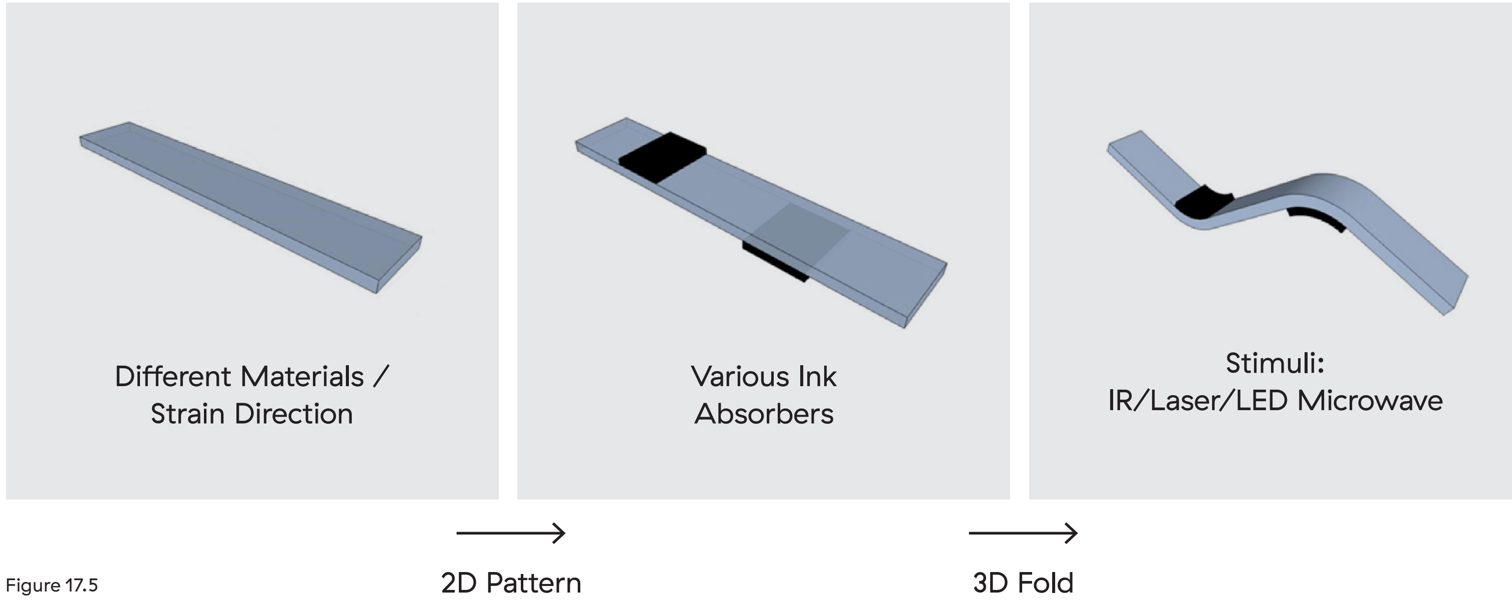

Figure 17.5
Generalization of this self-folding strategy utilizing other materials, various ink absorbers, and different stimuli.

NOTES

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18 Growing and Morphing Shapes: Using Swelling and Geometry to Control the Shape of Soft Materials

Douglas P. Holmes with Abdikhalaq Bade, P. T. Brun, Henry Hwang, Matteo Pezzulla, and Mark Steranka

18
Growing and Morphing Shapes: Using Swelling and Geometry to Control the Shape of Soft Materials

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Slender structures are ubiquitous—they include carbon nanotubes, airplane wings, blood vessels, spider silk, lipid membranes, contact lenses, and human hair. The behavior of these thin objects is fascinating because their geometry can change dramatically in response to small amounts of force—hair may curl and tangle, skin will wrinkle, and soda cans can crumple. If these shapes are active and adaptable, their bending, folding, and twisting will provide advanced engineering opportunities for deployable structures, soft robotic arms, mechanical sensors, and the rapid manufacturing of 4D materials.

