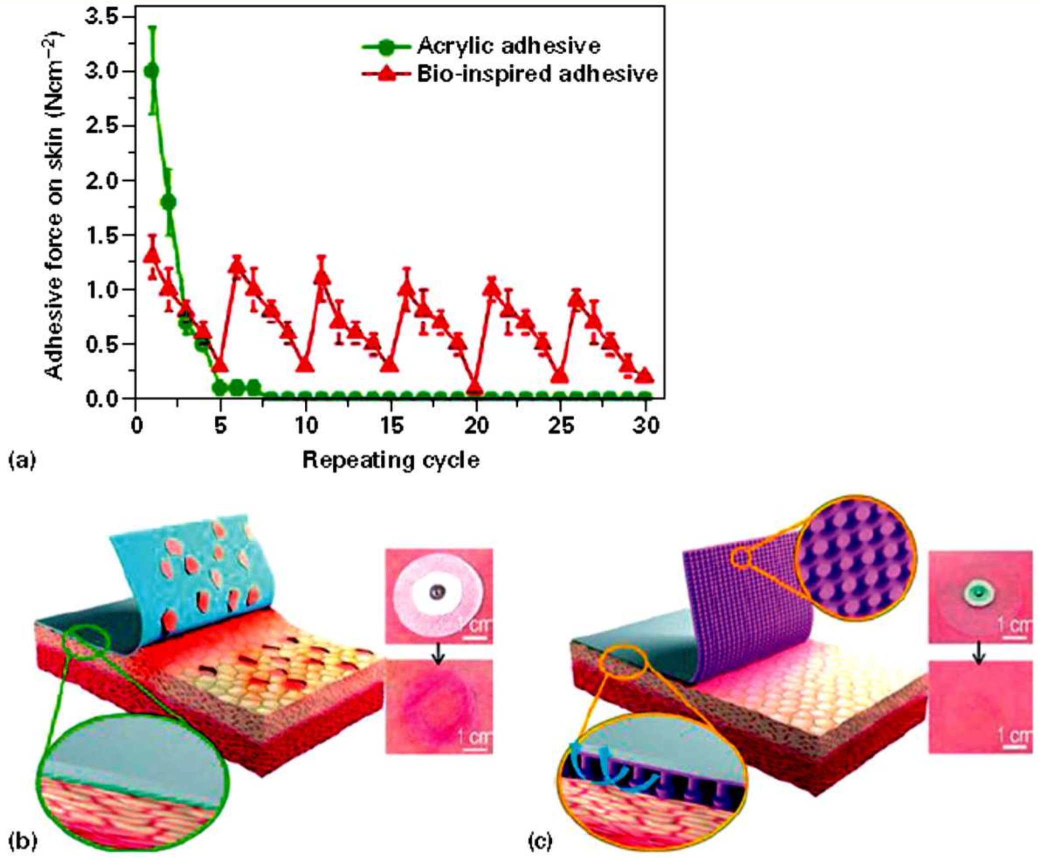


Fig. 3.2: Multi-contact adhesive patch. Multi-pillar surface morphology of an adhesive patch provides superior therapeutic properties. **(a)** Retaining of adhesive forces upon repeated applications of the adhesive, as compared to a complete loss of adhesive force for a conventional acrylic adhesive; **(b)** removal of acrylic patch results in skin damage and redness; **(c)** removal of the multi-pillar "dry" adhesive is smooth and less harmful to the skin. Reprinted with permission from Jeong, H.E. et al., *Adv. Mater.* 2011 *23*, 3949–3953. Copyright (2011) John Wiley and Sons.

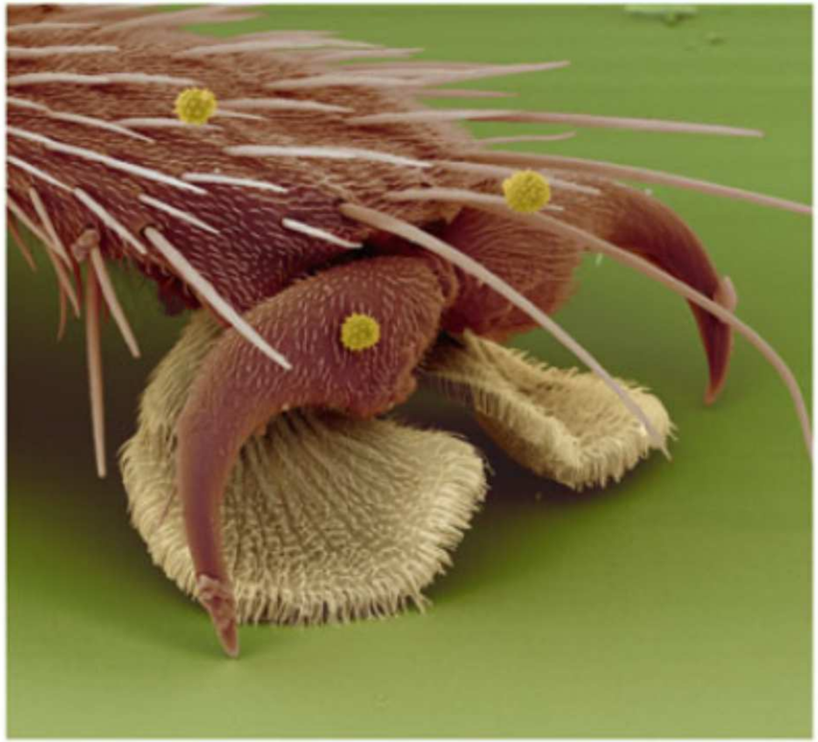
Raz Jelinek, *Biomimetics-A Molecular Perspective*-de Gruyter (2013)

