DYNAMICS AND STABILITY OF CAPILLARY SURFACES: LIQUID SWITCHES AT SMALL SCALES

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The dynamics and stability of systems of interfaces is central to a range of technologies related to the Human Exploration and Development of Space (HEDS). Our premise is that dramatic shape changes can be manipulated to advantage with minimal input, if the system is near instability. The primary objective is to develop the science base to allow novel approaches to liquid management in low-gravity based on this premise. HEDS requires efficient, reliable and lightweight technologies. Our poster will highlight our progress toward this goal using the capillary switch as an example.

A 'capillary surface' is a liquid/liquid or liquid/gas interface whose shape is determined by surface tension. For typical liquids (e.g., water) against gas on earth, capillary surfaces occur on the millimeter-scale and smaller where shape deformation due to gravity is unimportant. In low gravity, they can occur on the centimeter scale. Capillary surfaces can be combined to make a switch – a system with multiple stable states. A capillary switch can generate motion or effect force. To be practical, the energy barriers of such a switch must be tunable, its switching time (kinetics) short and its triggering mechanism reliable. We illustrate these features with a capillary switch that consists of two droplets, coupled by common pressure. As long as contact lines remained pinned, motions are inviscid, even at sub-millimeter scales, with consequent promise of low-power consumption at the device level. Predictions of theory are compared to experiment on i) a soap-film prototype at centimeter scale and ii) a liquid droplet switch at millimeter-scale.

Dynamics and stability of capillary surfaces: low-dissipation liquid switches

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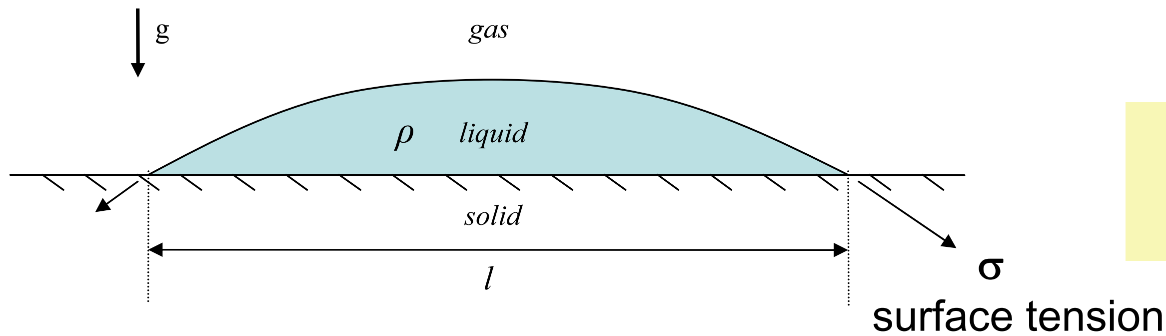
Will the liquid micro-switch become to ‘micro-fluidics’ as the transistor is to ‘micro-electronics’?

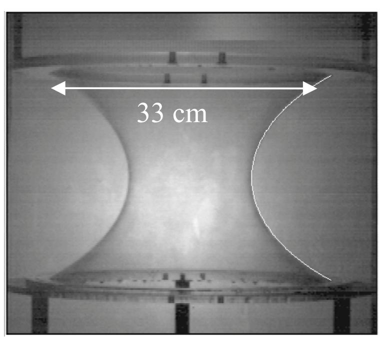
'Capillary surface' ~ shape determined by σ



