BIOPHYSICS

The Intrigue of the Interface

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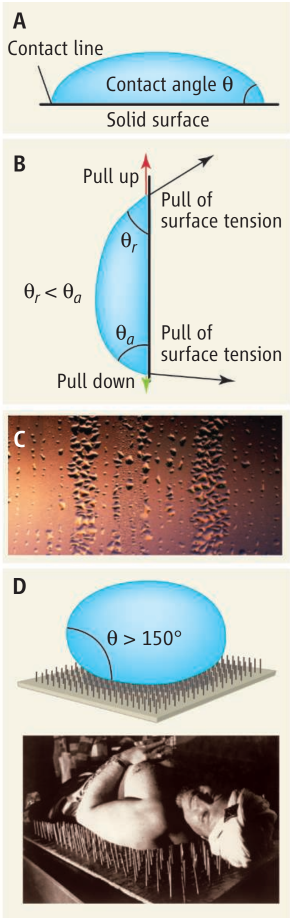
Diverse phenomena, ranging from the way shorebirds feed to self-cleaning by leaves, can be explained through surface tension effects.

The surface tension of water has profound effects on life (*1–3*). It makes possible the flow of water to the tops of trees, allows some insects to breathe underwater and others to walk on it, and resists the inflation of lungs in premature infants. Collaboration among biologists, engineers, mathematicians, and physicists has produced exciting advances in our understanding of surface tension's effects in both nature and technology. In a new twist on this theme, on page 931 in this issue, Prakash *et al.* (*4*) describe a "capillary ratchet" that explains how some shorebirds feed, highlighting a burgeoning research field that makes practical use of surface tension.

Because water molecules are attracted more to each other than they are to air, water acts to minimize its surface energy by minimizing its area of contact with the atmosphere (*2*, *3*). When a liquid drop contacts a solid surface, additional surface energies come into play (*2*, *5*), defining an equilibrium contact angle θ between liquid and solid (see the figure, panel A). In practice, a finite range of static contact angles ($\theta_r < \theta < \theta_a$) arises due to effects of microscopic irregularities on the solid surface, which explains how raindrops stick to window panes (panels B, C). As a drop attempts to slide earthward, its leading edge may have a contact angle as high as θ_a before it advances, whereas its trailing edge may have an angle as low as θ_r before it retreats. Because $\theta_r < \theta_a$, the upward pull of surface tension at the trailing edge wins and the drop sticks. The net force holding the drop in place is proportional to the length of the contact line between drop and solid, whereas the weight of the drop is proportional to the drop's volume. As a result, drops larger than a maximum size (~2 mm) cannot stick and slide down in streaks.



Water contacts: (**A**) Contact angle θ is measured within the liquid, and (**B**) can change as a drop moves, becoming asymmetric. This contact-angle hysteresis explains how raindrops stick to window panes (**C**). (**D**) Micrometer-scale roughness traps air between liquid drop and solid (the Cassie-Baxter or fakir state), producing large contact angles.

Prakash *et al.* build on these basic concepts to explain a novel method of feeding in shorebirds. In water too deep to stand, the bird spins on the surface, creating a vortex that draws up water and food particles (*6*). As it spins, it dips its beak into the water, capturing a drop of fluid and food between the halves of the beak (*7*). The bird then rapidly scissors its beak through a small angle. The beak is never fully closed, but the drop nonetheless moves upward to the mouth. It is here that surface tension comes into play. As the beak opens, the drop is stretched, and its contact lines with the beak's surface retreat. But the contact line nearest the beak's tip retreats more than the contact line nearest the mouth. As a result, the drop moves incrementally toward the mouth. The opposite happens when the beak closes. The drop is squeezed, contact lines advance—but asymmetrically—and the drop again moves toward the mouth. The efficiency of this capillary ratchet depends on the angle through which the beak moves and the surface energy of the beak's material. When the system is well tuned, a drop can move to the mouth in as little as two to three oscillations. Because the ratchet depends on the wetting properties of the beak, it could be stymied by detergents or oily pollutants on the water's surface.

Other research in this fast-paced field reveals how contact angles can be adjusted and how these adjustments have practical consequences (*5*, *8*). Inspired by observations that contact angles can approach 180° on the textured surfaces of plants and water-walking insects (*9*), engineers have determined that micrometer-scale roughness on hydrophobic surfaces can act to retain a microscopic layer of air between water and solid (known as a Cassie-Baxter or fakir state (panel D). Water drops on these superhydrophobic surfaces move with minimal resistance. In nature, the effect allows insects to walk on water (*10*), lotus leaves to clean themselves of dust (*11*), and desert beetles to capture fog droplets (*12*). Engineering analogs of these natural superhydrophobic surfaces are being developed to reduce the drag of fluids flowing through small pipes such as those in microfluidic devices (*13*), to produce self-cleaning and dew-resistant windows (*5*), and to form surfaces that are slippery in one direction and sticky in another (*8*, *14*). Butterflies have already met this last challenge: Scales on their wings have flexible nanotips that allow water drops to flow easily away from the body but inhibit flow toward it (*15*).

Note the interdependence of natural and physical sciences in these advances. If biologists had not reported odd phenomena from nature, physicists, mathematicians, and engineers might not have recognized the surprising potential of surface microtexture. The insights that followed have enabled biologists to explain the natural phenomena they originally observed and have sharpened their eye for further observation. It is not only the interface between water and air that is important here; it is also the productive collaboration at the interface between academic fields that matters.

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