Smart materials based on Gecko Adhesion

Smart materials (1 of 5)_ Gecko Adhesive fit for Spiderman-gzm7yD-JuyM_x264

Fly Feet

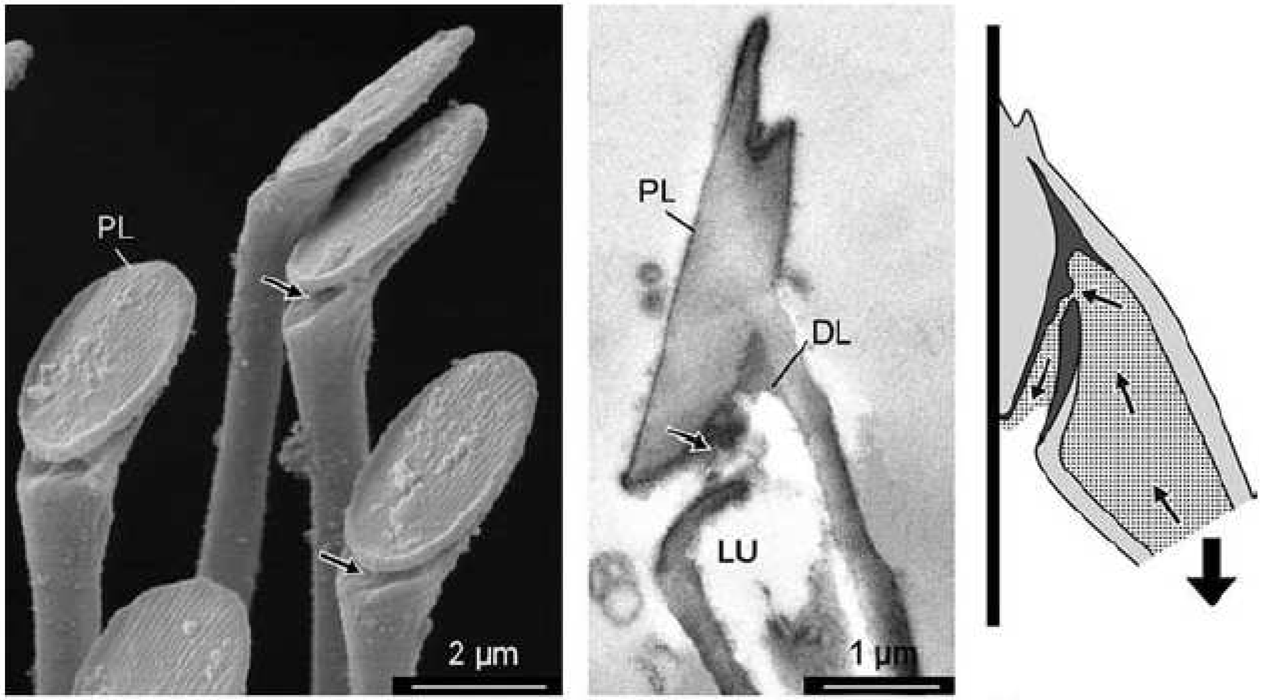
End of the legs of fruit fly (drosophila melanogaster)



End of the leg of syrphid fly

Bharat Bhushan-Biomimetics_ *Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology,* Springer-Verlag, 2012.

Biomimetic Attachment Structures of Flies

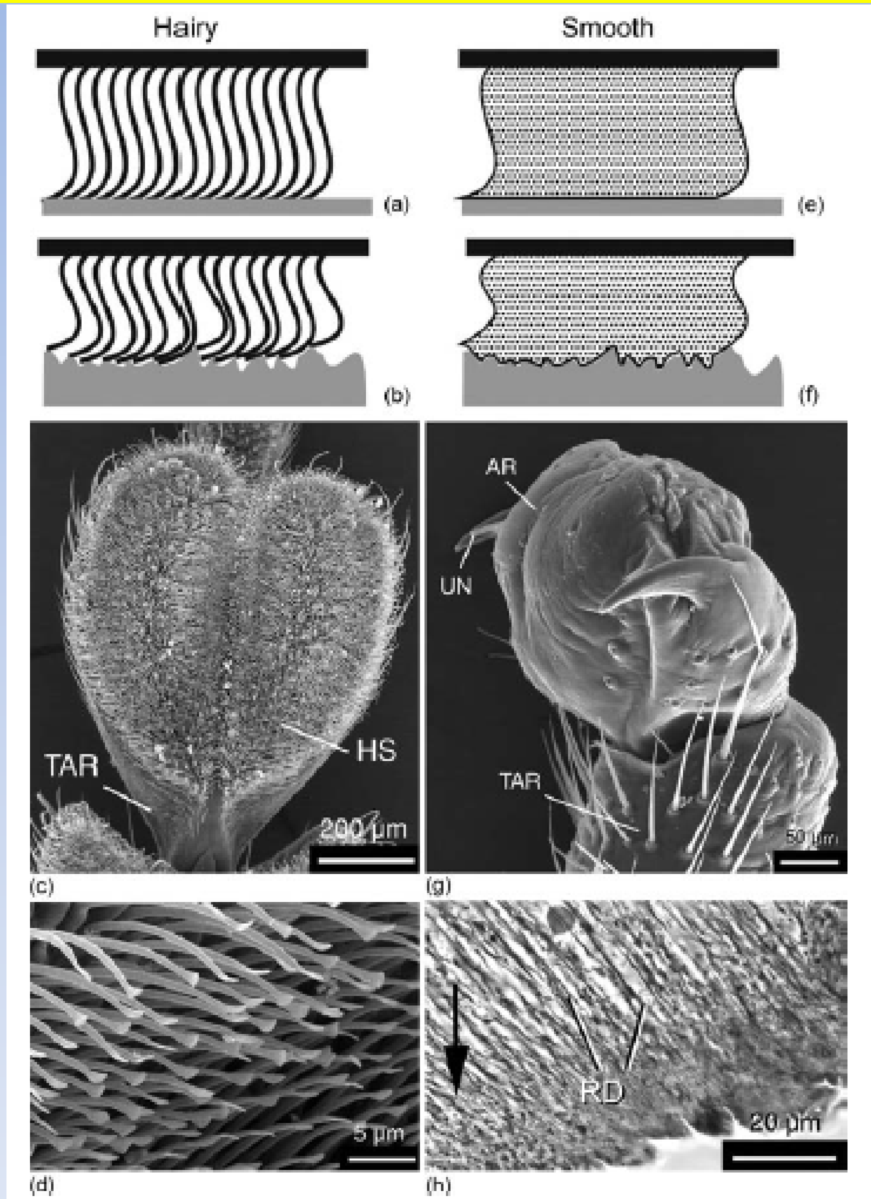


(a) (b) (c)

Figure 15.5 Dispensing system of the tenent seta in the syrphid fly *Episyrphus balteatus*. (From Gorb, S.N. (2001) *Attachment Devices of Insect Cuticle*. Dordrecht, Boston, London: Kluwer Academic Publishers. With permission of Springer Science + Business Media B.V.) (a, b) SEM (a) and TEM (b) micrographs of the tenent setae, (c) diagram of position of the seta on the substratum. Dotted area indicates lipid-containing secretion. Small arrows indicate the route of secretion release. Large arrow indicates direction of pulling force. DL, dense layer; LU, lumen; PL, end plate.

Yoseph Bar-Cohen-Biomimetics_ Biologically Inspired Technologies-CRC Press (2005)

Biomimetic Attachment Structures of Flies



Yoseph Bar-Cohen-Biomimetics_ Biologically Inspired Technologies-CRC Press (2005)

