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COMMUNICATION

Biomimicry and the culinary arts

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Abstract

We present the results of a recent collaboration between scientists, engineers and chefs. Two particular devices are developed, both inspired by natural phenomena reliant on surface tension. The cocktail boat is a drink accessory, a self-propelled edible boat powered by alcohol-induced surface tension gradients, whose propulsion mechanism is analogous to that employed by a class of water-walking insects. The floral pipette is a novel means of serving small volumes of fluid in an elegant fashion, an example of capillary origami modeled after a class of floating flowers. The biological inspiration and mechanics of these two devices are detailed, along with the process that led to their development and deployment.

(Some figures may appear in colour only in the online journal)

1. Introduction

"El gran llibre, sempre obert I que cal esforçar-se a llegir, és el de la Naturalesa."[5]

– Antoni Gaudi

Biomimicry has become a central theme in the engineering sciences, and can count the glider, Velcro and Scotch tape among its successes (Benyus 2002). Most recently, man has looked to nature to inspire means of reducing drag and corrosion on rigid surfaces by decorating the surface with microstructure, now possible owing to recent advances in microfabrication and materials science (Favre and Fuentes 2009). Biocapillarity, the relatively new subject at the border of interfacial science and biology, involves the elucidation of natural mechanisms reliant on interfacial tension. We present here two devices developed for use in the culinary arts, motivated by recent studies in biocapillarity.

Surface tension σ is a tensile force per unit length that acts along fluid–fluid or fluid–gas interfaces (de Gennes *et al* 2003). At the fluid–gas interface, the effects of surface tension dominate those of gravity for fluid systems small relative to the capillary length $\ell_c = \sqrt{\sigma/\rho g}$, where ρ represents the fluid density and g gravity. For air–water systems, the capillary length corresponds roughly to the size of a raindrop. Surface tension is thus an important player in the lives of small creatures such as insects, for their propulsion (Bush and Hu 2006), fluid uptake (Kim and Bush 2012), and many other critical functions (Bush *et al* 2007). Py *et al* (2007) demonstrated that interfacial forces may fold flexible solid sheets, and so presented the first examples of capillary origami. In their experiments, drops were placed on flexible sheets which folded into 3D shapes in response to interfacial forces, provided the sheet's size, L, exceeded the elastocapillary length, $L_{ec} = \sqrt{\frac{Eh^2}{\sigma}}$, where E is the Young's modulus and h is the sheet thickness.

Just as scientists draw inspiration from nature, chefs may draw inspiration from science to create novel processes and edible materials (Vega *et al* 2012). Our collaboration at the interface of the culinary arts has led to the development of two dynamic edible devices inspired by natural mechanisms reliant on, respectively, chemically induced surface tension gradients and capillary origami.

[5] "The great book, always open, that we should strive to read, is that of Nature."

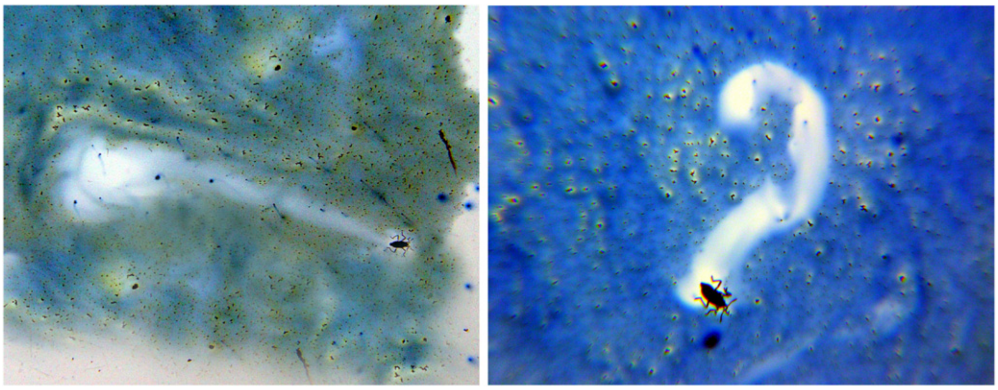

Figure 1. The semi-aquatic insect Microvelia releases a surface-active lipid in its wake, resulting in a surface tension gradient that propels it forward via Marangoni propulsion (Bush and Hu 2006). The Microvelia is approximately 2 mm in length.