At play in many soft and active systems is the coupling between fluid motion and structural deformation. The fluids may provide fuel or contain materials necessary for self-healing or sensing. These fluid–structure interactions occur across many length scales within synthetic and biological systems. At large scales, inertial flows and fluid weight can cause substantial structural deformations, while at small length scales, surface tension may dominate a material's deformation. In addition to the forces that a fluid exerts externally onto a flexible structure, the diffusion of fluid into the material can cause substantial swelling and deformation.

CURLING WITH DROPLETS

When you put a straw into a liquid, the liquid rises via capillary action—surface tension draws the fluid up while gravity pulls it down. The smaller the straw's diameter, the higher the fluid rises. If the walls of that straw are flexible, the fluid rises higher still as surface tension pulling on the walls is strong enough to bend them closer together. This is known as elastocapillarity, and it is what you see when bristles of a paintbrush or wet hairs clump together. Now, if the material is flexible and absorbent, like a sponge, the fluid will swell the walls, causing them to curl apart when wetted. So there are two competing effects—surface tension pulling the flexible objects together, and swelling curling them apart. In figure 18.1, two flexible and absorbent silicone rubber fibers are dipped into a bath of silicone oil.

Initially, a balance between elasticity and capillarity pulls the fibers together, and then the swelling of the fluid into the material slowly curls the fibers apart. Eventually, the fibers peel from the surface of the bath, and a fluid droplet moves upward. These large deformations are caused by an amount of fluid smaller than the volume of water in a raindrop. The addition of swelling to the study of elastocapillarity may bring new insights to the swelling and drying of many soft, porous engineered materials, such as textiles and paper, as well as swellable biological structures, such as hair, certain types of plants, and other soft tissues. Elastocapillary swelling could also lead to the design of new types of soft actuators involving liquid transport and shape changes, building on recent advances in capillary origami.

