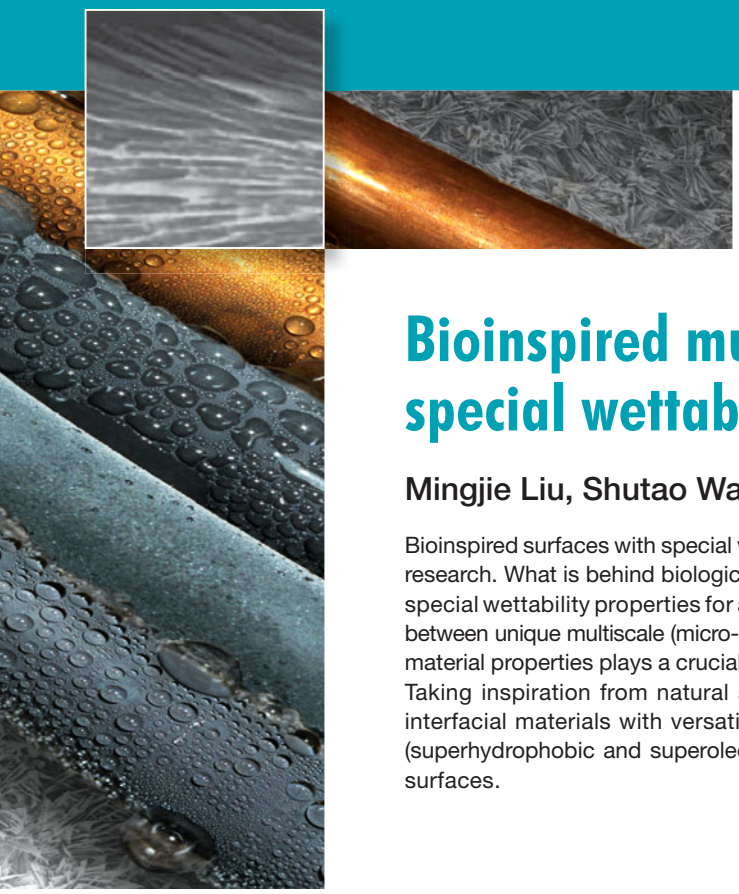


Bioinspired multiscale surfaces with special wettability

Mingjie Liu, Shutao Wang, and Lei Jiang

Bioinspired surfaces with special wettability have rapidly emerged at the forefront of materials research. What is behind biological surfaces with special wettability, and how can we realize special wettability properties for artificial materials? This article describes how the interplay between unique multiscale (micro- and nanoscale) structures of biological surfaces and intrinsic material properties plays a crucial role in achieving the desired wettability and functionalities. Taking inspiration from natural surfaces, researchers have designed and created novel interfacial materials with versatile special wettability, such as superantiwetting surfaces (superhydrophobic and superoleophobic), smart switchable surfaces, and water collecting surfaces.

Introduction

Biological systems in nature have achieved various intelligent processes and properties during the long course of evolution, and several of these have inspired the development of functional materials.[1] A fundamental and important property is wettability, which provides many unique functions for biological systems.[2,3] Examples include the self-cleaning property of lotus leaves,[4] the superior water-walking ability of water striders,[5] the directional adhesion of butterfly wings,[6] the antifogging functionality of mosquito eyes,[7] the antireflection of superhydrophobic cicada wings,[8] water collection observed in the desert beetle,[9] spider silk, and cactus,[10,11] as well as the self-cleaning ability of fish scales.[12] Recent biomimetic studies reveal that the cooperation of unique multiscale structures of biological surfaces with intrinsic materials properties plays a crucial role in achieving the desired wettability and other functionalities.[13] These versatile biological surfaces have further inspired people to design and create novel interfacial materials with special wettability properties, such as superantiwetting surfaces—superhydrophobic (surfaces with water contact angles larger than 150°) and superamphiphobic (surfaces with water and oil contact angles larger than 150°) surfaces in air and superoleophobic (surfaces with oil contact angles larger than 150°) interfaces in water—smart switchable surfaces, and water collecting surfaces.[14–16]

To date, bioinspired surfaces with special wettability have been widely studied and have attracted a broad range of researchers. The design of bioinspired surfaces typically involves five steps: (1) discovery of a unique wetting phenomenon in nature; (2) illustration of the correlation between multiscale structures and wettability; (3) design and synthesis of functional molecules; (4) design of heterogeneous and multiscale interfaces; and (5) fabrication of a cooperative complementary interface via weak interactions and bi-stable states.[1,13] Based on these principles, we can mimic the special wettability of biological surfaces and design corresponding smart interfacial materials. Finally, we might eventually exceed nature in some aspects.

In this review, we primarily discuss the rational design of bioinspired multiscale surfaces with special wettability, from natural to artificial, from tri-phase systems to multi-phase systems, and from 2D systems to 1D systems. Examples of unique wetting phenomena in nature and correlated structure effect models are presented. Recent progress in wettability of 1D systems such as fibers and ion channels will also be discussed.

Special wettability in biological systems

With the discovery of unique wetting phenomena in nature, the field of wettability has been greatly broadened, from air/liquid/solid systems (liquid wettability on a solid surface in air) to liquid/liquid/solid systems (liquid wettability on a solid surface in a liquid), and from 2D surfaces to 1D fibers and

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channels. Superhydrophobic surfaces are no longer confined to the property of low adhesion. High adhesion and directional adhesion superhydrophobic surfaces also have been developed. As shown in **Figure 1**, every kind of special wettability has its representative examples in nature.

Lotus leaves and cicada wings are low adhesion superhydrophobic surfaces.[8,17] Water droplets on their surfaces are almost spherical and can roll off easily at small inclinations, which results in the ability to self-clean. In a highly humid environment, mosquitoes can maintain excellent vision, which is attributed to the strikingly low adhesion superhydrophobic and antifogging properties of their eyes (Figure 1a).[7]

Compared to low adhesion surfaces, gecko feet, an example of a high adhesion surface, are superhydrophobic but can firmly attach to specific types of surfaces.[18] Rose petals are another kind of superhydrophobic surface with high adhesion to water (Figure 1b).[19] Tiny raindrops landing on rose petals are almost spherical but resist rolling off the flower.