2. The cocktail boat

Marangoni flows are those forced by surface tension gradients, as may result from gradients in temperature or chemistry along an interface (Scriven and Sternling 1960). The most commonly observed Marangoni flow is that responsible for the tears of wine (Thomson 1855). Owing to the dependence of surface tension on alcohol concentration, evaporation of alcohol from the thin film on the side of a wine glass increases the local surface tension relative to that of the bulk, and the resulting surface tension gradient pumps fluid up the thin film. Fluid thus accumulates in a horizontal band at the top of the film that grows until becoming gravitationally unstable and releasing the tears of wine. The tears, whose form serves as an indicator of the sugar and alcohol content of the wine, fall until there is insufficient alcohol to drive the system.

Surfactants, such as common soaps, are molecules that find it energetically favorable to reside at the free surface, and act to decrease the local surface tension. The simplest demonstration of a Marangoni flow is the soap boat, a close cousin of the cocktail boat. If a small floating object such as a toothpick of width w is placed on a water surface after one end has been dipped in soap, the surface tension at the clean end is greater than at the soapy end by an amount $\Delta\sigma$; consequently, it is propelled away from the soap by a Marangoni force of characteristic magnitude $F_M = w\Delta\sigma$ (e.g., Nakata *et al* 2005). The boat thus accelerates until the hydrodynamic drag balances the propulsive Marangoni force. Most soaps decrease the surface tension at an air–water surface, $\sigma = 70$ dyn cm^{-1}, by a factor of 2, resulting in the soap boat achieving speeds of approximately 10 cm s^{-1}. Note that the soap boat's journey is relatively short ($\sim$10 s) in a closed geometry as the interface soon becomes saturated in surfactant, which suppresses the propulsive surface tension gradient. Nakata *et al* (2005) demonstrated that this limitation may be avoided by using volatile surfactants such as camphor, which evaporates rapidly from the surface, thus enabling sustained Marangoni propulsion.

Marangoni propulsion as a means of biolocomotion was first reported by Billard and Bruylant (1905) who observed its use by a terrestrial insect when it accidentally fell onto the water surface. By releasing a surfactant, specifically a surface-active lipid, it was able to propel itself toward and up the meniscus bordering land and so return to its preferred terrestrial environment. Marangoni propulsion by the rove beetle has been reported by Betz (2002), and by semi-aquatic insects, for example Microvelia (figure 1) and Velia, by Linsenmair and Jander (1976) and Andersen (1976). Schildknecht (1976) found that the surfactant released by the rove beetle reduced the surface tension from 72 to 49 dyn cm^{-1}. Peak speeds during Marangoni propulsion for Microvelia are approximately 17 cm s^{-1}, or twice their peak walking speed (Andersen 1982). In figure 1, it is apparent that the surfactant ejected by Microvelia not only gives rise to a propulsive force, but clears the initially dyed surface layer in its wake. Marangoni propulsion by such insects is analogous to that of the soap boat: the chemically-induced gradient in the surface tension generates a propulsive force (Hu and Bush 2005).

The cocktail boat relies on precisely the same propulsive mechanism as the soap boat and the Marangoni swimmers. The floating cocktail boat (figures 2 and 3) is filled with its fuel, alcohol, which spills into its wake by way of a small outlet on its aftward side. Alcohol acts to reduce both the surface tension and the contact angle on the aftward side, thus decreasing the horizontal force relative to that on the front (see figure 2(*b*)). Alcohol reduces the surface tension at an air–water interface from approximately $\sigma_{\text{bulk}} = 70$ to $\sigma_{\text{fuel}} = 35$ dyn cm^{-1}. In our system, the contact angle between water and plastic is $\theta_{\text{bulk}} \simeq 80^\circ$ and between an alcohol–water mixture and plastic is $\theta_{\text{fuel}} \simeq 30^\circ$. Consequently, a cocktail boat of width $w = 1$ cm is subjected to a propulsive force

$$F_{\text{prop}} = (\sigma_{\text{bulk}} \sin\theta_{\text{bulk}} - \sigma_{\text{fuel}} \sin\theta_{\text{fuel}})w \simeq 51 \text{ dynes}, \quad (1)$$

owing to the fore-aft difference in surface tension and contact angles. The resulting steady speed U may be computed from the horizontal force balance, according to which F_{prop} is balanced by the drag force $F_{\text{drag}} = \rho U^2 wd$, where d is the intrusion depth of the boat, so wd the projection of its submerged exposed area (see figure 2). We thus obtain

$$U = \sqrt{\frac{(\sigma_{\text{bulk}} \sin\theta_{\text{bulk}} - \sigma_{\text{fuel}} \sin\theta_{\text{fuel}})}{\rho d}}. \quad (2)$$