Biomimetic Attachment Devices Based on a Tree Frog

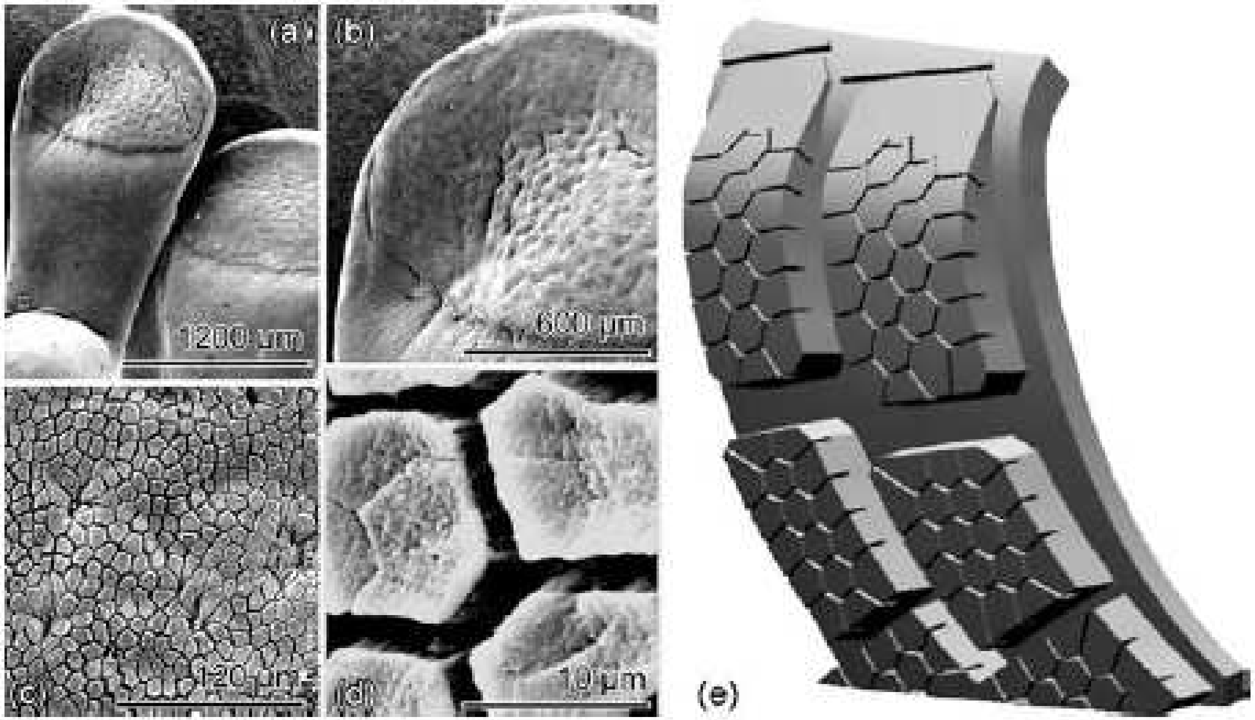


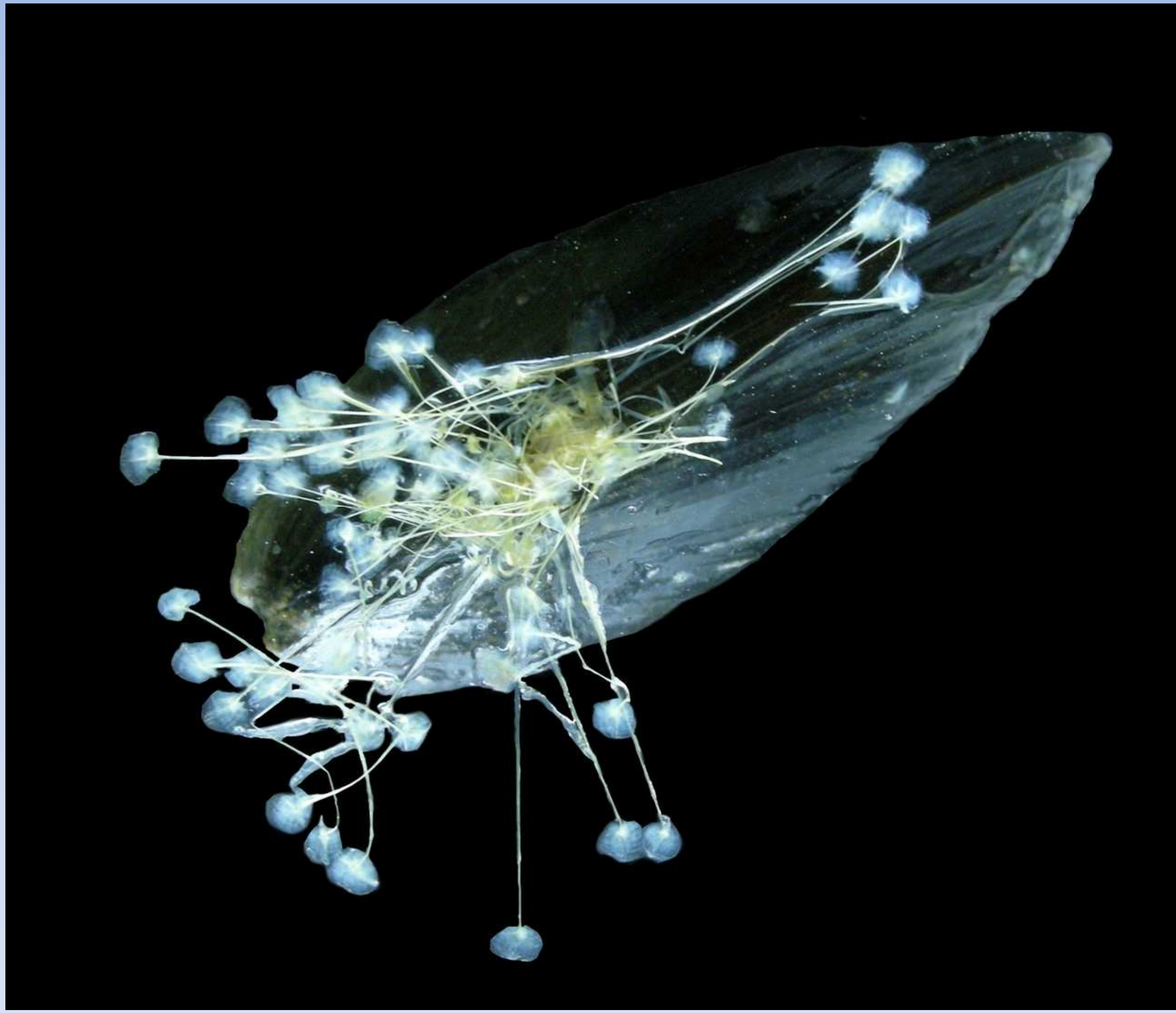
Figure 15.8 Surfaces generating grip on the wet substrata. (a–d) Scanning electron micrographs of the toe pads of the tree frog *Phyllomedusa trinitatis*. (Courtesy of J. Barnes, University of Glasgow.) (a) Low power view of the terminal portions of two toes, with toe pad epithelial cells just visible, (b) expanded view of a single toe pad, (c) medium power view of toe pad epithelium with mucous pores, (d) high power view to show detailed structure of the columnar epithelial cells separated from each other by grooves which, in life, would be filled with mucus, and (e) hexagonal sipes of Conti Winter Contact TS780. (Courtesy of R. Mundl, Continental AG.)

Yoseph Bar-Cohen-Biomimetics_ Biologically Inspired Technologies-CRC Press (2005)

Mussel Adhesion

https://cosmosmagazine.com/biology/new-underwater-glue-inspired-mussels

Byssal threads and adhesive pads are clearly visible in this photo of a mussel attached to a pane of glass.