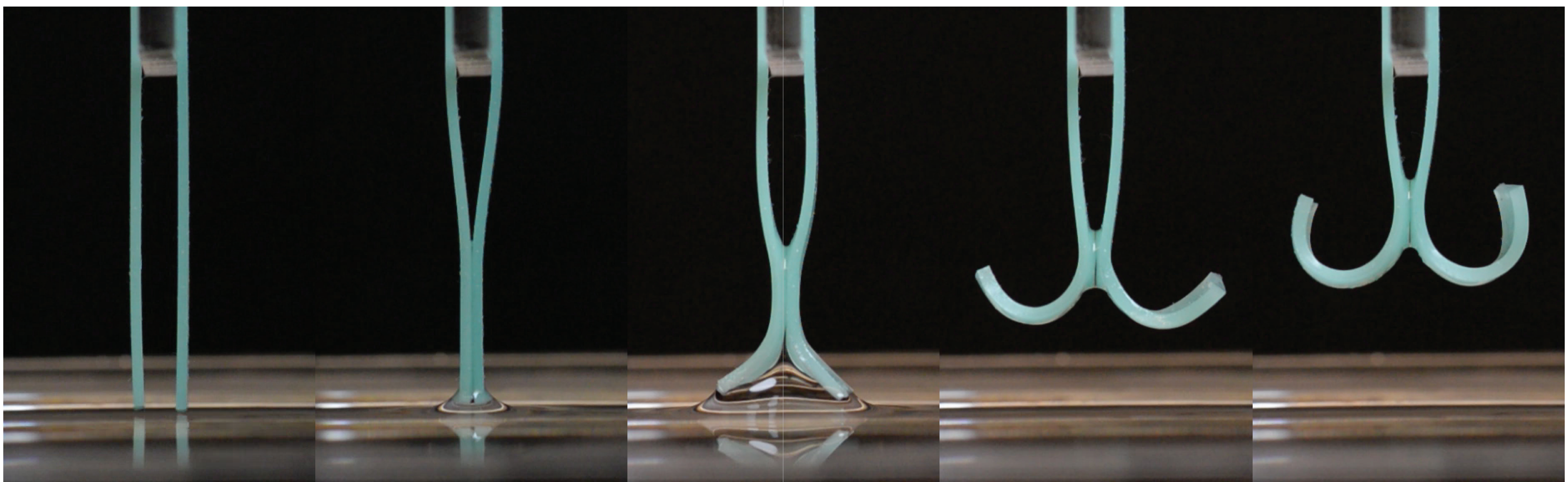

Figure 18.1
Capillary curling. Fibers of silicone rubber are lowered into a bath of silicone oil. Coupling capillary action with flexibility pulls the fibers together, while swelling of the beams begins to slowly curl them apart. Finally, the curling fibers peel from the bath, entrapping a droplet of fluid which is ratcheted upward.

GROWING SHEETS INTO SHELLS

For thin structures, geometry is paramount. It's easy to roll a sheet of paper into a cylinder, but impossible to wrap it around a sphere. Wrapping a sheet (which is intrinsically flat) around a sphere (which is intrinsically curved) requires you to stretch it, while bending it around a cylinder does not. Thin structures will deform in a way that avoids changing their intrinsic geometry whenever possible, because it is far easier to bend a thin structure than to stretch one. In engineering design, this constraint is important because it provides a means for large, controllable shape changes with minimal energy input. So flat sheets of any shape will morph into cylinders (figure 18.2), while shells bend into spindles (figure 18.3), mimicking the shape transition of a drying pollen grain. Much of swelling is slow, as the permanent structural morphing is driven by the diffusion of viscous fluid—a process that may

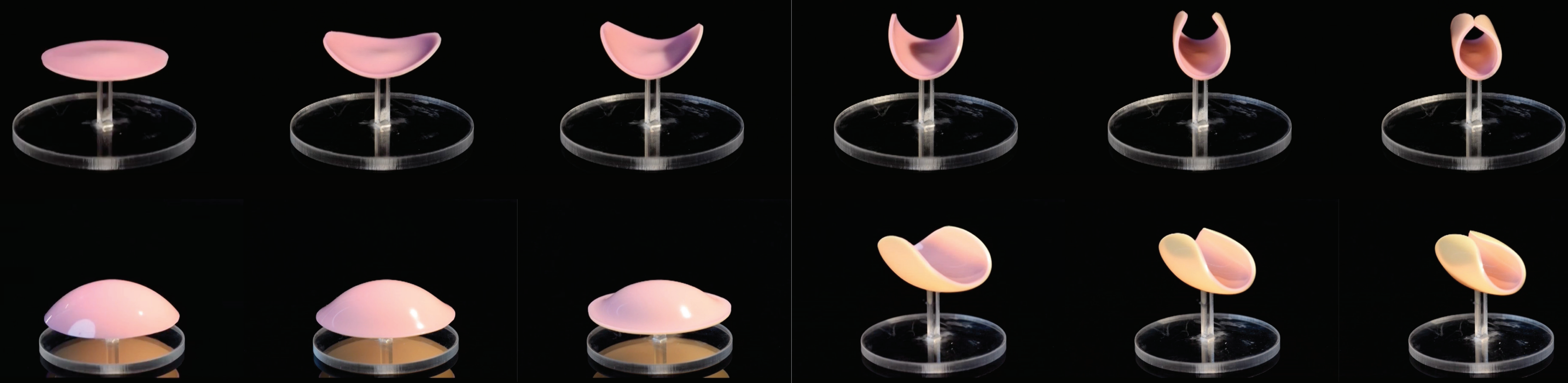

Figure 18.2
Morphing bilayers. Top: A flat, circular plate morphs into a cylinder as its top layer shrinks and its bottom layer swells. Bottom: A spherical cap snaps into a spindle as its outer layer shrinks. Both morphing bilayers adopt deformed shapes that require a minimal amount of stretching.

take hours. However, when aided by structural instability, large shape changes can occur in fractions of a second. A shell can dynamically snap between shapes (figure 18.2), similar to an umbrella on a windy day. These transitions are governed by geometry rather than diffusion, and can occur at the speed of a sound wave propagating through the material.