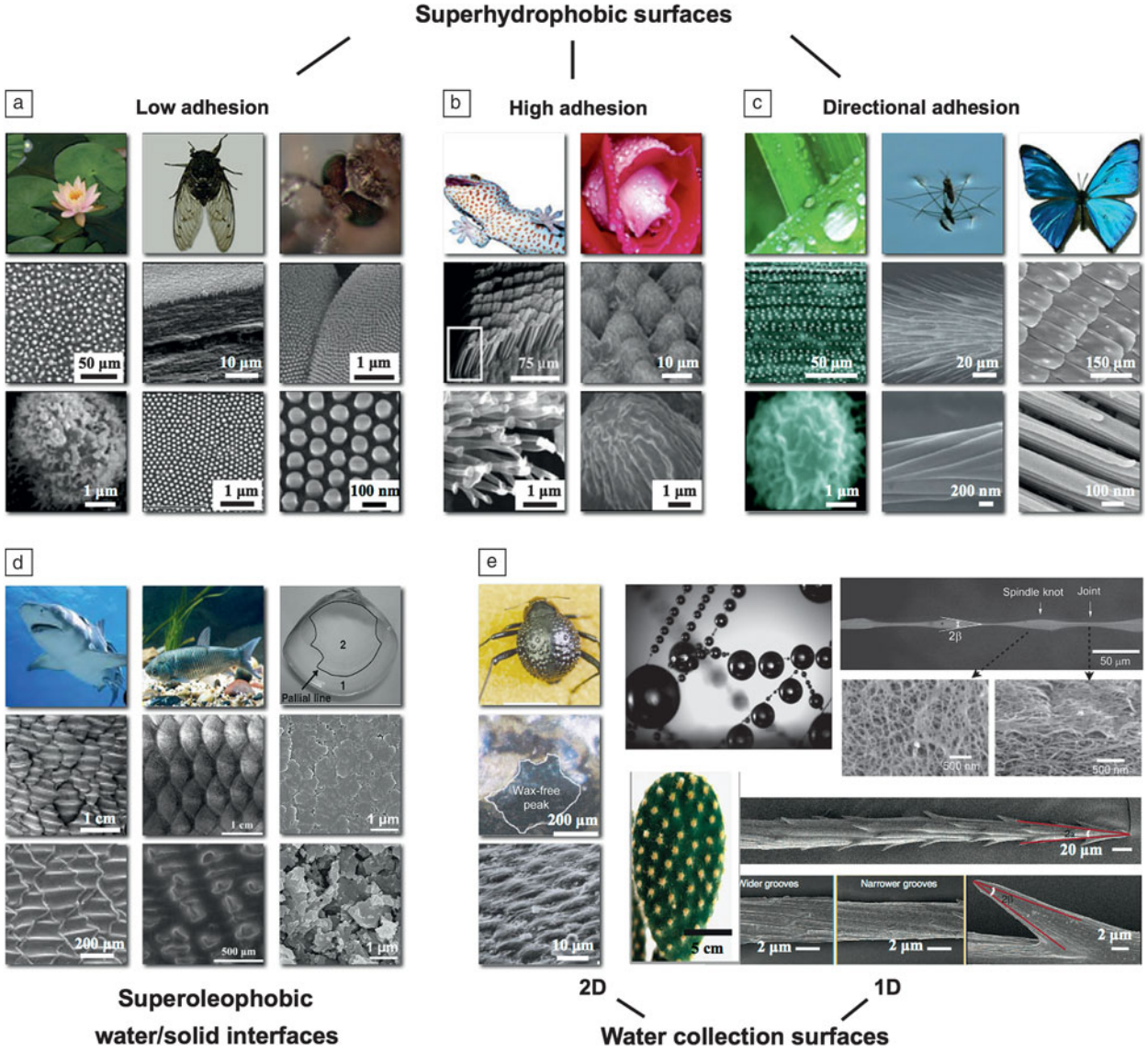


Figure 1. Multiscale structures in biological surfaces with special wettability. Several interesting wetting properties can be found in nature: (a) Low-adhesion superhydrophobic surfaces: lotus leaf,[14] cicada wings,[13] and mosquito compound eyes[7] (from left to right); (b) high-adhesion superhydrophobic surfaces: gecko feet[18] (the white box shows where the high magnification below was taken) and rose petals;[19] (c) directional-adhesion superhydrophobic surfaces: rice leaf,[14] water strider legs,[5] and butterfly wings[6]; (d) superoleophobic water/solid interfaces: shark skin,[21] fish scales,[12] and clam shells[22] (the pallial line separates the internal shell into two regions: the glossy edge region: region 1—shown in the middle image—and the white and coarse inside region, region 2, shown in the bottom image); and (e) water collecting surfaces: beetle's back (2D)[9] (middle image: the black area within the white outline shows where the high magnification below was taken), spider silk (1D),[10] and cactus spines (1D).[11] In each case, the first row shows a photograph of the biological feature, while the second and third rows show scanning electron microscopy images of corresponding micro- and nanometer-scale structures. Note: 2β, apex angle of the barbs.

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Besides isotropic adhesion on natural superhydrophobic surfaces, directional adhesion can also be seen in nature. For example, rice leaves, water strider legs, and butterfly wings offer a robust model to regulate fluid (Figure 1c).[6,14,20] On these surfaces, water droplets can usually easily roll off in one direction but can have difficultly moving or can even be pinned in another direction.

Sharkskin, fish scales, and clam shells can keep their surfaces clean because they exhibit anti-bioadhesion in a water environment (Figure 1d).[12,21–23] These biological surfaces show superoleophobicity and low adhesion under water.