Stephen Ornes PNAS 2013;110:16697-16699

Mussel Adhesion

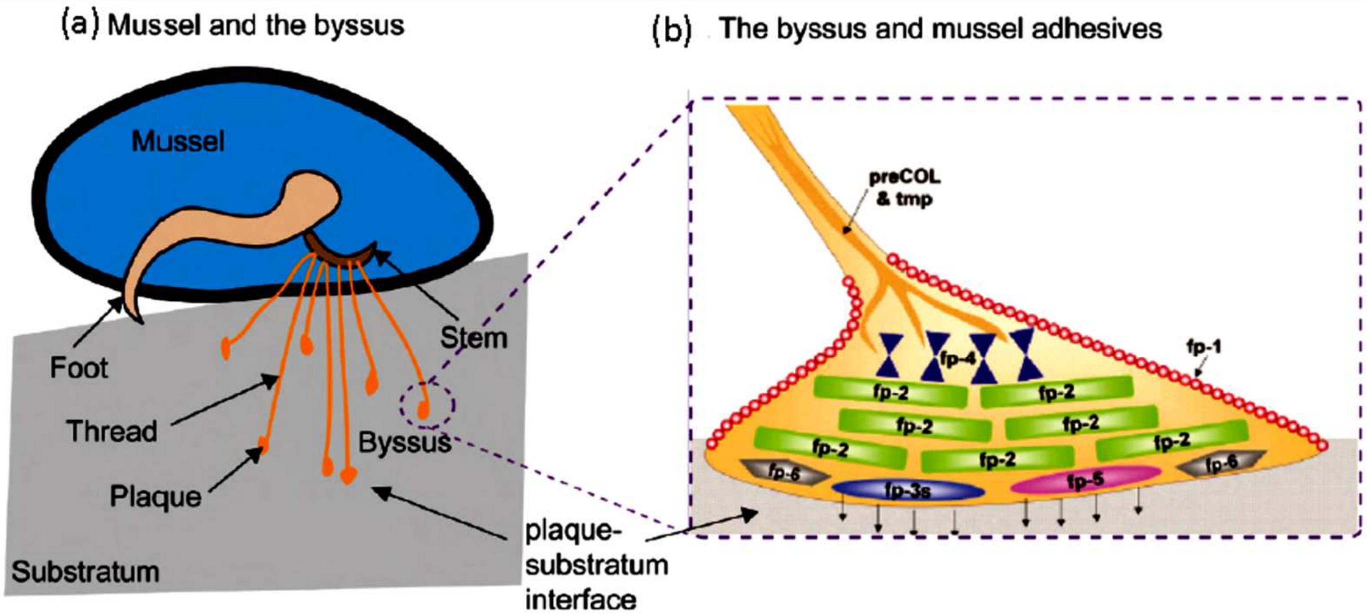
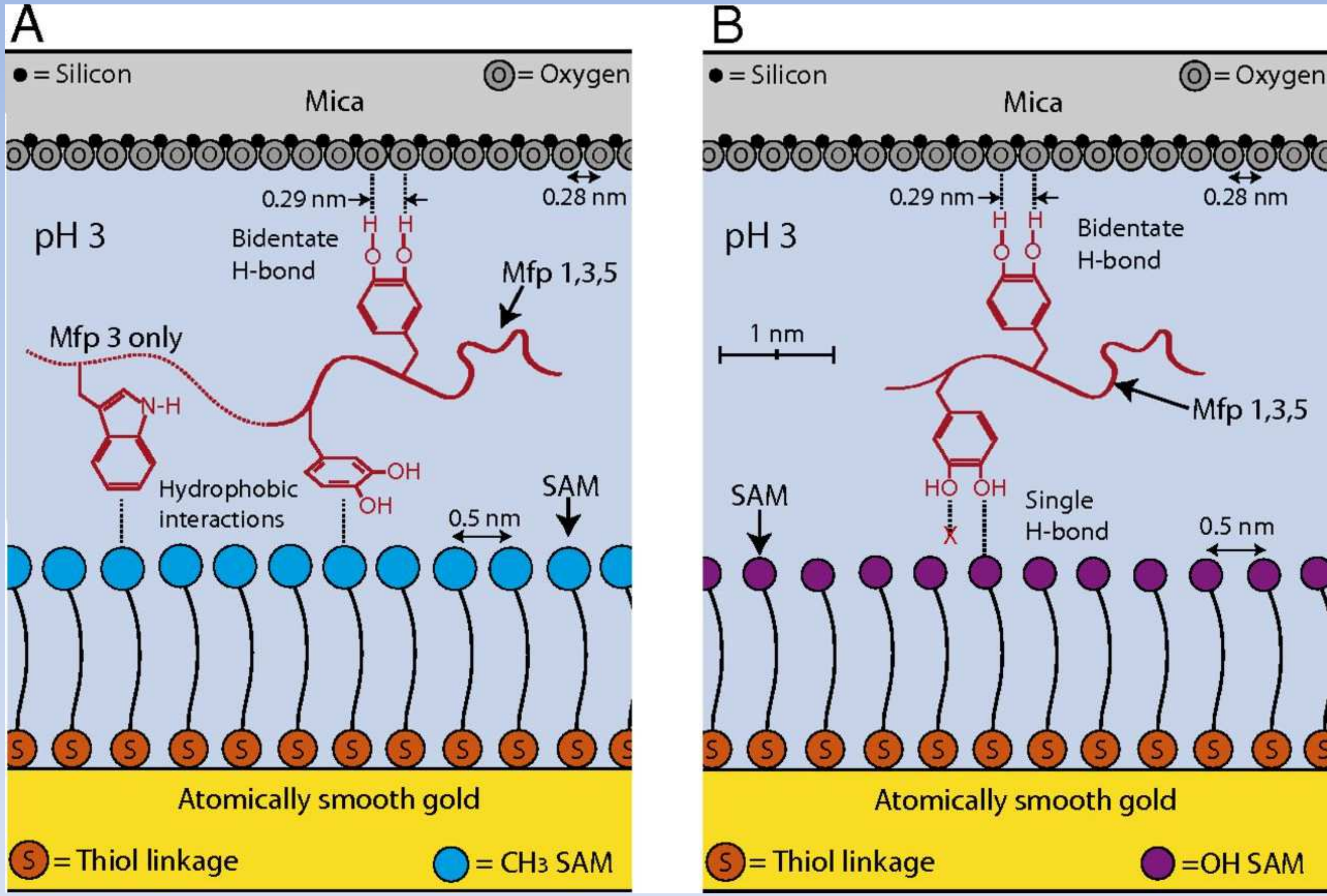


Figure 3.1 Schematic of mussel adhesive system: (a) mussel and the byssus, showing typical adult mussel with a byssus attached to a substrate, which contains four parts: plaque, thread, stem, and root (at the base of the mussel foot); (b) the byssus and mussel adhesives, showing typical byssal plaque proteins of *Mytilus* in the byssus. Panel b was modified based on a figure published in the reference [21]. Copyright © the American Society for Biochemistry and Molecular Biology.

Zeng et al. In: Havazelet Bianco-Peled_ Maya Davidovich-Pinhas-Bioadhesion and biomimetics _ from nature to applications-Pan Stanford Publishing (2015), pp. 49ff

The adhesion mechanisms of Mussel foot proteins between mica and Self Assembled Monolayer (SAM) surfaces.