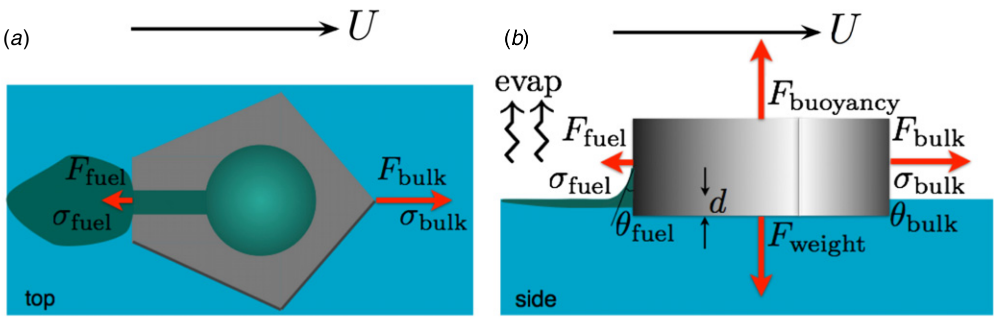

Figure 2. (*a*) Top and (*b*) side view of the cocktail boat elucidates design considerations and the propulsion mechanism. A lighter boat is desirable, so that the boat's intrusion depth d, and induced drag, are minimized.

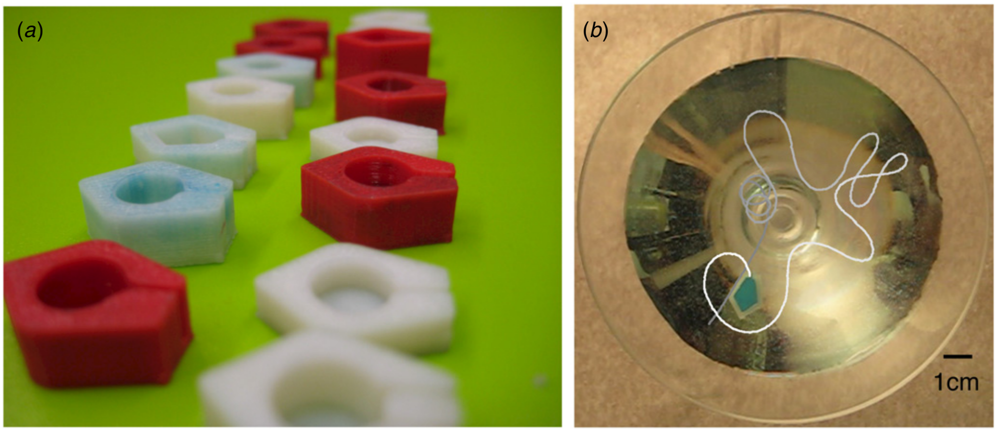

Figure 3. (*a*) A fleet of cocktail boats with varying shape and slit size were tested, fueled by different liquors. We found that the alcohol content of the fuel was the most important design factor for performance, with higher proof alcohol leading to faster and more vigorous boat motion. (*b*) A cocktail boat propels itself, fueled by Bacardi 151 (75% alcohol). Boat lengths are approximately 1.5 cm.

Observed peak speeds of the cocktail boat are approximately 10 cm s^{-1}, comparable to the theoretically predicted speeds of 4–6 cm s^{-1}. Like the camphor used by Nakata *et al* (2005), alcohol is volatile and evaporates from the interface on a time scale faster than the motion of the boat. Consequently, the cocktail boat exhibits sustained motion until it runs out of fuel.