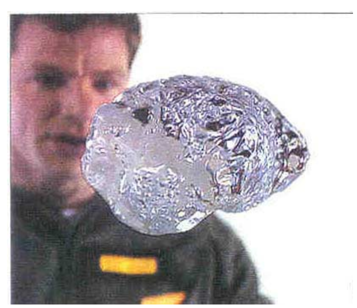
λ~ 3 mm
for water

Capillary length

$$\lambda \equiv \left(\frac{\sigma}{\rho g} \right)^{\frac{1}{2}}$$



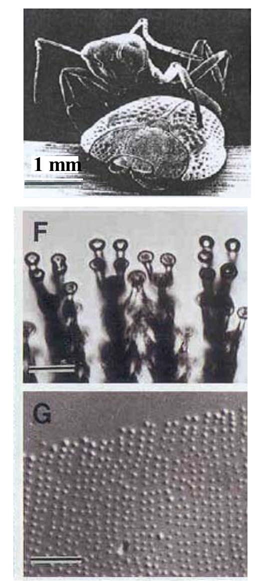
Robinson & phs
JCIS 2001



Weislogel & Lichter
Phys. Fluids 1998

10 μm

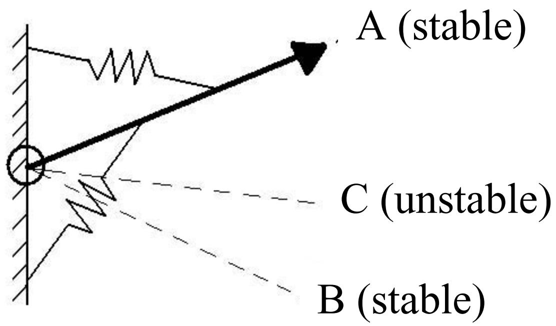
50 μm



Eisner & al.
PNAS 2000

Switches

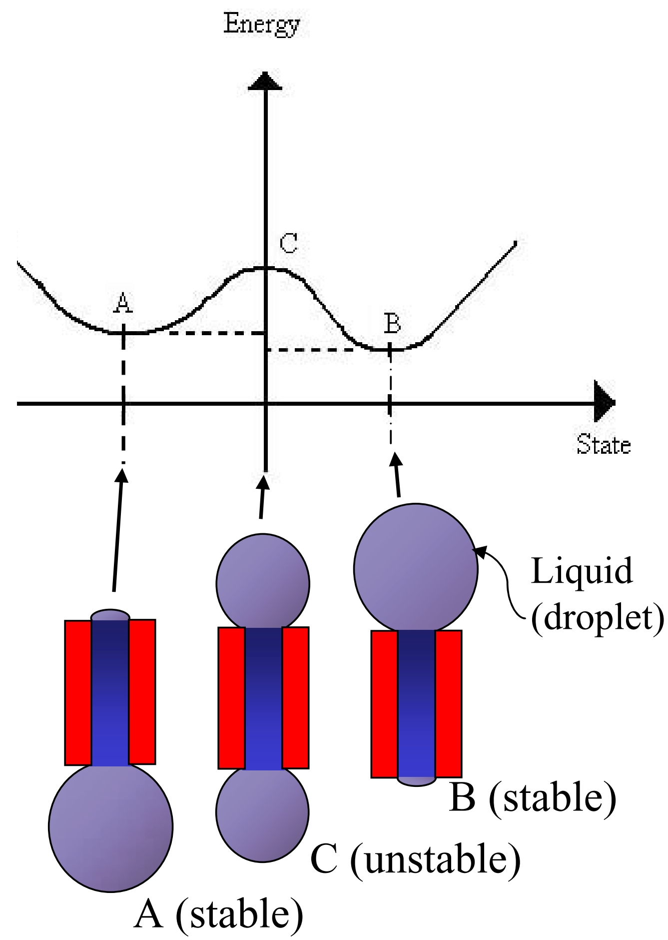
Mechanical Switch



Concept:
Use capillary instability to advantage to produce devices that require low power

Issues:

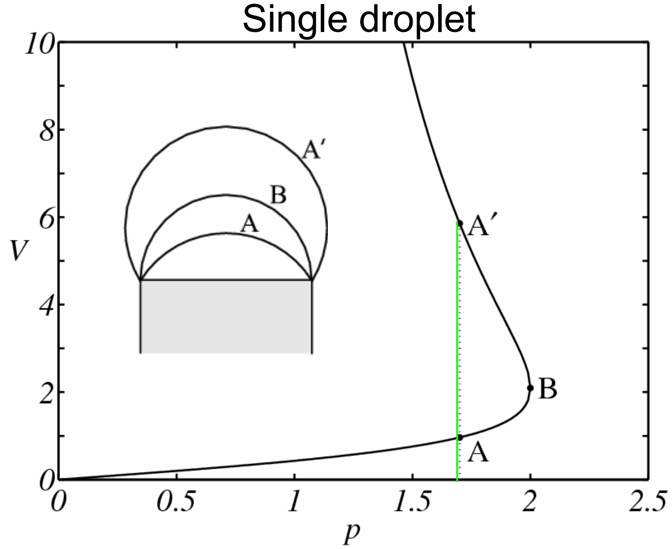
- bistability (thermostatics)
- toggling (activation physics)
- switching time (kinetics)
- robustness (basins of attraction)

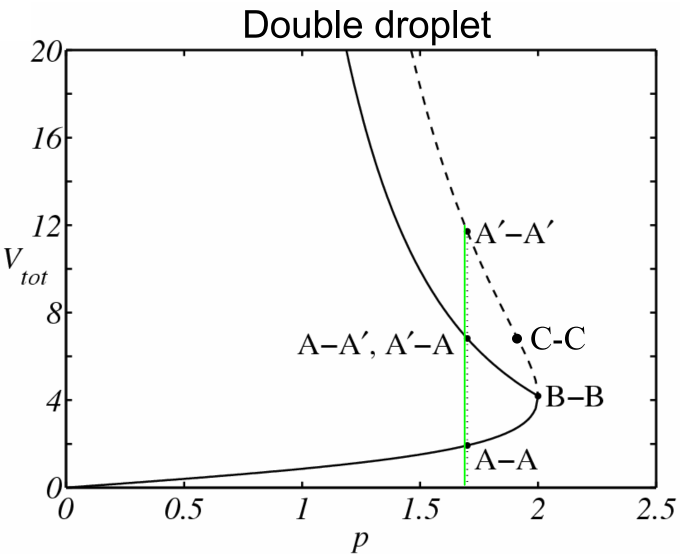


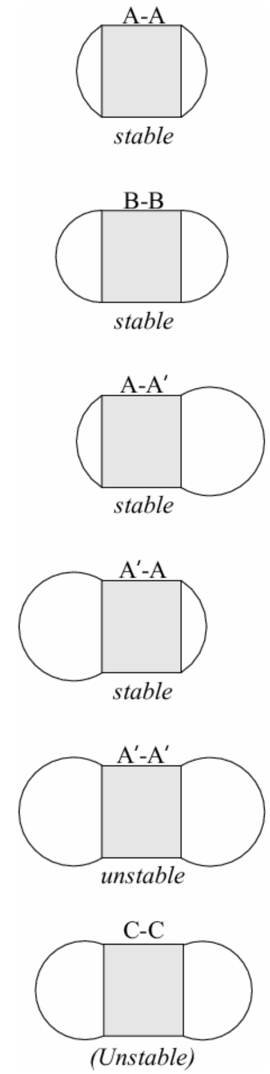
capillary bistability
(axisymmetric)