Jing Yu et al. PNAS 2013;110:15680-15685

See also: Levine et al., Surface force measurements and simulations of mussel-derived peptide adhesives on wet organic surfaces, *PNAS* 2016, *113,* 4332–4337; doi: 10.1073/pnas.1603065113

PNAS

L-Dopa Derived Mussel Glue Mimetics

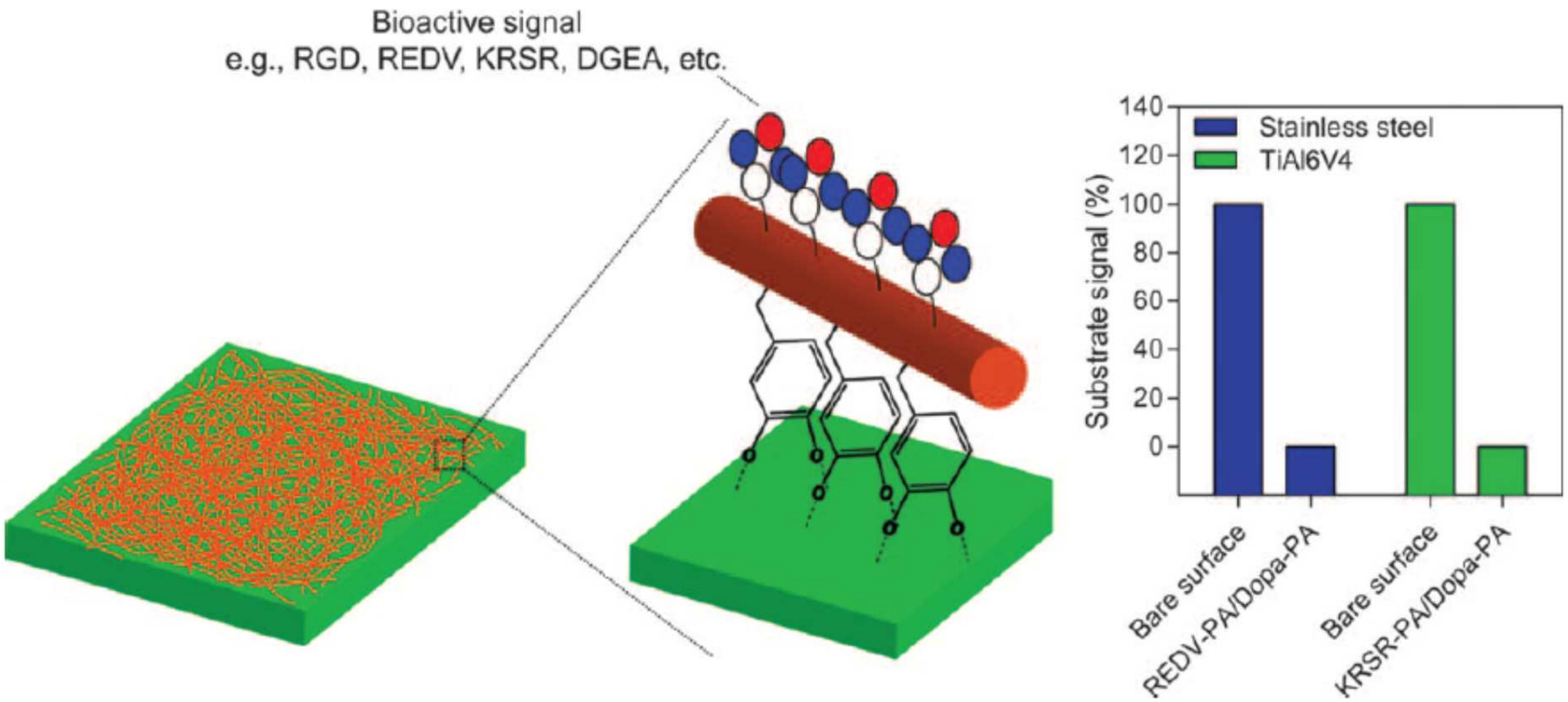


Figure 3 *A sketch showing nanofiber adhesion onto surface through mussel-mimetic catechol chemistry, carrying biofunctional ligands that construct an artificial cellular microenvironment on the surface. The figure was reconstituted from references 18 and 19.*

Ceylan et al. In: Patrick Flammang-Biological and biomimetic adhesives-Royal Society of Chemistry (2013), pp. 103ff

The Centipede *Henia vesuviana*

The centipede *Henia vesuviana* secretes copious amounts of proteinaceous glue in response to attack from potential predators (HOPKIN et al. 1990). The glue hardens within a few seconds of exposure to air and is able to physically immobilise large insects such as the Devil's Coach Horse beetle (*Staphylinus olens* MÜLLER) for more than 20 minutes (Figs 1, 2) (HOPKIN & GAYWOOD 1987).

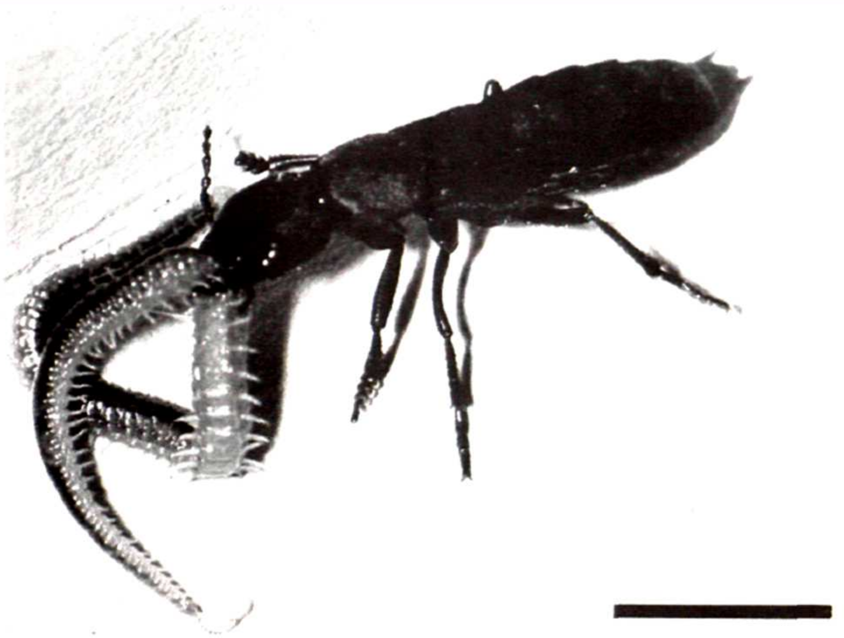


Fig. 1: *Staphylinus olens* attacking *Henia vesuviana*. Scale bar = 1 cm.