The back of a desert beetle can collect moisture from air such that they can survive in extreme drought areas.[9] In contrast, some 1D biological materials such as spider silks and cactus spines can also harvest water from humid air (Figure 1e).[10,11] All of these unique and intriguing wetting properties in nature can inspire the creation of functional interfacial materials.

Effect of multiscale structures

All biological surfaces with special wettability discussed previously have multiscale structures (Figure 1). Discovering the correlation between multiscale structures and special wettability is a key issue for designing bioinspired materials. The study of the lotus effect led to a better understanding for constructing superhydrophobic surfaces. Micro- and nanoscale hierarchical structures (i.e., branch-like nanostructures on top of micropapillae, which are hair-like projections) were found on the surface of a lotus leaf (Figure 1a).[4] An air layer exists between the lotus leaf and water, which can prevent water from wetting the surface, thereby showing superhydrophobic properties (**Figure 2**a).[24,25] Theoretical studies show that the critical distance between two microstructures to generate superhydrophobicity is 100 nm, and this was confirmed by studies on the superhydrophobic property of water strider legs and the compound eyes of mosquitos.[26] Ribbed nanoneedle arrays with oriented nanogrooves that mimic water strider legs can help in the design of dynamic stable superhydrophobic surfaces (Figure 2a), which may have applications in robust antifouling and non-wettable coatings.[27]

The remarkable adhesive ability of gecko feet arises from the millions of nanoscale foot hairs on its feet (Figure 1b).[18] Although high adhesion of gecko feet happens on a solid-solid interface, this phenomenon can also inspire fabrication of superhydrophobic surfaces with high adhesion to water. To mimic a gecko's foot, we designed structures with nanoscale

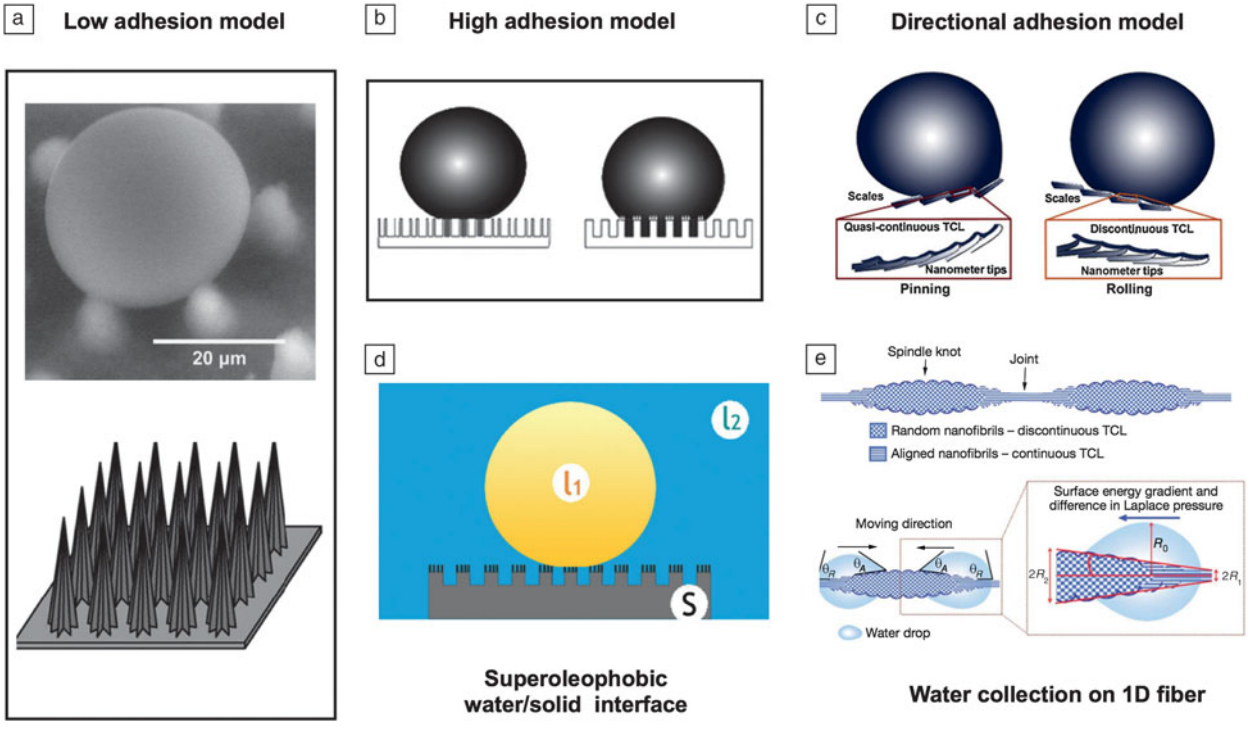


Figure 2. Multiscale structure effect on surface wettability. (a) Low adhesion model inspired by a lotus leaf[25] (top) and water strider legs[27] (bottom); air is trapped in solid structures. (b) High adhesion model inspired by gecko feet (left), air sealed in nanotubes can provide negative pressure; rose petals (right) where water partly wets microstructures while air is kept in nanostructures.[13] (c) Directional adhesion model inspired by butterfly wings; two wetting states can be tuned.[6] (d) Superoleophobic water/solid interfaces inspired by fish scales; wettability of liquid/liquid/solid triphase system, where a repulsive liquid phase is introduced into solid structures.[12] (e) Driving of water droplets on 1D fiber inspired by spider silk; wettability of a 1D system.[10] Note: θ_A and θ_R, advancing and receding angles of a water drop on spider silk, respectively; l_1, liquid 1; l_2, liquid 2; S, solid; R_0, drop radius; R_1, radius of the joint; R_2, radius of spindle knot; TCL, three-phase contact line.