To utilize the swelling of soft materials to dynamically morph sheets and shells, the swelling fluid can be incorporated directly into the material. Since thin structures can significantly deform in response to swelling by small volumes of fluid, we can actively deform structures by moving small amounts of fluid around within a material, thereby causing specific regions to swell or shrink. This process is analogous to the heating of bimorphs—materials that are bound together but expand to different lengths when heated. Using a process known as residual swelling, where residual amounts of fluid are left within an elastomer and free to swell nearby regions, we can permanently grow bilayer sheets into shells.

In some cases, stretching is unavoidable. If residual swelling occurs in the plane of the object, rather than through its thickness, bending alone will not suffice. These shapes will change their intrinsic curvature, morphing from flat sheets into saddles (figure 18.4). Here all the fluid is moving from the center of the disk to its edges, and since the disk's circumference is increasing in length more than its radius, it buckles with wavy edges. This structural morphing is driven by the same mechanism of differential growth that governs the wavy edges in growing leaves and flowers, such as a blooming lily.

Behind all of these shape transitions is the interplay between fluid and structure; swelling and geometry. Thin structures bend easily and soft materials can morph on command in response to the movement of small amounts of fluid. Perhaps what is most compelling is that the mechanics and mathematics that describe these shape changes are indifferent to the chosen stimulus—we can replace swelling with heat, or voltage, or magnetism, and the structures will morph accordingly.

Figure 18.3 (left)
Pollen grains. Before and after images of a spherical shell (top) rolling into a spindle and (bottom) pinching closed due to residual swelling.

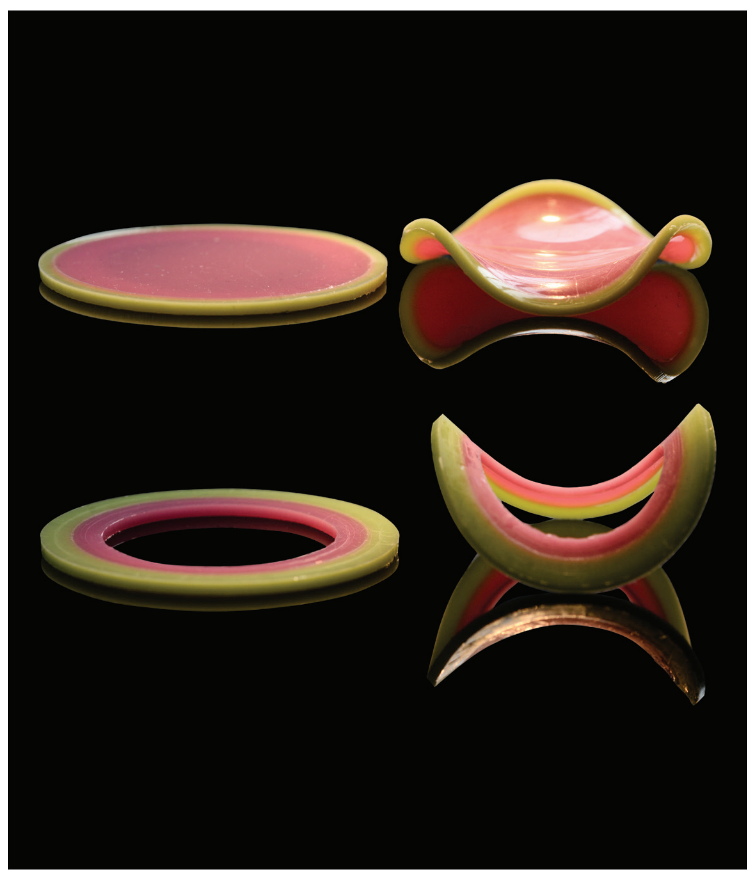

Figure 18.4 (right)
Soft saddles. Top: A flat sheet undergoes differential growth and buckles into "monkey saddle." Bottom: A ring experiencing residual swelling morphs into a saddle that while curved in space is locally flat on the surface.

19 Coffee Bags and Instinctive Active Materials: The Path to Ubiquity

Greg Blonder