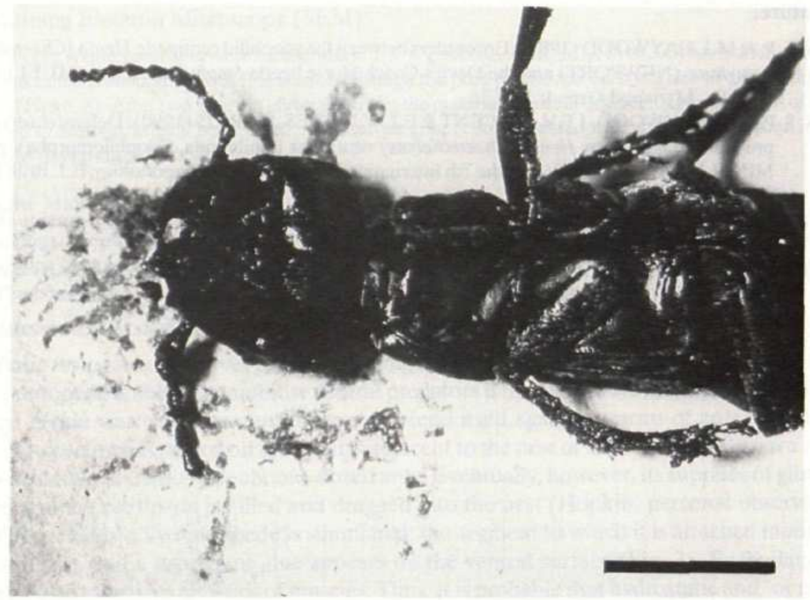
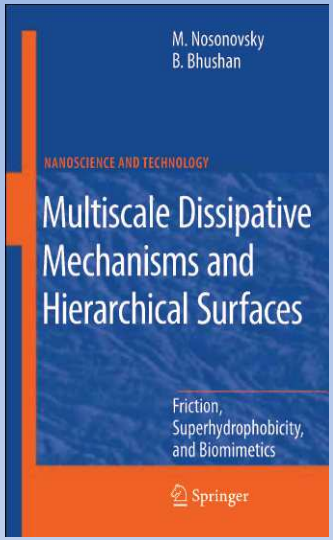


Fig. 2: The mouthparts of the beetle are stuck together with glue secreted by the centipede. The beetle remained in this position with its head glued to the substrate for 20 minutes before it was able to mount another attack. Scale bar = 0.5 cm.

www.zobodat.at/pdf/BERI_S10_0071-0079.pdf

Ber. nat.-med. Verein Innsbruck	Suppl. 10	S. 71 – 79	Innsbruck, April 1992

8th International Congress of Myriapodology, Innsbruck, Austria, July 15 - 20, 1990



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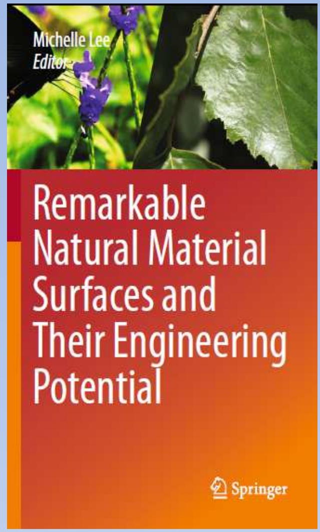

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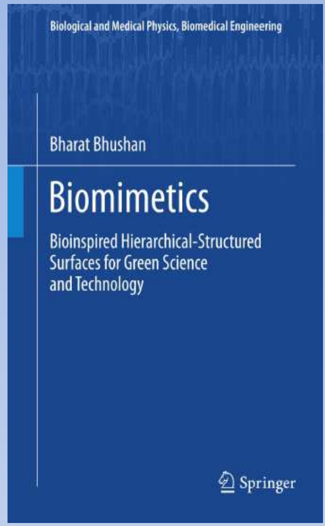

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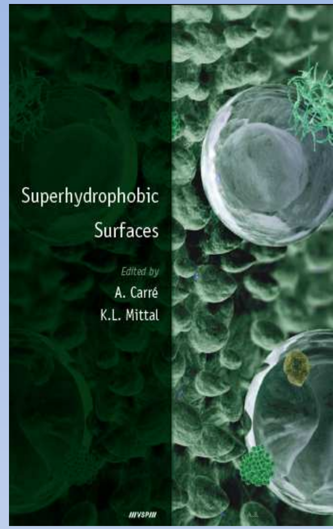

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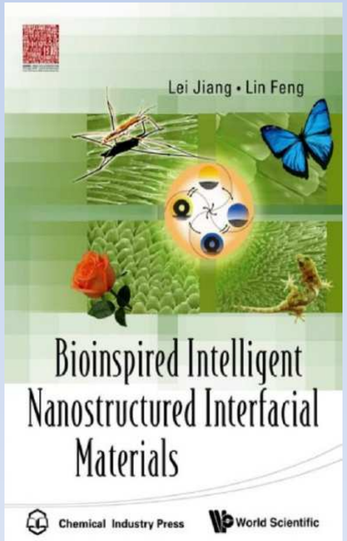
http://www.intechopen.com/books/biomimetics-learning-from-nature



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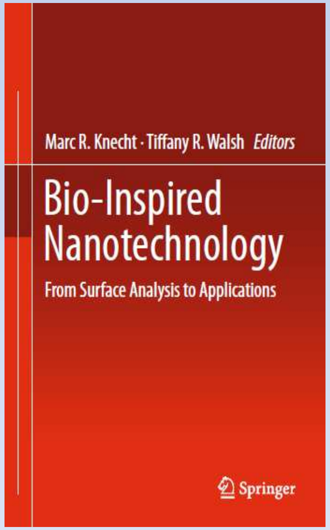

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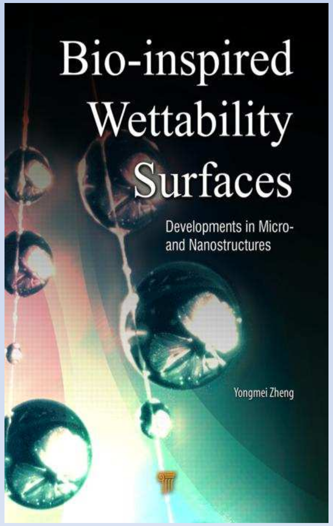

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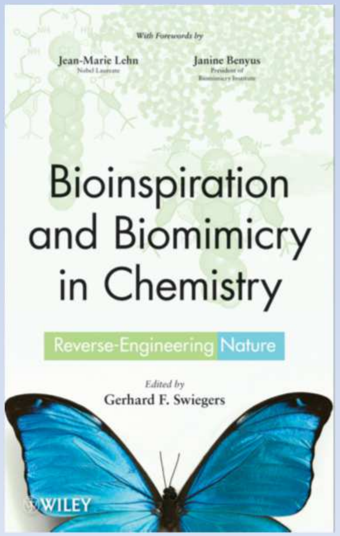

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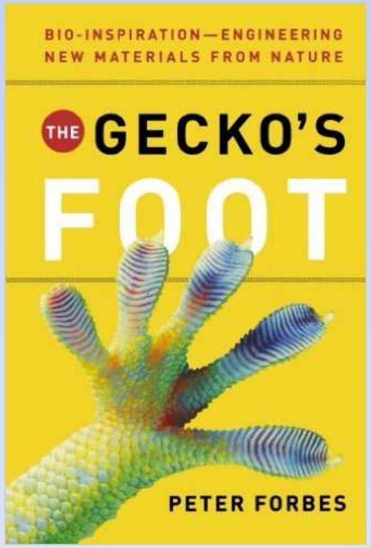