Initial prototypes of the boats were first made of acrylonitrile butadiene styrene (ABS plastic) generated on a Stratasys Dimension 3D printer. Boat designs with various slit sizes and shapes were tested, resulting in a range of speeds, stability, and travel duration. The boat performance was most sensitive to the slit size and alcohol concentration in the fuel rather than the shape of the boat's footprint. Boat speed generally increased with increasing slit width over the range considered, from 0.5 to 1.5 mm. The longest runs achieved were two minutes. Subsequently, we cast edible cocktail boats from silicone molds. The molds were created using a 3D-printed mold negative. A number of different edible and semi-edible materials were used including gelatin, agar, melted wax and various candies. Once we had verified the feasibility of creating edible boats and optimized the mold design, ThinkFoodGroup refined the composition of the edible boats, making them more pleasing to both the eye and the palate.

3. The floral pipette

A family of flowers, including the water lily, float at the surface of ponds or lakes while remaining anchored to the underlying ground. When the water level rises, the petals or leaves wrap up, capturing an air pocket in order to keep the flower's genetic material dry (figure 4). Since most such flowers are considerably larger than the capillary length, hydrostatic forces play the dominant role in prompting closure; however, capillary forces are critical in preventing water from intruding between the petals (figure 5). Inspired by this class of floating flowers, Reis *et al* (2010) developed a technique for grabbing water that they termed the elastocapillary pipette, in which the role of gravity is reversed.

Instead of forcing the flower to sink relative to the interface (figures 4 and 5), an elastic sheet cut into the shape of a flower is drawn upwards, and grabs a volume of fluid from the free surface (figure 6). As the flower is withdrawn from the surface it zips shut, giving rise to a fluid drop enclosed by an elastic shell. The hydrostatic suction associated with the vertical fluid displacement prompts the closure of the flower, while the leakage of fluid from the closing flower is prevented by surface tension (figure 7). While the elastocapillary designs of Py *et al* (2007) were constrained to scales less than the capillary length, for the pipette, hydrostatic pressure is causing rather than

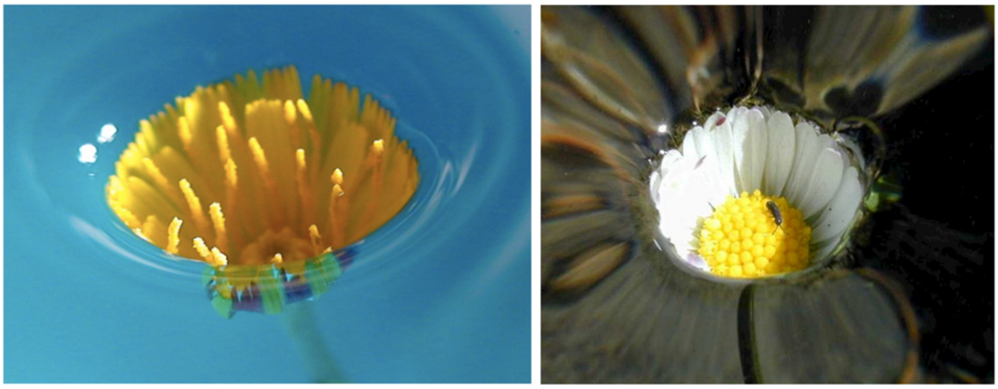

Figure 4. Flowers that float at the air–water interface are supported by hydrostatic, elastic and capillary forces. The flower's petals close in the presence of high water levels to protect their genetic material (Left: reprinted with permission from Jung *et al* (2009). Copyright 2009, AIP Publishing LLC. Right: licensed under the Creative Commons Attribution ShareAlike 3.0 License: http://en.wikipedia.org/wiki/File:Dscn3156-daisy-water_1200x900.jpg).