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pores that could trap air isolated from the atmosphere (Figure 2b). In this case, the negative pressure induced by the volume change of sealed air as the droplet is pulled away from the surface can produce a high adhesive force.[2,28]

In contrast, rose petals show a different adhesive model. Detailed scanning electron microscopy (SEM) images show that a periodic array of micropapillae is compactly arranged on the rose petal, and additionally there exist nanoscaled cuticular folds on top of the micropapillae (Figure 1b).[19] A water droplet on the petal surface is expected to penetrate into the microscale grooves, but air gaps are present in the nanoscale folds, thus forming a partial wetting state (Figure 2b). Water sealed in micropapillae clings to the petal's surface, resulting in strong adhesion between the solid surface and liquid. These two biomimetic approaches can help with the fabrication of high-adhesion superhydrophobic surfaces.

It is generally recognized that directional liquid-solid adhesion—anisotropic adhesion when liquid droplets move on solid surfaces along different directions—is ascribed to the arrangement and orientation of micro- and nanostructures. For example, ordered multiscale structures exist on butterfly wings. Flexible nanotips are directionally arranged on the top of ridging nanostrips, and microscales overlap on the wings at the one-dimensional level (Figure 1c). Two distinct contact modes of a water droplet coexist on the orientation-tunable microstructured surface and thus produce directional adhesion (Figure 2c).[6]

Examples from nature in air rather than in water environments have attracted the attention of biomimetics researchers. For example, seabirds with superhydrophobic surfaces, rather than fish, are endangered by pollution from spilled oil, such as from a shipwreck. We recently reported an interesting phenomenon of fish keeping their surfaces clean in oil-polluted water.[12] A fish is covered with sector-like scale arrays. SEM images revealed that oriented micropapillae with fine nanoscale roughness on the fish scales are arranged in the radial direction (Figure 1d). It was found that the superoleophobic fish surface originates from water-wetted micro/nanohierarchical structures (Figure 2d). Other underwater organisms' structures, such as the clam shell, have similar properties (Figure 1d).[22] A new area of wettability, surface wetting in liquid/liquid/solid tri-phase systems (Figure 2d), has recently opened up.[29]

Water collection in nature, where plants and animals living in an arid environment have surfaces that can harvest water from the humidity in the air, is a dynamic process that is different from the study of static contact angles, for which a water droplet is simply placed on solid surfaces. During the water collecting process, small water droplets need to be propelled by the surface and further merged into larger droplets. Recently we reported directional water collection on wetted spider silk.[10] The spider silk is found to be composed of two main-axis fibers covered with periodic puffs of nanofibers. After a structural wet-rebuilding process (the structures of dry spider silk can be changed when tiny water drops condense on it), a unique multiscale fibrous structure can form, which is characterized by periodic spindle knots made of random nanofibrils and separated by joints made of aligned nanofibrils (Figure 1e). Two driving forces of propelling water droplets, a surface energy gradient between the spindle knots and the joints and a difference in Laplace pressure—the pressure difference between the inside and outside of a droplet—result from these structural features. With both factors acting together, water drops are continuously condensed and directionally collected around spindle knots (Figure 2e).

Switching between two extreme wetting states

Learning from multiscale effects on natural surfaces is helpful for designing superantiwetting surfaces. By simply combining low surface energy materials with micro/nanostructures, superhydrophobic surfaces can be easily achieved.[30–32] For example, the preparation of a lotus leaf-like porous microsphere/nanofiber composite film of polystyrene, a cheap industrial polymer, by a simple electrohydrodynamics technique, which afforded superhydrophobicity without any modifications, has been reported.[30] It is worth noting that natural systems are "smart." They can tune their output performance based on different environmental cues. Smart-responsive artificial materials are of great interest and have attracted much attention because they can switch between bi-stable states via multi-weak-interactions triggered by external stimuli.[13] Many responsive materials with their surface free energy or morphology sensitive to the external environment are being used to alter the surface wettability.[33]

If a molecule can alter its surface energy between hydrophobic and hydrophilic by introducing a multiscale structural effect, a smart surface whose wettability can be modulated reversibly between superhydrophobic and superhydrophilic, or even superoleophobic and superoleophilic, can be obtained (**Figure 3**a).[34,35] In contrast, if the molecule can alter its polarity but seldom changes the surface energy by introducing a multiscale structure effect, a superantiwetting surface with switchable solid-liquid adhesion can be obtained.[36] The mobility of a liquid droplet on such surfaces can be controllably switched from rolling to a pinned state (Figure 3b). Based on this strategy, various kinds of smart-responsive materials, such as polymers, liquid crystal molecules, and semiconducting inorganic oxides can be used to fabricate wettability switches that are controlled by external stimuli, such as temperature, light, electric field, magnetic field, mechanical forces, and pH.[15,37–39]

Liquid-infused multiscale surfaces

The wetting/antiwetting behavior of liquid droplets on a solid surface sometimes involves multiple phases. Making surfaces that are repellent to organic liquids is much more difficult than preparing superhydrophobic surfaces. This is because organic liquids are usually polar and have a low surface energy.[40] From fish scale inspired liquid/liquid/solid tri-phase systems, researchers have learned that superoleophobicity can be achieved by introducing another repulsive liquid phase into multiscale structures.[12] Recently, Aizenberg et al. reported a slippery liquid-infused porous surface (SLIPS) with exceptional liquid- and

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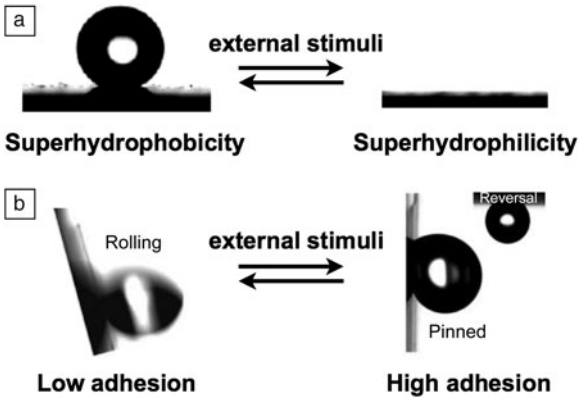