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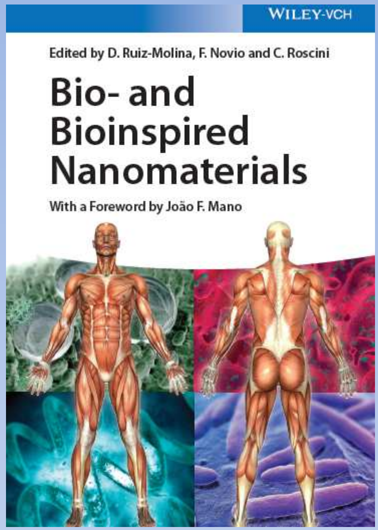

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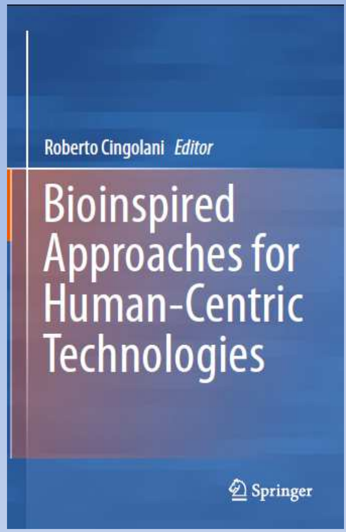

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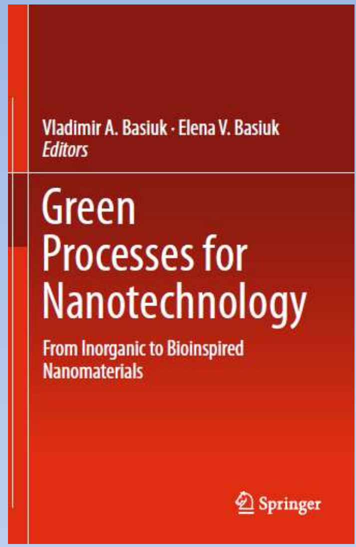

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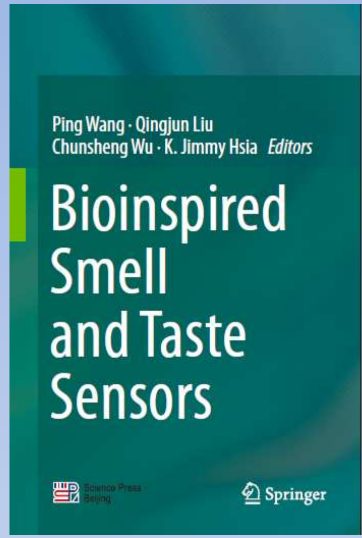

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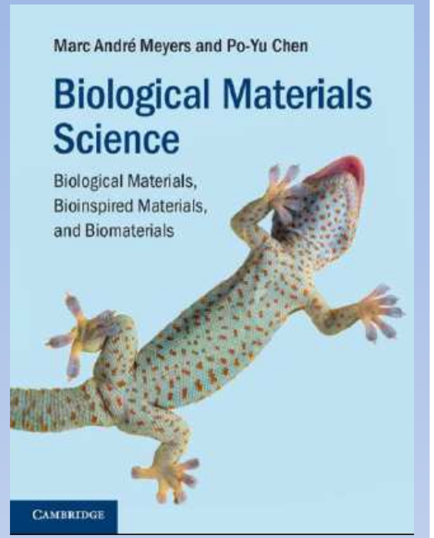

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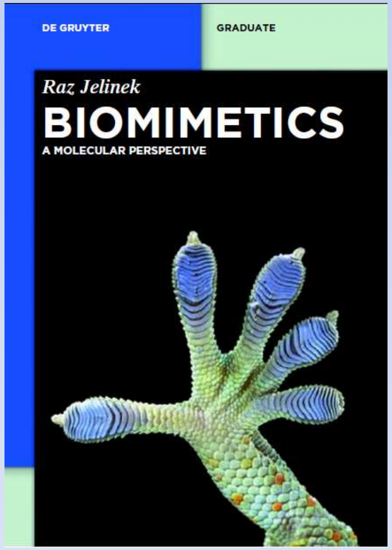

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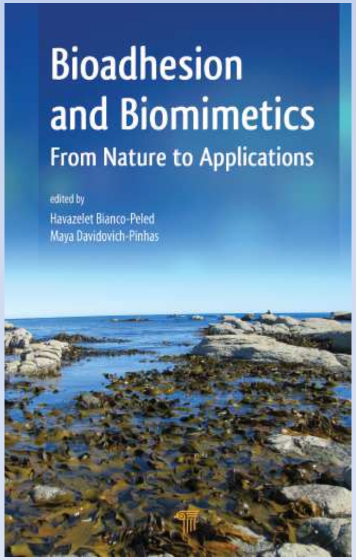

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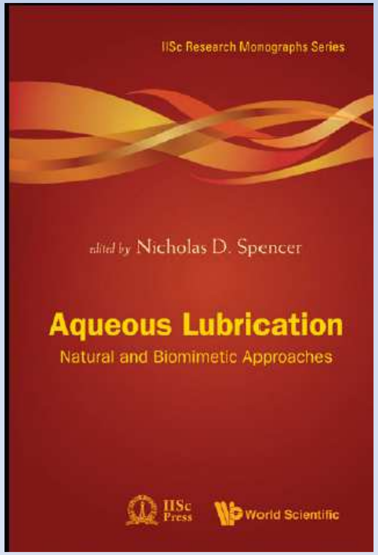

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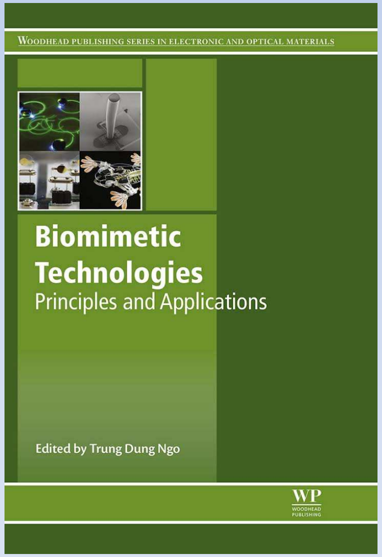

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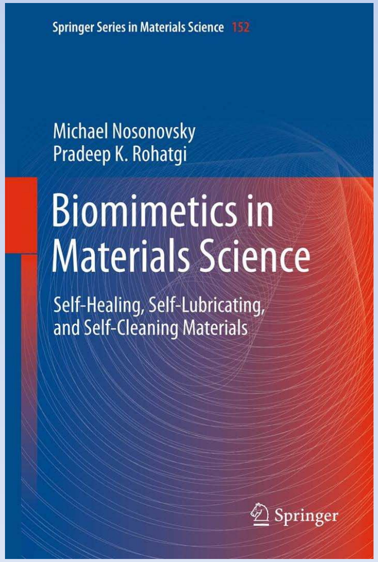