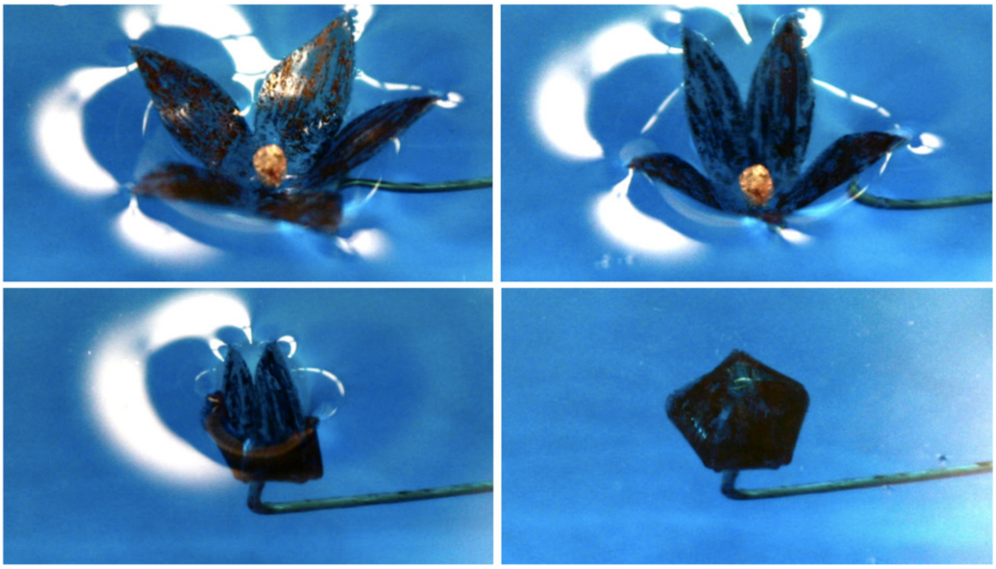

Figure 5. When submerged, artificial flowers made of polymer elastic sheets mimic the petal closure observed in nature by floating flowers. The undeformed flower diameter is approximately 1.8 cm (Reprinted with permission from Jung *et al* 2009. Copyright 2009, AIP Publishing LLC).

resisting the folding. Consequently, fluid capture is possible on a significantly larger scale, that of the elastogravity length, $L_{eg} = \sqrt{\frac{B^{1/4}}{\rho g}}$, where B is the bending stiffness per unit width (Reis *et al* 2010). The synthetic flowers were composed of vinylpolysiloxane of thickness 0.25 mm and Young's modulus $E = 0.5$ MPa, resulting in a bending stiffness of $B \simeq 10^{-6}$ Nm^2. Reis *et al* (2010) computed the petal shape that optimizes the fluid volume trapped in this manner, and so were able to successfully grab approximately 0.5 mL of water with elastocapillary pipettes of diameter 5 cm.

The culinary application of the elastocapillary pipette is a device resembling a flower, constructed of edible gels and used as a means by which to imbibe fluid drop by drop, after which the flower itself is to be consumed. It represents an intriguing method of serving small fluid volumes, and is intended to be used in cleansing the palate between courses in multicourse meals. Flower geometries were optimized for the particular flower material according to the specifications detailed in Reis *et al* (2010), and molds for casting them were printed on a high-resolution 3D printer. Members of ThinkFoodGroup tested several edible gelling agents, including gelatin, agar, and combinations of locust bean gum and carrageenan, in order to match the elastic properties of the synthetic materials used at MIT. They were thus able to ensure their robustness, and avoid damage to the petals during use. ThinkFoodGroup then explored flavors for the edible design with a view to integrating it into a dish.

Lastly, aesthetics motivated our incorporation of an LED into the center of the flower (figures 6 and 8). The flowers were cast in 3D-printed molds using vinylpolysiloxane (Zhermack) with a hardness of 8 Shore A. The molded flower is 35 mm in diameter and 0.8 mm thick. The petal and stem configuration were 3D printed and the LED was powered by a battery stored in the base, where a small switch controls the light.