CV Boys 1890

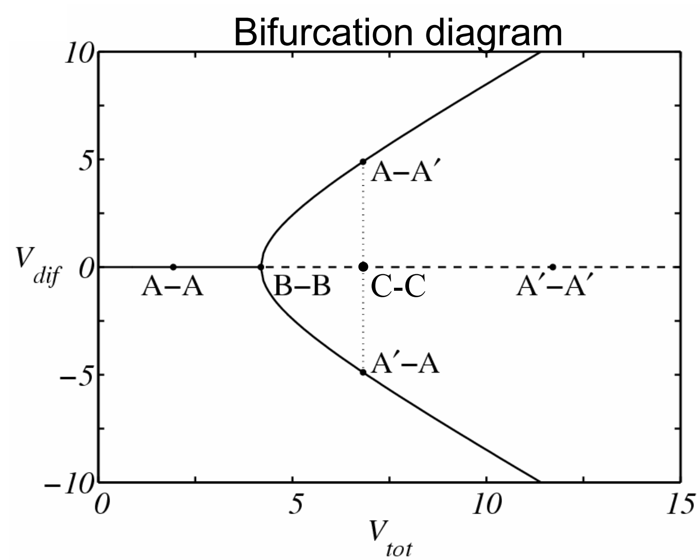
Response of droplet-droplet system: bistability







Young-Laplace:
p=2σ/R



Energy minimization
⬇
spherical surfaces

(Steen et. al. 2002)

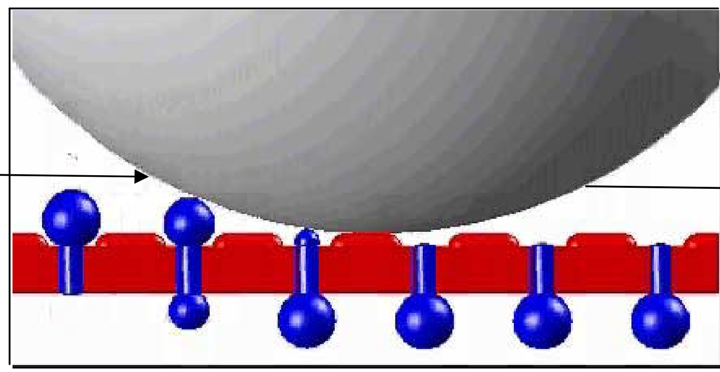
NASA/CP—2004-213205/VOL2

Conceptual applications: towards efficient, reliable and lightweight HEDs technology

Droplet/Particle Mover

(e.g., transport droplets to analysis sites on a 'lab on a chip')

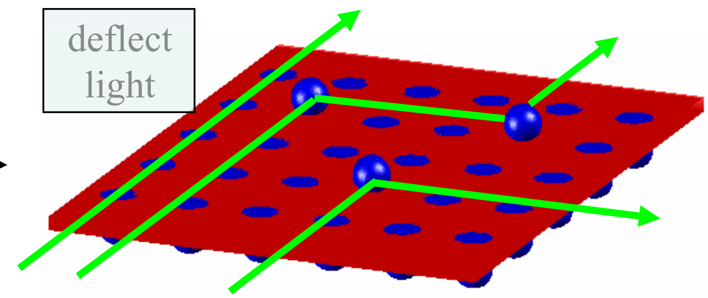
effect motion



Optical 'Switchboard'

(redirect optical signals, acting as microlens)

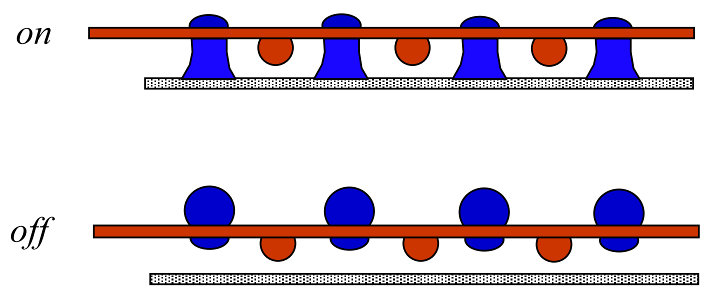
deflect light

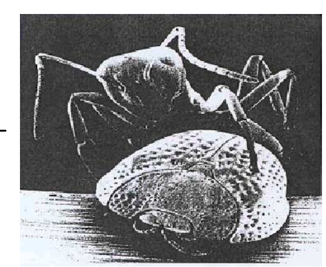


Adhesion Device

(to grip objects, as does palm beetle)