Figure 3. Photos of water droplets, obtained by a contact angle machine, on smart surfaces that can switch between two extreme states by external stimuli. (a) Reversible switching between superhydrophobicity and superhydrophilicity.[37] Left, a water droplet on the surface displays a spherical shape with a contact angle larger than 150°. Right, the water droplet spreads on the surface with a contact angle of 0°; (b) reversible switching of liquid-solid adhesion while keeping a superhydrophobic state. A water droplet can be switched between rolling and pinned states on solid surfaces.[36] Left, the water droplet rolls off the solid surface; right, the water droplet can be pinned on a vertical surface and reversed on a solid surface (top right corner). Note: The volume of all of the water droplets is 2–5 μL.

ice-repellence, pressure stability, and enhanced optical transparency.[41] This slippery surface is modeled after Nepenthes pitcher plants, whose self-cleaning effect is different from the lotus effect. Pitcher plants combine well-matched solid and liquid surface energies with microtextural roughness, creating a highly stable liquid-infused film that is effective in catching insects that step on it.[42] Inspired by this idea, researchers used micro-/nanostructured substrates to lock the infused lubricating fluid in place (**Figure 4**a). SLIPS shows almost perfect slipperiness, where liquids slip on the surface without any hysteresis, toward practically everything: pure liquids, complex liquids such as blood and oil, and even solid materials such as ice, dust, and insects. SLIPS has broad applications in the self-cleaning, anti-bioadhesion, anti-fogging, and anti-icing coatings. The wettability of liquid-infused surfaces involves an air/liquid/liquid/solid four-phase system. Different from traditional superhydrophobicity caused by an air/solid composite surface, the omniphobic liquid-infused surfaces arise from a liquid/solid composite surface.

Quéré et al. also studied the slip properties of liquid-infused surfaces using the classical behavior of evaporating coffee drops.[43] As shown in Figure 4b, on solid/air composite surfaces, no matter the roughness, particles are redistributed after evaporation in a ring within the area where the contact line initially formed. In contrast, on liquid-infused surfaces, the drop continuously retracts and eventually leaves a small homogeneous cluster of particles, without any trace beyond. This experiment illustrates another application of slippery surfaces, which can be used for concentrating solid particles in a localized place after evaporation. This may help to pattern nanoparticles at high resolution based on printing.[43]

Wettability of 1D systems

A fiber and channel are two kinds of representative 1D materials. Inspired by spider silk, a series of functional fibers with special wettability have been fabricated by either creating special structures on the fiber surface, or modifying it with responsive molecules. For example, we fabricated artificial nylon fibers that mimic the structural features of wet-rebuilt spider silk by a dip-coating method.[10] The artificial silk has periodic spindle knots similar to those of the wetted spider silk (**Figure 5**a). The artificial joints have a stretched porous structure, such as aligned nanofibrils, and the artificial spindle knots exhibit random porous surface structures (Figure 5b–d). Not only the structures but also the water collection ability of artificial silk are similar to that of wetted spider silk. When the artificial silk was exposed to a mist, small droplets started to condense randomly on it, the droplet volume increased, and those located on joints moved toward spindle knots (Figure 5a). Furthermore, by optimizing the interplay of curvature, chemical, and roughness gradients on the fiber surfaces, tiny water droplets (tens of picoliters) could be driven controllably in one direction (i.e., "toward" or "away from" the knot).[44,45]

Except for the controllable direction, the water collecting efficiency of bioinspired silk can be tuned by the size and

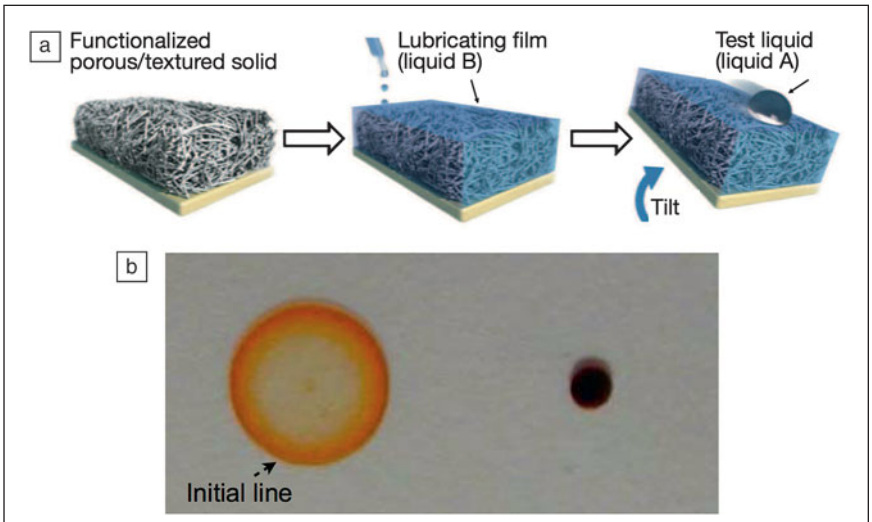


Figure 4. Liquid-infused multiscale surfaces. (a) Schematic showing the fabrication of a slippery liquid-infused porous surface by infiltrating a functionalized porous/textured solid with a low surface energy, chemically inert liquid to form a homogeneous lubricating film on the surface.[41] Liquids A and B are two immiscible liquids. (b) Patterns left by coffee drops (initial diameter of 5 mm) after evaporation on a plastic (textured or not, left) and on a slippery liquid-infused material (right).[43]