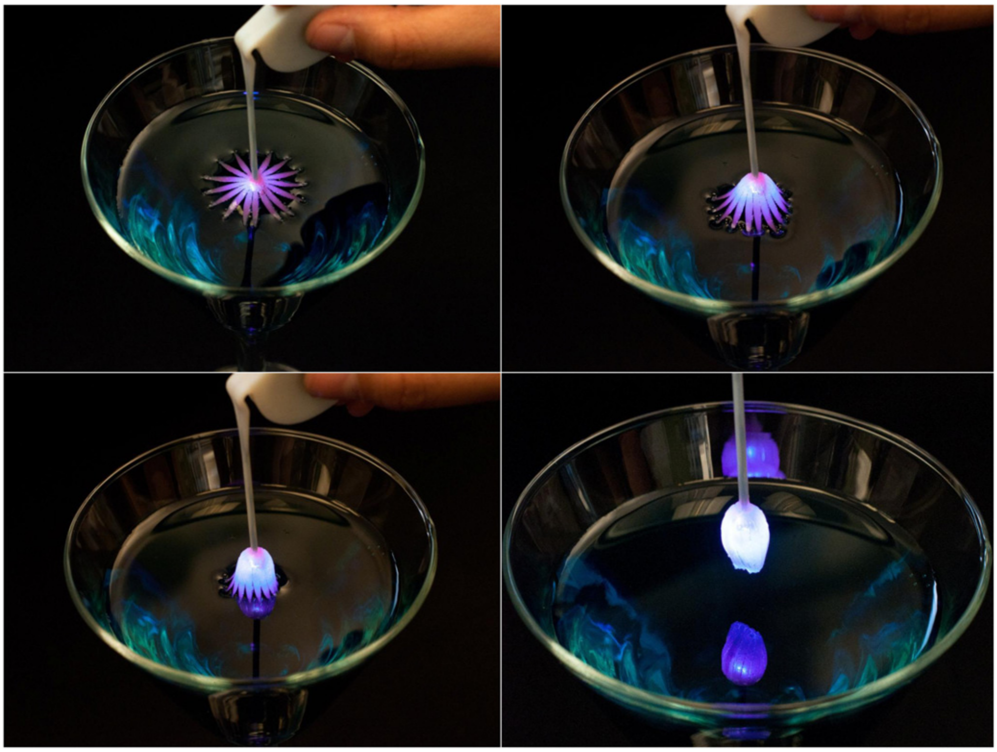

Figure 6. The floral pipette is drawn up from the interface, enclosing a small volume of fluid. An LED at the pipette's center adds visual appeal.

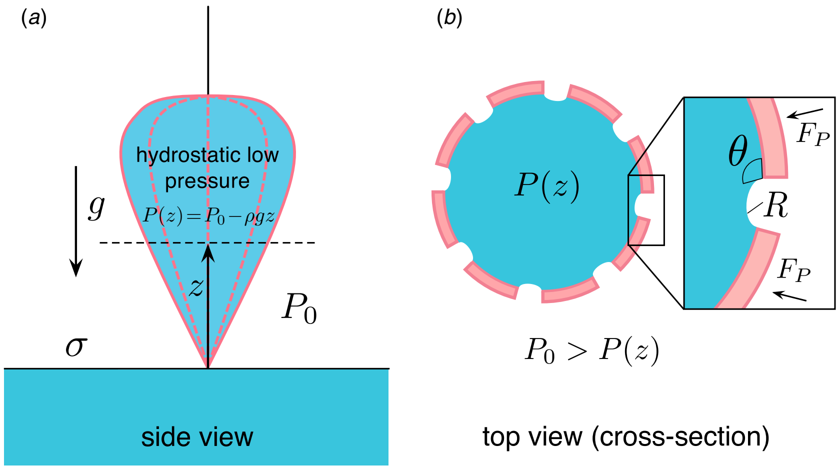

Figure 7. (*a*) The floral pipette captures fluid inside an elastic shell through the action of the hydrostatic suction induced during withdrawal. Within the enclosed region, the pressure is less than atmospheric pressure P_0, varying with height as $P(z) = P_0 - \rho g z$. (*b*) Horizontal cross-section. During withdrawal, intrusion of air between neighboring petals and into the relative low-pressure of the trapped fluid is resisted by the influence of surface tension, which generates a Laplace pressure σ/R, R being the local radius of curvature. Note that the associated surface tension force per length on the petal, $2\sigma \sin\theta$, augments the pressure force, F_p, resulting from hydrostatic suction.

The shape of the base allows two resting configurations: on the side of a cocktail glass or on a flat surface, as illustrated in figure 8.

4. Discussion

We have described the inspiration, mechanics, design and development of two instances of biomimicry in the culinary arts. Both involve striking examples of biocapillarity, in which nature exploits mechanisms that depend explicitly on interfacial effects. The cocktail boat, inspired by a class of insects that use Marangoni propulsion, is propelled in a cocktail glass by alcohol-induced surface tension gradients. The floral pipette is an example of capillary origami, an inversion of floating flowers that enables the imbibition of droplets drawn from a fluid interface. While both mechanisms may be of interest to the scientific and engineering communities, the development into a device of interest to the