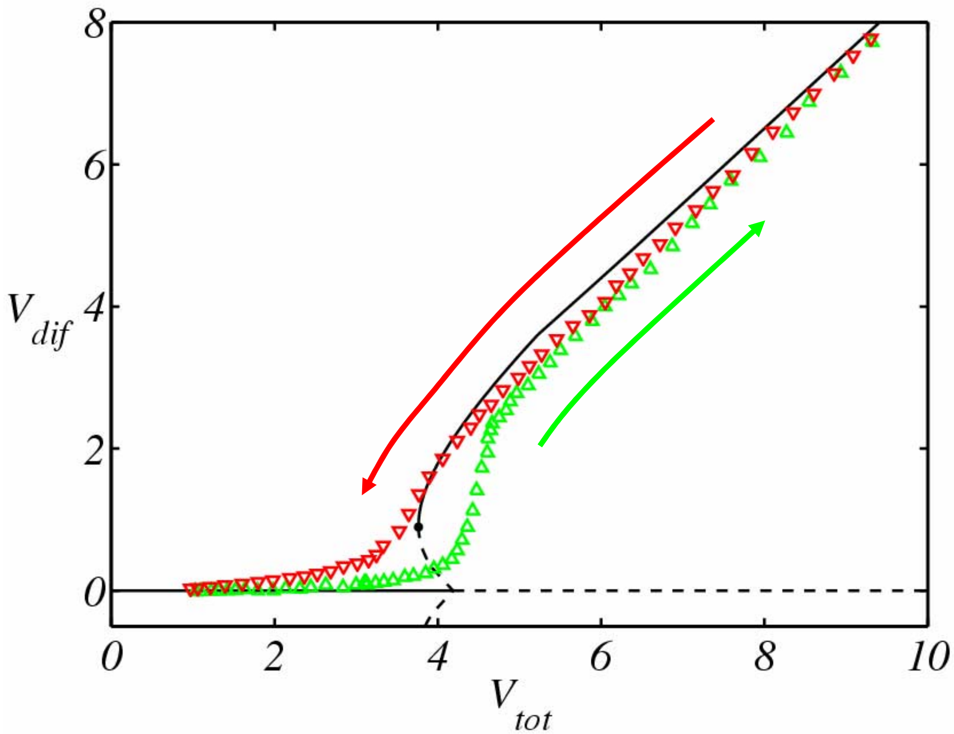
exert force

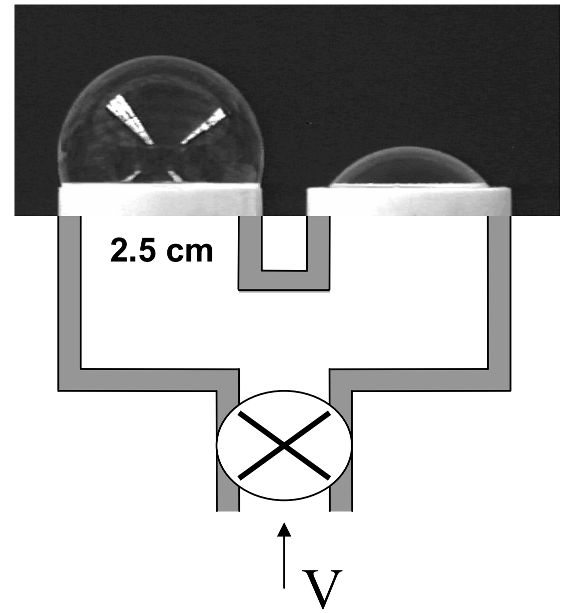


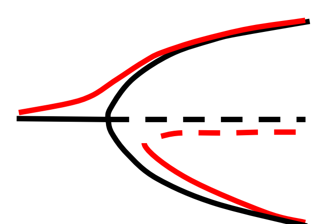


(Eisner & Aneshansley 2000)