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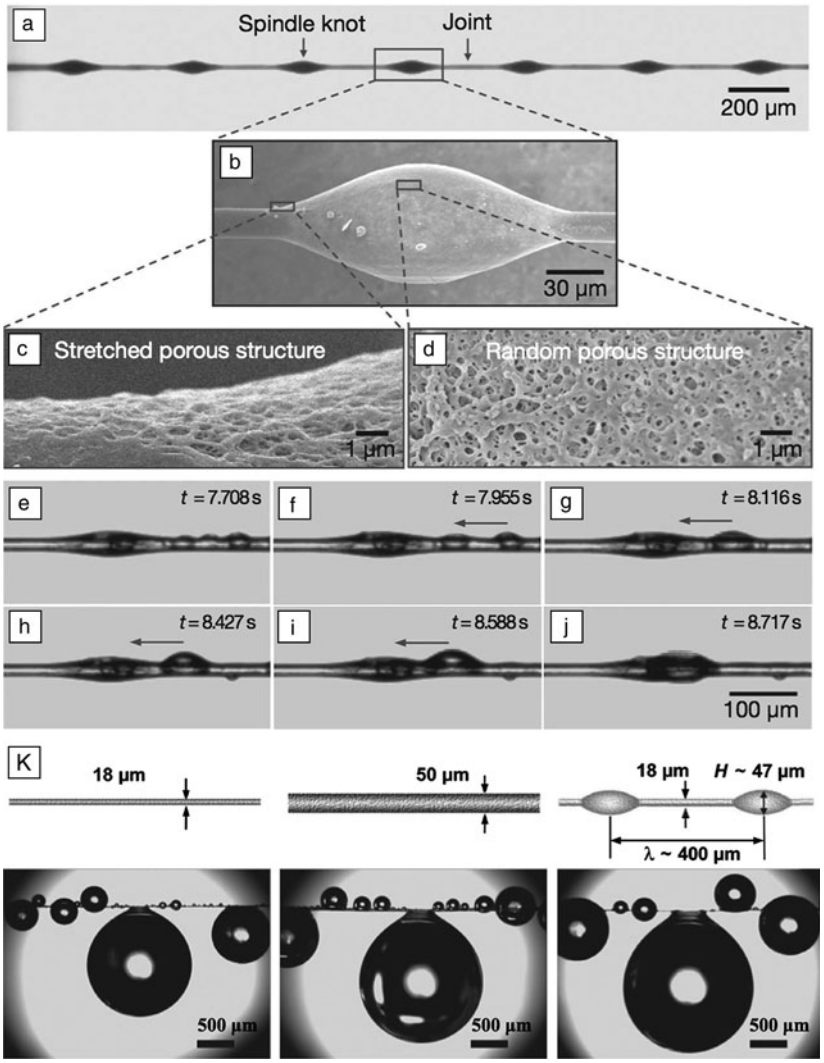


Figure 5. Artificial spider silk that mimics the structure and water collection capability of natural spider silk. (a)–(j) Images of spindle knot/joint structure and directional water collection.[10] These structural features can give rise to a surface energy gradient and a difference in Laplace pressure. (k) Spindle knot structure enhances solid-liquid adhesion on bioinspired fibers that can capture larger water droplets (right), compared to smooth fibers (left and middle).[47] Note: *H*, diameter of the spindle knot; λ, distance between two spindle knots.

geometry of the spindle knots. From the volume of the water droplets on the bioinspired fibers at different collection times, it is found that bioinspired fibers with larger spindle knots collect more water than those with smaller ones.[46] Compared to smooth fibers, bioinspired fibers with periodic spindle knots have much stronger water hanging ability, which is based on the maximum volume of water that hangs on the fibers, due to the enhanced liquid-solid adhesion. As shown in Figure 5, the fiber with a larger diameter exhibits a stronger hanging ability. However, when a thinner fiber is fabricated with spindle knots, the maximum volume of water hung on it exceeds that on the smooth fiber with a larger diameter (Figure 5b).[47] It is believed that a spindle knot structure induces an unusual three-phase contact line on the fiber surface and makes it more stable through tuning the slope and curvature of the spindle knot. As a result, the solid-liquid adhesion has been greatly enhanced.

For practical applications, it is necessary to fabricate bioinspired fibers on a large scale at low cost. Jiang et al. thereby developed a fluid-coating method to continuously fabricate bioinspired fibers with periodic spindle knots.[48] These bioinspired functional fibers may have applications in many fields, such as water collection, smart catalysis, and sensing.

Ion channels in biological systems are usually nanoscale in size and play significant roles in maintaining normal living conditions.[49,50] Artificial nanochannels that can reproduce the function of ion channels in nature will have potential applications in many fields, such as biosensing, sequencing, and energy conversion.[49,51] Recent progress in microfabrication technology allows preparing single nanochannels or multi-nanochannels in organic or inorganic membranes, which provide a suitable platform to design bioinspired smart nanochannels through surface engineering.[52]

The bioinspired strategy of fabricating 2D surfaces can be extended to build 1D smart nanochannels. By tuning the inner surface wettability of nanochannels, controllable ion movement can be achieved. For example, a responsive surface that can switch among stable superhydrophilic, metastable superhydrophobic, and stable superhydrophobic states based on pH responsive C4-DNA molecules has been developed.[53] When this type of smart surface is extended to the nanoscale, a synthetic nanopore-DNA system can be realized by immobilizing the C4-DNA onto the inner wall of the nanopore by a two-step chemical reaction. The single solid-state conical nanopores can be reversibly gated by folding and unfolding of the C4-DNA molecules immobilized inside the nanopores. High (on-state) and low (off-state) conductance states were found within this nanopore-DNA system corresponding to the single-stranded and i-motif structures of the attached DNA motors, which are DNA that can switch their structures under external stimuli.[54] Furthermore, a potassium-responsive nanochannel system has been realized, where G4-DNA molecules, which have a different molecular structure from C4-DNA, were immobilized into a synthetic nanochannel and underwent a potassium-responsive conformational change so as to obtain a nonlinear response to potassium ions.[55] These gating properties closely mimic the gating mechanism of biological ion channels; one such example found in nature is acid-sensing ion channels.[56] Since there are so many examples of smart

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interfacial materials that are suitable candidates for designing nanochannel systems, various bioinspired smart gating nanochannels are built by using responsive molecules, such as light, pH, ion and thermal, and protein, instead of DNA molecules (**Figure 6**).[51]

Conclusion

In this review, we have mainly discussed the bioinspired design of smart interfacial materials with special wettability. Biological systems utilize multiscale effects of molecular structures, nanostructures, and microstructures to create functional surfaces with special wettability. Taking inspiration from nature, the design of material systems should not be confined to engineer bulk materials or synthesize new molecules, but also should be applied to control the structures of materials over multiple scales. That is, materials can exhibit unusual macroscopic properties when the structures extend from the molecule to molecular clusters to micro- and nanostructures. Although significant progress has been achieved in the special wettability field, there are still many challenges. Future perspectives include new fundamental theories of explaining the special wettability phenomena, biocompatible superhydrophobic surfaces and exploring their applications in biomedical fields, ultrafast responsive surfaces, and multifunctional surfaces. For practical applications, low cost and facile strategies are necessary. Enhancing the mechanical stability, robustness, durability, and self-healing ability of superhydrophobic and superoleophobic surfaces is also important.

