

## Placing Marangoni instabilities under arrest

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Soap bubbles occupy the rare position of delighting and fascinating both young children and scientific minds alike. Newton [1], Plateau [2], Marangoni [3], and de Gennes *et al.* [4], not to mention countless others [5], have discovered remarkable results in optics, molecular forces, and fluid dynamics from investigating this seemingly simple system. We present here a compilation of curiosity-driven experiments that systematically investigate the surface flows on a rising soap bubble. From childhood experience, we are familiar with the vibrant colors and mesmerizing display of chaotic flows on the surface of a soap bubble. These flows arise due to surface tension gradients, also known as Marangoni flows or instabilities. In Video 1, we show the surprising effect of layering multiple instabilities on top of each other, highlighting that unexpected new phenomena are still waiting to be discovered, even in the simple soap bubble.

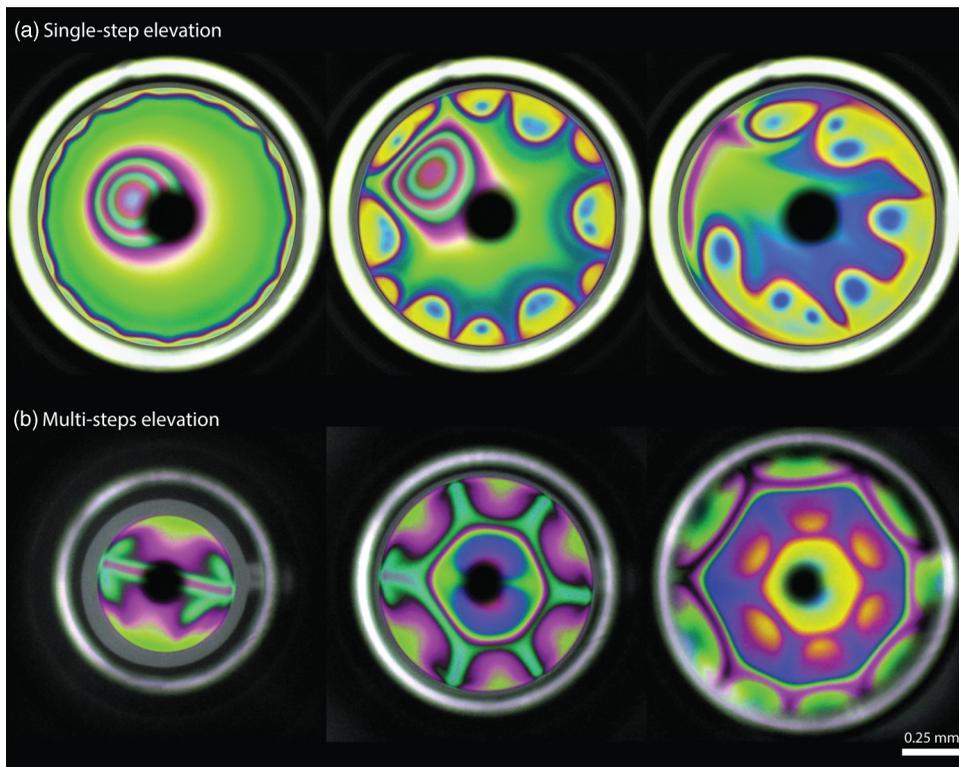
We conduct the experiment as follows. We place a plastic chamber containing surfactant solution [0.3 mM sodium dodecyl sulfate (SDS) in water] onto a motorized stage. In this solution, we generate an air bubble (1 mm diameter) at the tip of a U-shaped glass capillary (Fig. 1). We initially position the bubble just beneath the surface. Next, using the stage, we elevate the bubble in controlled, discrete steps to expose a spherical cap of the bubble at the surface. This protruding cap is essentially a draining curved film, which under white light illumination exhibits interference patterns that we record using a color charge-coupled device (CCD) camera.

We find that the Marangoni instabilities can be reproduced by a broad range of soluble surfactants that have negligible surface shear viscosity. Thus, this experiment serves as a facile technique for probing the surface mobility of surfactant systems [6], including artificial lung surfactant therapeutics [7]. However, a complete theoretical analysis of this problem remains an open challenge.

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VIDEO 1. Snapshots of Marangoni instabilities on a soap film elevated in (a) a single step (0.9 mm) and (b) multiple steps (3 steps of 0.3 mm). In the first row, the dimple in the center is unstable and flees towards the periphery as plumes of surfactant rise from the periphery, resulting in chaos. However, in the second row, elevation in smaller steps creates a cascade of instabilities that arrest each other, resulting in beautiful dynamic structures. To fully appreciate these incredible flow patterns, we urge the reader to watch the accompanying multimedia video appended as Supplemental Material and located here <http://dx.doi.org/10.1103/APS.DFD.2015.GFM.V0040>

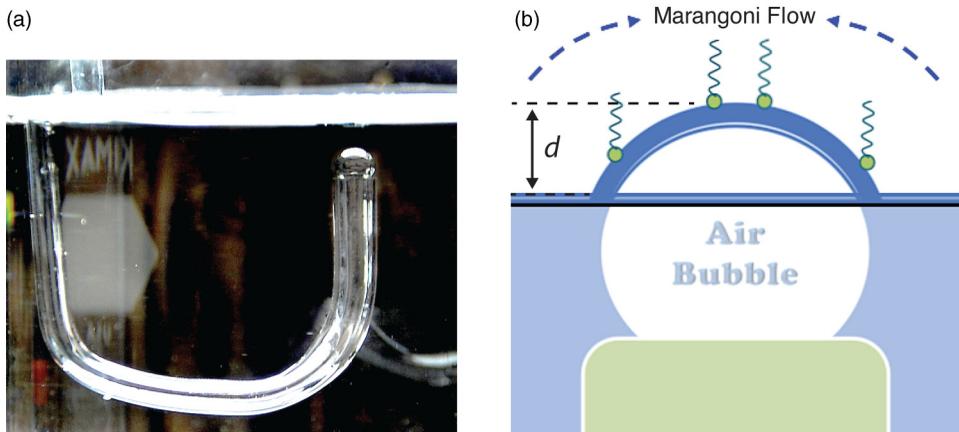


FIG. 1. (a) Image of experimental setup. (b) Schematic illustrating the Marangoni flow generated due to redistribution of surfactant molecules as the bubble is elevated through the solution interface, where  $d = 0.9$  mm is the vertical displacement from initial starting point just beneath the air-solution interface.

## PLACING MARANGONI INSTABILITIES UNDER ARREST

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