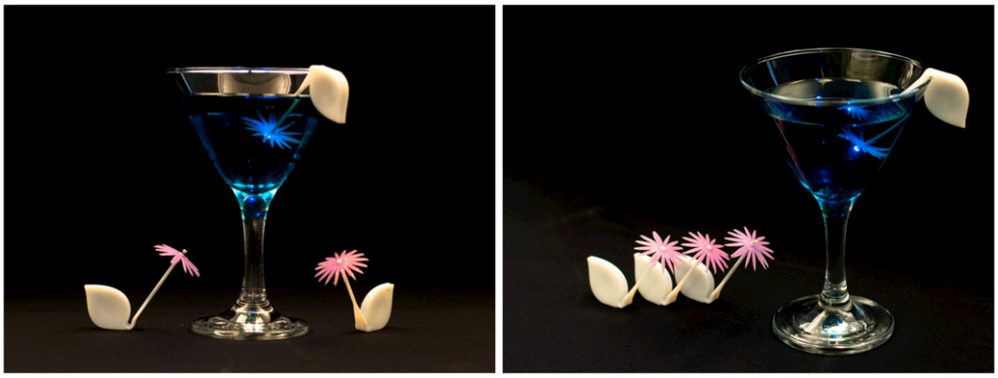

Figure 8. The floral pipette features two resting positions: on a glass's edge and on a flat surface. Undeformed flowers are approximately 3.5 cm in diameter.

culinary arts required an additional step, the mimicry not only of nature's function, but of her elegance.

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References

Andersen N M 1976 A comparative study of locomotion on the water surface in semi-aquatic bugs (Insects, Hemiptera, Gerromorpha) *Vidensk. Medd. Dan. Naturhist. Foren.* **139** 337–96

Andersen N M 1982 *The Semiaquatic Bugs (Hemiptera, Gerromorpha): Phylogeny, Adaptations, Biogeography and Classification* (Klampenborg: Brill Academic)

Benyus J M 2002 *Biomimicry: Innovation Inspired by Nature* (New York: William Morrow Paperbacks)

Betz O 2002 Performance and adaptive value of tarsal morphology in rove beetles of the genus Stenus (Coleoptera, Staphylinidae) *J. Exp. Biol.* **205** 1097–113

Billard G and Bruylant C 1905 Sur un mode particulier de locomotion de certains stenus *C. R. Soc. Biol.* **59** 102

Bush J W M and Hu D 2006 Walking on water: biolocomotion at the interface *Annu. Rev. Fluid Mech.* **38** 339–69

Bush J W M, Hu D L and Prakash M 2007 The integument of water-walking arthropods: form and function *Adv. Insect Physiol.* **34** 117–92

de Gennes P, Brochard-Wyart F and Quere D 2003 *Capillarity and Wetting Phenomena: Drops, Bubbles, Pearls, Waves* (Berlin: Springer)

Favre E A and Fuentes N O 2009 *Functional Properties of Bio-Inspired Surfaces (Characterization and Technological Applications)* (Singapore: World Scientific)

Hu D and Bush J W M 2005 Meniscus-climbing insects *Nature* **437** 733–6

Jung S, Reis P, James J, Clanet C and Bush J W M 2009 Capillary origami in nature *Phys. Fluids* **21** 091110

Kim W and Bush J W M 2012 Natural drinking strategies *J. Fluid Mech.* **705** 7–25

Linsenmair K and Jander R 1976 Das 'entspannungsschwimmen' von Velia and Stenus *Naturwissenschaften* **50** 231

Nakata S, Doi Y and Kitahata H 2005 Synchronized sailing of two camphor boats in polygonal chambers *J. Phys. Chem.* B **109** 1798–802

Py C, Reverdy P, Doppler L, Bico J, Roman B and Baroud C N 2007 Capillary origami: spontaneous wrapping of a droplet with an elastic sheet *Phys. Rev. Lett.* **98** 156103

Reis P, Hure J, Jung S, Bush J W M and Clanet C 2010 Grabbing water *Soft Matter* **6** 5705–8

Schildknecht H 1976 Chemical ecology—a chapter of modern natural products chemistry *Angew. Chem. Int. Edn Engl.* **15** 214–22

Scriven L E and Sternling C V 1960 The Marangoni effects *Nature* **187** 186–8

Thomson J 1855 On certain curious motions observable at the surfaces of wine and other alcoholic liquors *Phil. Mag.* **10** 330–3

Vega C, Ubbink J and van der Linden E 2012 *The Kitchen as Laboratory: Reflections on the Science of Food and Cooking* (New York: Columbia University Press)