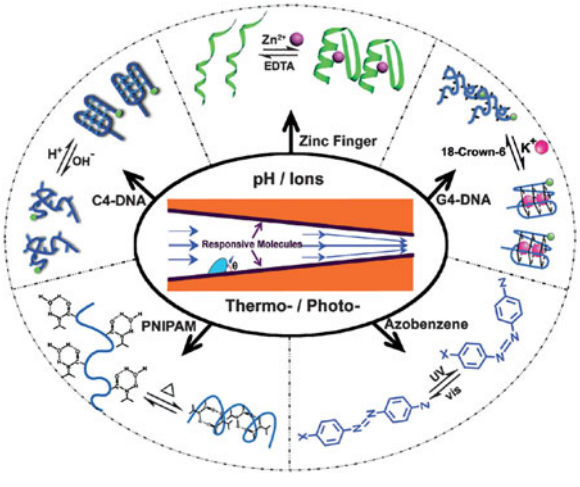


Figure 6. Scheme of smart gating of micro/nanochannels based on control of surface wettability.[51] Center: Smart nanochannel systems. Blue arrows represent the direction of fluid travel from the base side of the conical channel to the nanochannel, the tip side of the conical channel. The two purple lines in the modified channel wall represent the functional molecules, which results in the changes of the surface properties, such as contact angle in the microchannel and the smart gating in the nanochannel. Surroundings: Typical responsive molecules that can switch their conformations, molecular dipole, charge distribution, and atomic arrangement due to external stimuli, such as light, temperature, and ionic content. Note: PNIPAM, poly(N-isopropylacryamide); EDTA, ethylenediaminetetraacetic acid; θ, liquid contact angle on the solid surface.

Acknowledgments

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References

1. L. Jiang, L. Feng, Eds., *Bioinspired Intelligent Nanostructured Interfacial Materials* (World Scientific Publishing, China, 2010).
2. M.J. Liu, Y.M. Zheng, J. Zhai, L. Jiang, *Acc. Chem. Res.* **43**, 368 (2010).
3. T.L. Sun, L. Feng, X.F. Gao, L. Jiang, *Acc. Chem. Res.* **38**, 644 (2005).
4. R. Blossey, *Nat. Mater.* **2**, 301 (2003).
5. X.F. Gao, L. Jiang, *Nature* **432**, 36 (2004).
6. Y.M. Zheng, X.F. Gao, L. Jiang, *Soft Matter* **3**, 178 (2007).
7. X.F. Gao, X. Yan, X. Yao, L. Xu, K. Zhang, J.H. Zhang, B. Yang, L. Jiang, *Adv. Mater.* **19**, 2213 (2007).
8. W. Lee, M.K. Jin, W.C. Yoo, J.K. Lee, *Langmuir* **20**, 7665 (2004).
9. A.R. Parker, C.R. Lawrence, *Nature* **414**, 33 (2001).
10. Y.M. Zheng, H. Bai, Z.B. Huang, X.L. Tian, F.Q. Nie, Y. Zhao, J. Zhai, L. Jiang, *Nature* **463**, 640 (2010).
11. J. Ju, H. Bai, Y.M. Zheng, T. Zhao, R. Fang, L. Jiang, *Nat. Commun.* **3**, 1247 (2012).
12. M.J. Liu, S.T. Wang, Z.X. Wei, Y.L. Song, L. Jiang, *Adv. Mater.* **21**, 665 (2009).
13. F. Xia, L. Jiang, *Adv. Mater.* **20**, 2842 (2008).
14. L. Feng, S.H. Li, Y.S. Li, H.J. Li, L.J. Zhang, J. Zhai, Y.L. Song, B.Q. Liu, L. Jiang, D.B. Zhu, *Adv. Mater.* **14**, 1857 (2002).
15. X.J. Feng, L. Jiang, *Adv. Mater.* **18**, 3063 (2006).
16. M.J. Liu, L. Jiang, *Adv. Funct. Mater.* **20**, 3753 (2010).
17. W. Barthlott, C. Neinhuis, *Planta* **202**, 1 (1997).
18. K. Autumn, Y.A. Liang, S.T. Hsieh, W. Zesch, W.P. Chan, T.W. Kenny, R. Fearing, R.J. Full, *Nature* **405**, 681 (2000).
19. L. Feng, Y.A. Zhang, J.M. Xi, Y. Zhu, N. Wang, F. Xia, L. Jiang, *Langmuir* **24**, 4114 (2008).
20. D.L. Hu, B. Chan, J.W.M. Bush, *Nature* **424**, 663 (2003).
21. P. Ball, *Nature* **400**, 507 (1999).
22. X.L. Liu, J. Zhou, Z.X. Xue, J. Gao, J.X. Meng, S.T. Wang, L. Jiang, *Adv. Mater.* **24**, 3401 (2012).
23. Y.C. Jung, B. Bhushan, *Langmuir* **25**, 14165 (2009).
24. P.P. Chen, L. Chen, D. Han, J. Zhai, Y.M. Zheng, L. Jiang, *Small* **5**, 908 (2009).
25. Y.M. Zheng, D. Han, J. Zhai, L. Jiang, *Appl. Phys. Lett.* **92**, 084106 (2008).
26. K. Lum, D. Chandler, J.D. Weeks, *J. Phys. Chem. B* **103**, 4570 (1999).
27. X. Yao, Q.W. Chen, L. Xu, Q.K. Li, Y.L. Song, X.F. Gao, D. Quere, L. Jiang, *Adv. Funct. Mater.* **20**, 656 (2010).
28. Y.K. Lai, X.F. Gao, H.F. Zhuang, C.J. Lin, L. Jiang, *Adv. Mater.* **21**, 3799 (2009).
29. M.J. Liu, Z.X. Xue, H. Liu, L. Jiang, *Angew. Chem. Int. Ed.* **51**, 8348 (2012).
30. L. Jiang, Y. Zhao, J. Zhai, *Angew. Chem. Int. Ed.* **43**, 4338 (2004).
31. H.J. Li, X.B. Wang, Y.L. Song, Y.Q. Liu, Q.S. Li, L. Jiang, D.B. Zhu, *Angew. Chem. Int. Ed.* **40**, 1743 (2001).
32. Q.D. Xie, J. Xu, L. Feng, L. Jiang, W.H. Tang, X.D. Luo, C.C. Han, *Adv. Mater.* **16**, 302 (2004).
33. K. Ichimura, S.K. Oh, M. Nakagawa, *Science* **288**, 1624 (2000).
34. T.L. Sun, G.J. Wang, L. Feng, B.Q. Liu, Y.M. Ma, L. Jiang, D.B. Zhu, *Angew. Chem. Int. Ed.* **43**, 357 (2004).
35. M.J. Liu, X.L. Liu, C.M. Ding, Z.X. Wei, Y. Zhu, L. Jiang, *Soft Matter* **7**, 4163 (2011).
36. C. Li, R.W. Guo, X. Jiang, S.X. Hu, L. Li, X.Y. Cao, H. Yang, Y.L. Song, Y.M. Ma, L. Jiang, *Adv. Mater.* **21**, 4254 (2009).
37. X.J. Feng, L. Feng, M.H. Jin, J. Zhai, L. Jiang, D.B. Zhu, *J. Am. Chem. Soc.* **126**, 62 (2004).
38. F. Xia, L. Feng, S.T. Wang, T.L. Sun, W.L. Song, W.H. Jiang, L. Jiang, *Adv. Mater.* **18**, 432 (2006).
39. M.J. Liu, F.Q. Nie, Z.X. Wei, Y.L. Song, L. Jiang, *Langmuir* **26**, 3993 (2010).
40. K. Tsujii, T. Yamamoto, T. Onda, S. Shibuichi, *Angew. Chem. Int. Ed.* **36**, 1011 (1997).
41. T.S. Wong, S.H. Kang, S.K.Y. Tang, E.J. Smythe, B.D. Hatton, A. Grinthal, J. Aizenberg, *Nature* **477**, 443 (2011).