Bistable capillary system: coupled bubbles

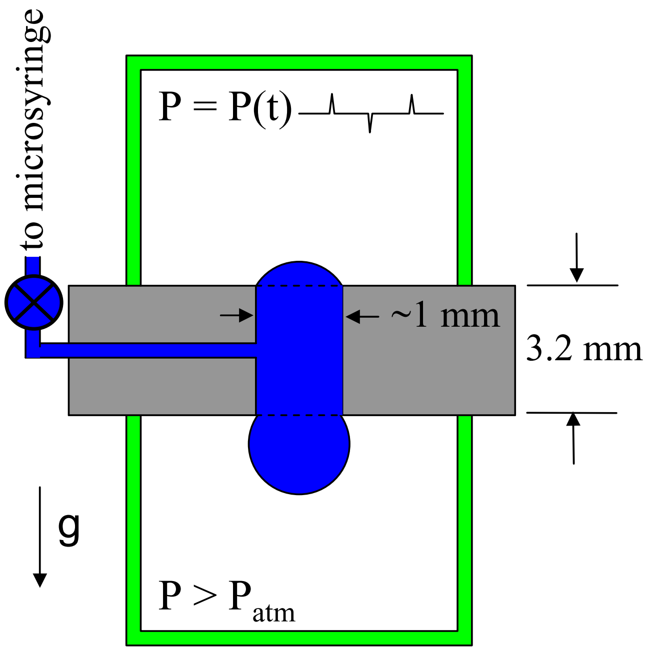




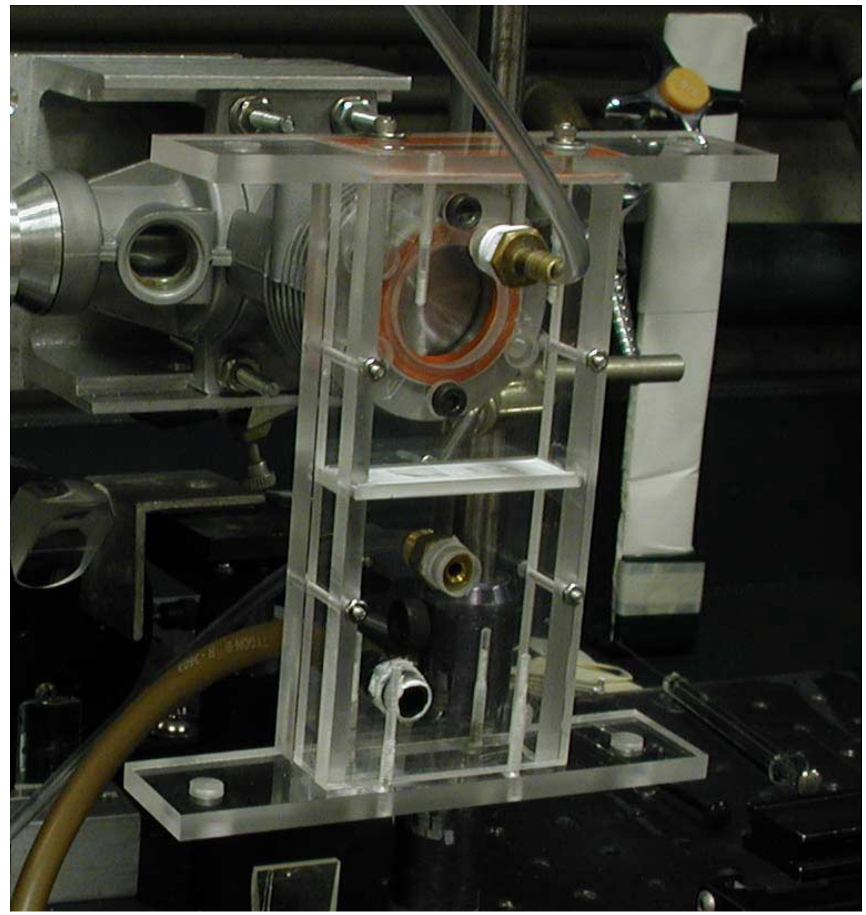


Imperfection theory

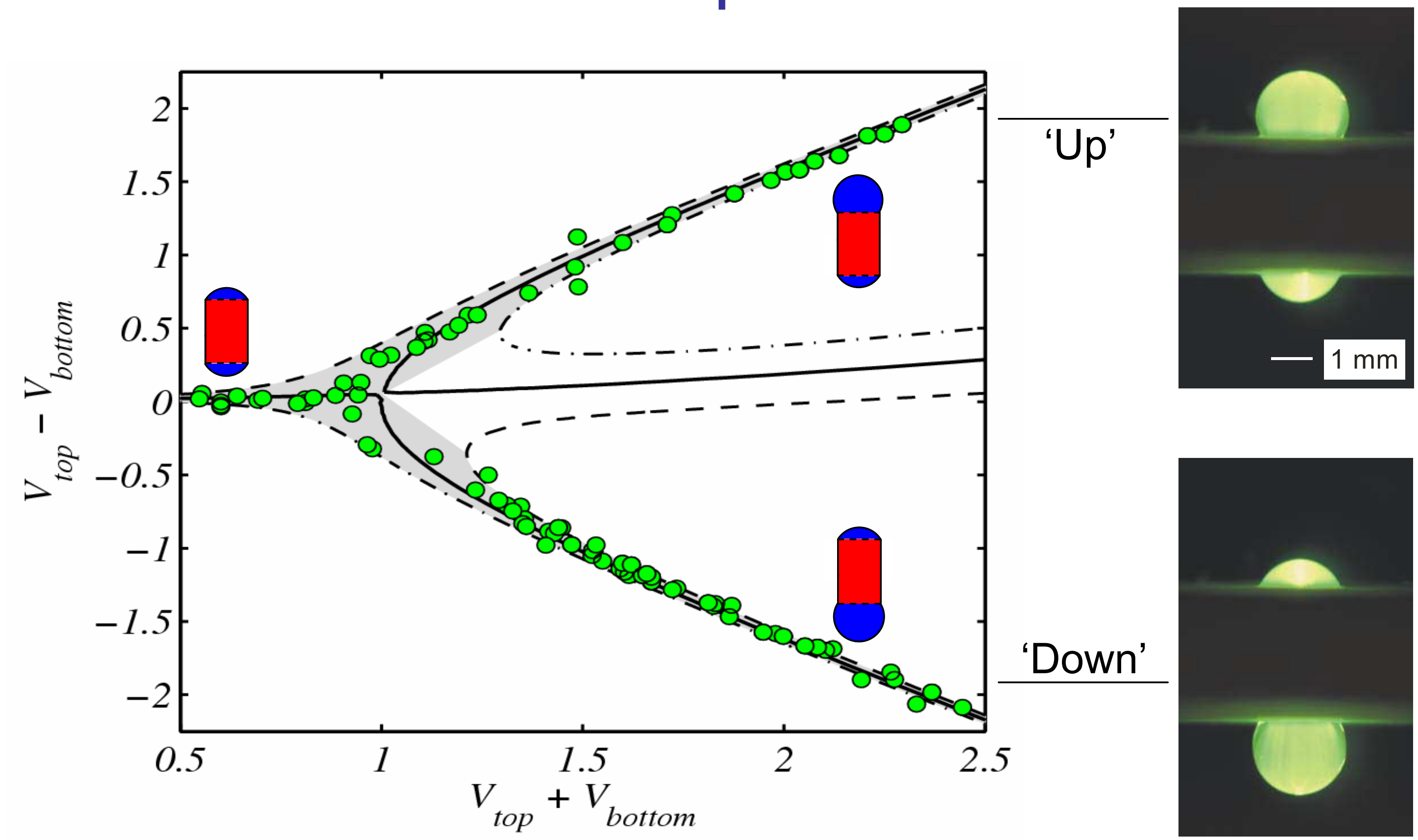
Pressure-toggled droplet switch



Laytin et. al. 2003



Bifurcation comparison

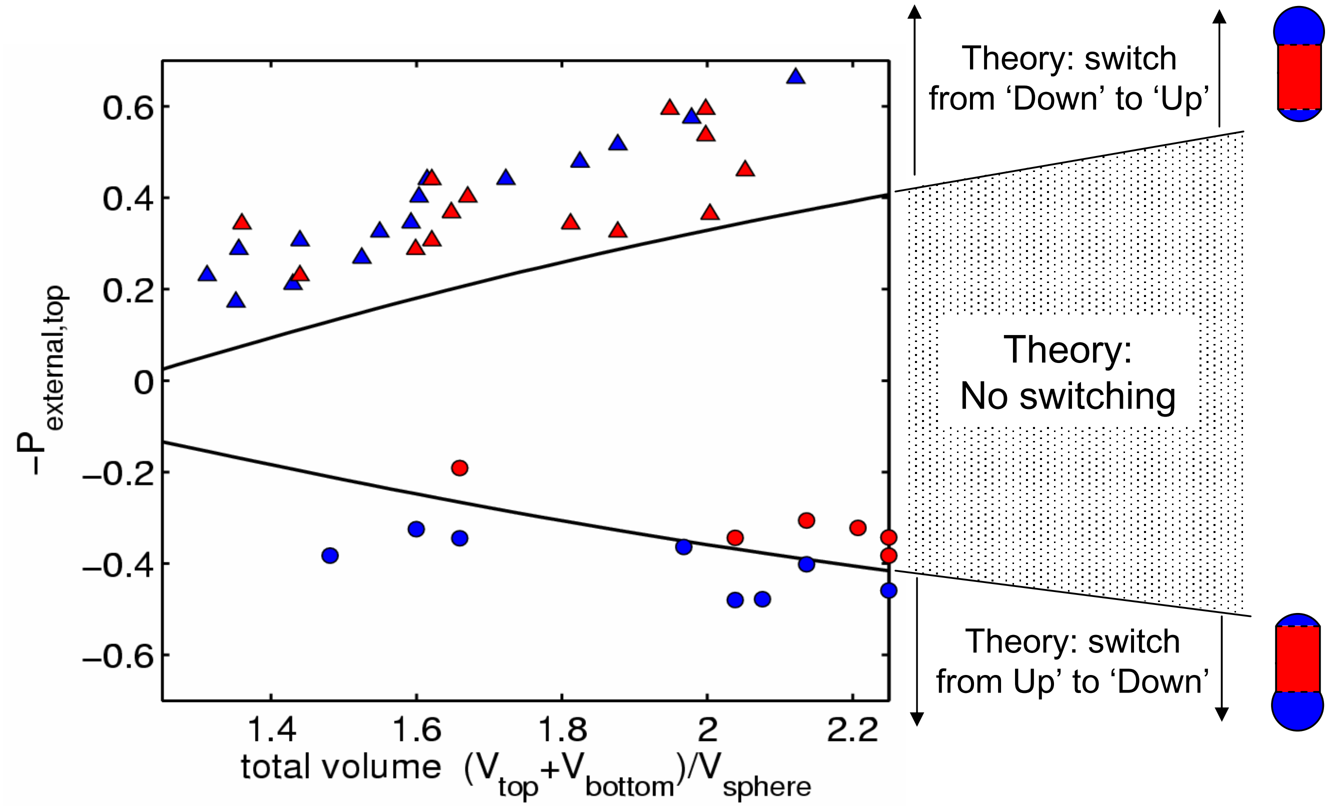


Experiment (symbols)
Theory (solid line) →

- with gravity
- pressure bias perfectly offsets gravity