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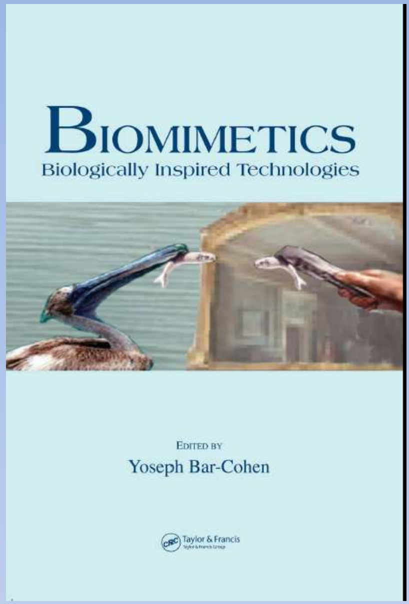

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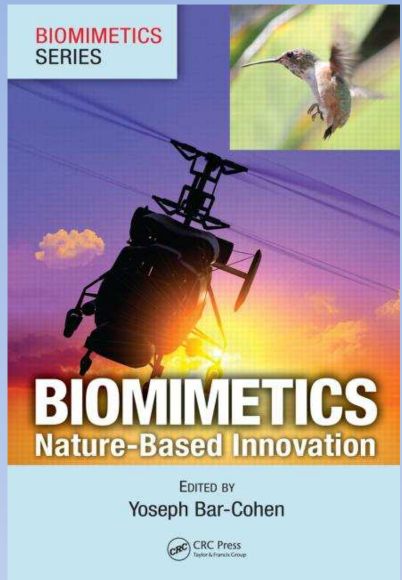

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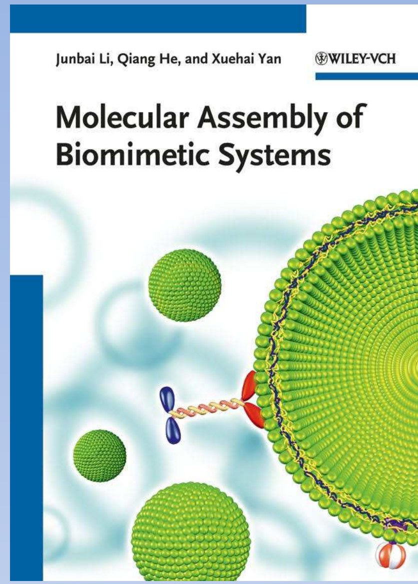

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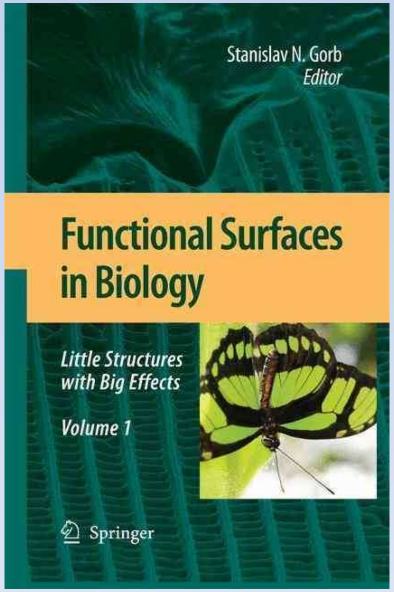
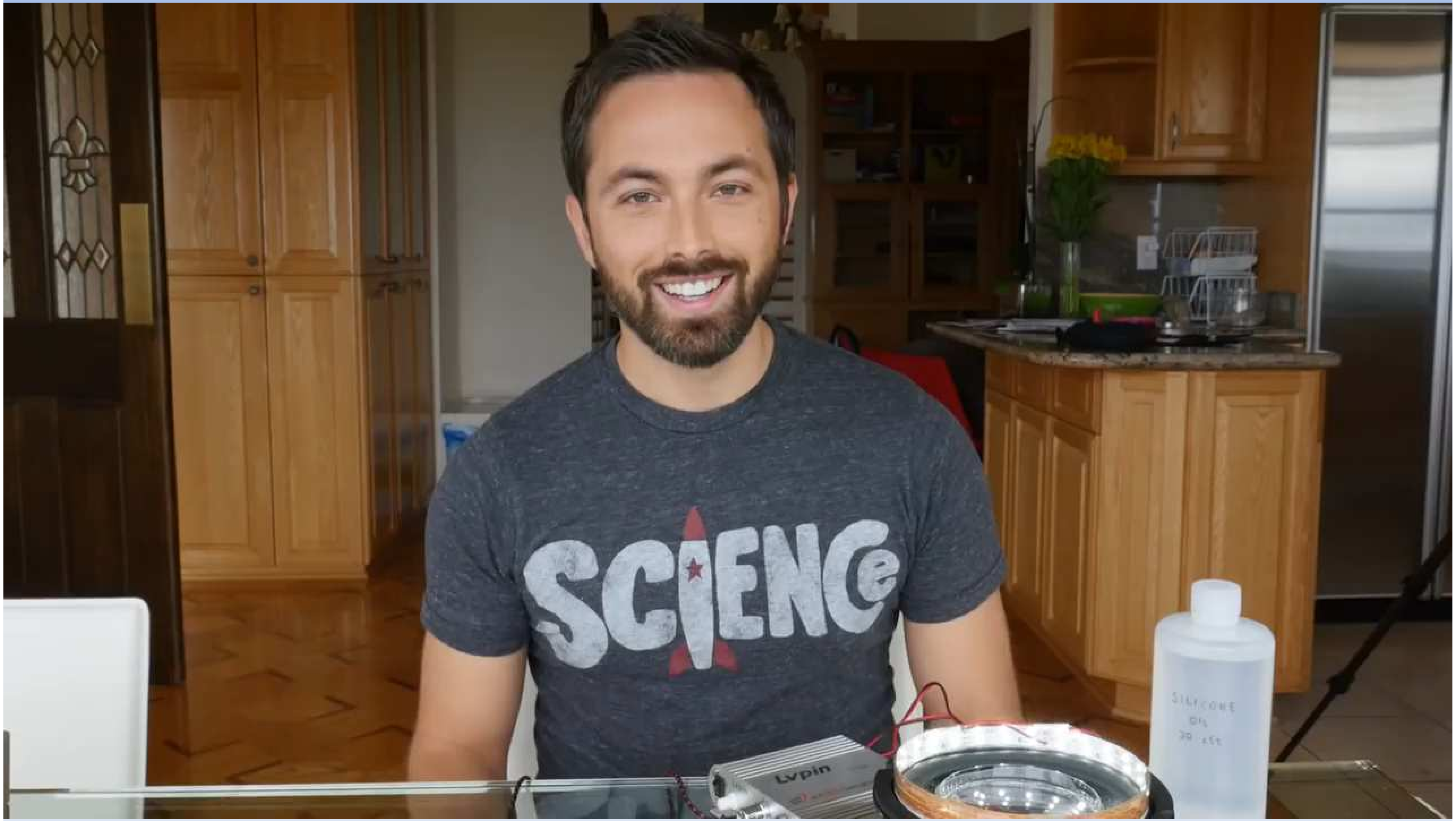


2013

Bouncing Drops and Quantum Mechanics



Fog Catchers in the Atacama Desert – North of Chile

#02 Fog Catchers in Atacama Desert - Living Atlas Chile

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