https://doi.org/10.1557/mrs.2013.100 Published online by Cambridge University Press

42. H.F. Bohn, W. Federle, *Proc. Natl. Acad. Sci. USA* **101**, 14138 (2004).
43. A. Lafuma, D. Quéré, *Europhys. Lett.* **96**, 56001 (2011).
44. H. Bai, J. Ju, Y.M. Zheng, L. Jiang, *Adv. Mater.* **24**, 2786 (2012).
45. H. Bai, X.L. Tian, Y.M. Zheng, J. Ju, Y. Zhao, L. Jiang, *Adv. Mater.* **22**, 5521 (2010).
46. H. Bai, J. Ju, R.Z. Sun, Y. Chen, Y.M. Zheng, L. Jiang, *Adv. Mater.* **23**, 3708 (2011).
47. X.L. Tian, Y. Chen, Y.M. Zheng, H. Bai, L. Jiang, *Adv. Mater.* **23**, 5486 (2011).
48. H. Bai, R. Sun, J. Ju, X. Yao, Y.M. Zheng, L. Jiang, *Small* **7**, 3429 (2011).
49. C.R. Martin, Z.S. Siwy, *Science* **317**, 331 (2007).
50. D. Branton, D.W. Deamer, A. Marziali, H. Bayley, S.A. Benner, T. Butler, M. Di Ventra, S. Garaj, A. Hibbs, X.H. Huang, S.B. Jovanovich, P.S. Krstic, S. Lindsay, X.S.S. Ling, C.H. Mastrangelo, A. Meller, J.S. Oliver, Y.V. Pershin, J.M. Ramsey, R. Riehn, G.V. Soni, V. Tabard-Cossa, M. Wanunu, M. Wiggin, J.A. Schloss, *Nat. Biotechnol.* **26**, 1146 (2008).
51. L.P. Wen, X. Hou, Y. Tian, F.Q. Nie, Y.L. Song, J. Zhai, L. Jiang, *Adv. Mater.* **22**, 1021 (2010).
52. X. Hou, L. Jiang, *ACS Nano* **3**, 3339 (2009).
53. S.T. Wang, H.J. Liu, D.S. Liu, X.Y. Ma, X.H. Fang, L. Jiang, *Angew. Chem. Int. Ed.* **46**, 3915 (2007).
54. F. Xia, W. Guo, Y.D. Mao, X. Hou, J.M. Xue, H.W. Xia, L. Wang, Y.L. Song, H. Ji, O.Y. Qi, Y.G. Wang, L. Jiang, *J. Am. Chem. Soc.* **130**, 8345 (2008).
55. X. Hou, W. Guo, F. Xia, F.Q. Nie, H. Dong, Y. Tian, L.P. Wen, L. Wang, L.X. Cao, Y. Yang, J.M. Xue, Y.L. Song, Y.G. Wang, D.S. Liu, L. Jiang, *J. Am. Chem. Soc.* **131**, 7800 (2009).
56. J. Jasti, H. Furukawa, E. B. Gonzales, E. Gouaus, *Nature* **449** 316 (2007). □

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