  (dashed lines and shaded region show
  +/- 15% error in the pressure bias)
- circular contact-lines

Hirsa et. al. 2004

Pressure perturbation for activation

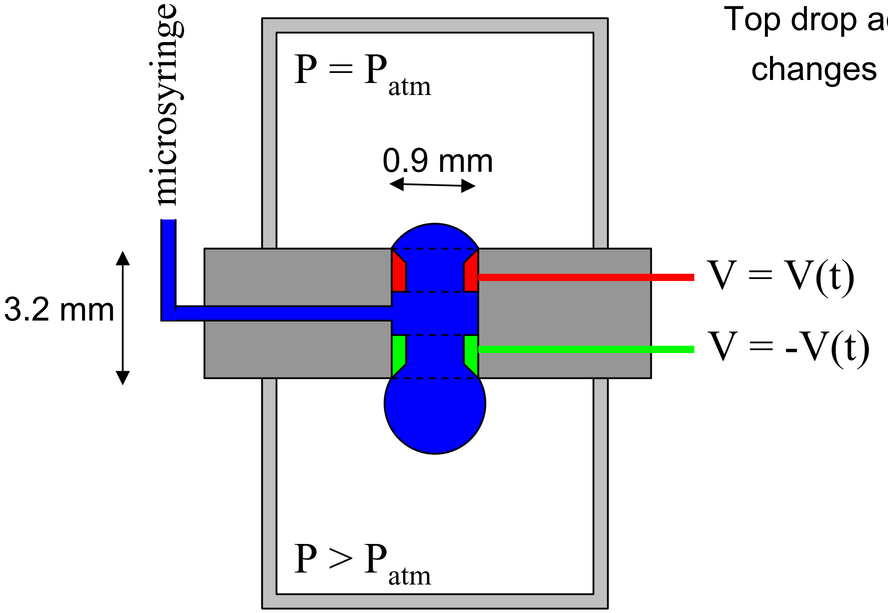


Theory (solid line)
Experiment (symbols)

- triangle = switch from 'Down' to 'Up'
- circle = switch from 'Up' to 'Down

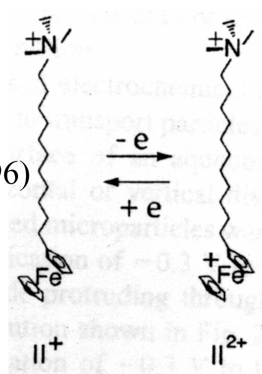
- blue = successful switch
- red = insufficient pressure for switching

Individually addressable droplet switches

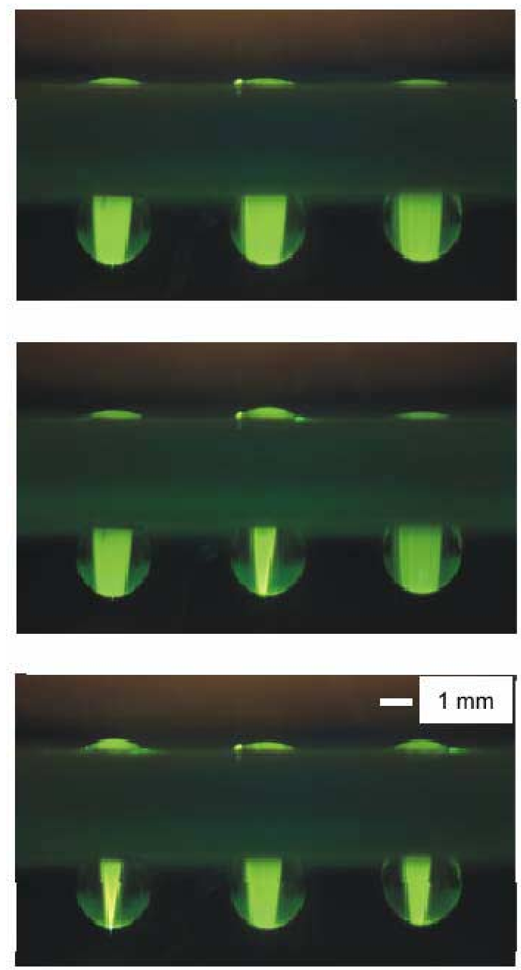


Top drop acts as microlens to laser sheet; change in shape changes focal length, as seen amplified in bottom drop.

FTMA
(Gallardo et. al. 1996)



electrochemical shape-change mechanism



applied voltage

0 0 0

0 + 0

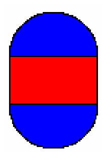
+ 0 +

Hirsa et. al. 2004

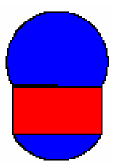
Electroosmotic pump as toggling physics

$$\Theta \equiv \frac{V_{total}}{\frac{4}{3}\pi B^3}$$

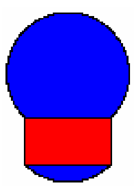
(constant)



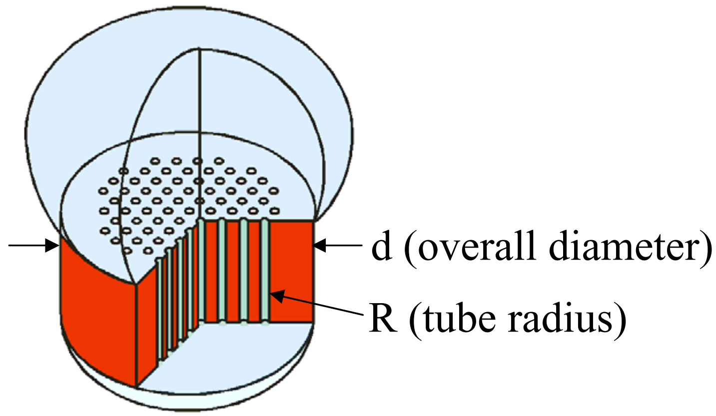
$\Theta = 1$

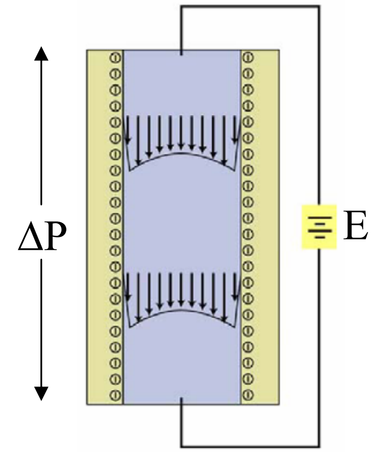


$\Theta = 2$

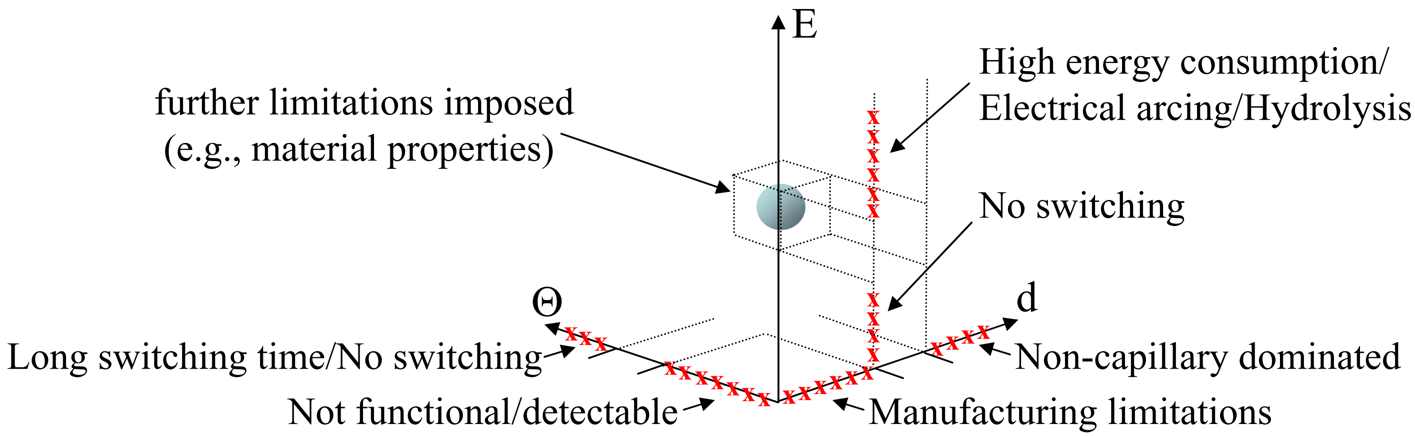


$\Theta = 3$





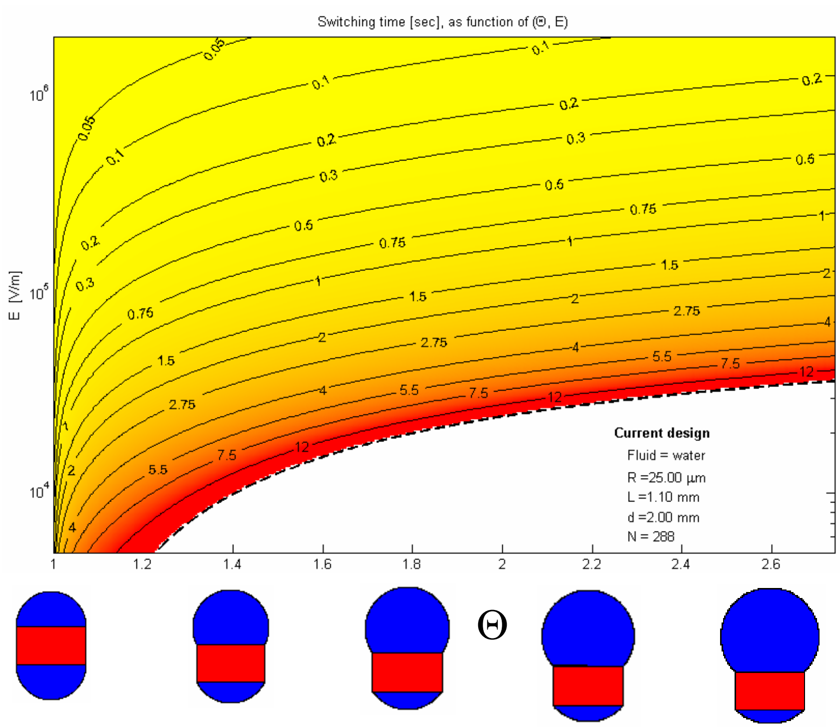
Design/operation parameter space



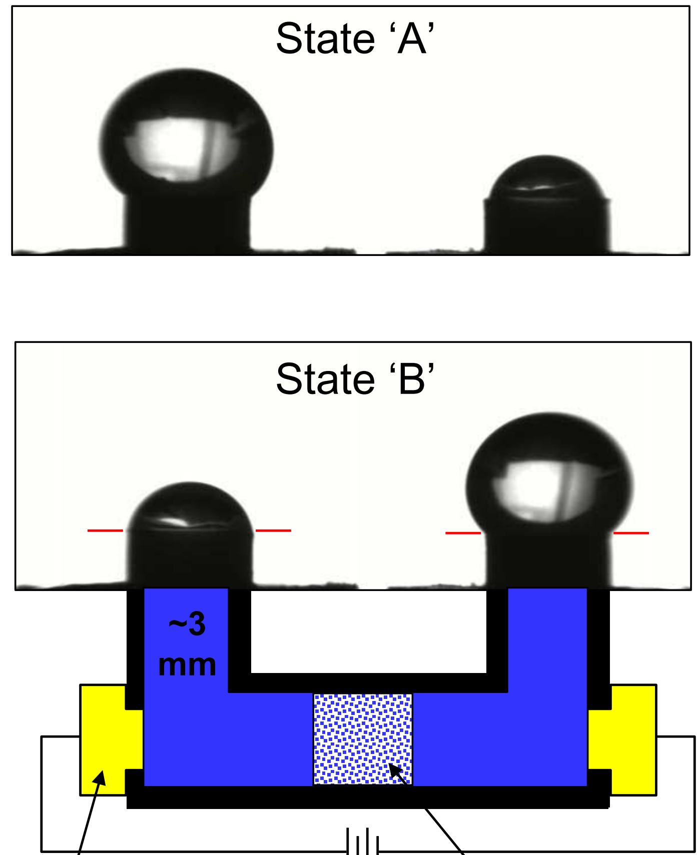
Realization

(April 2004, IKET, FzK)

switching time [sec], *f*(electric field, total volume)



prototype device



References & Acknowledgements

References

Boys, CV (1890), *Soap bubbles and the forces which mold them*, Society for Promoting Christian Knowledge; New York E.& J.B. Young.

Steen PH, C Matalanis, AH Hirsa, and C Cox (2002) "Capillary micro-switches," *Bulletin of the American Physical Society* **47** (10), 129-130.

Eisner, T and DJ Aneshansley (2000) "Defense by foot adhesion in a beetle," *Proc. Nat. Acad. Sci.* **92**(12), 6568-73.

Laytin, M. CC Lee, A Wirecki, J. Meyerholz, A. Hirsa and PH Steen (2003) "Capillary micro-switch activation", *Bulletin of the American Physical Society* **48** (10), 24.

Hirsa AH, C Lopez, M. Laytin, CC Lee, and PH Steen (2004) "Low-dissipation capillary switches at small scales," (submitted).

Gallardo, B. S., Metcalfe, K. L. & Abbott, N. L. (1996) Ferrocenyl surfactants at the surface of water: Principles for active control of interfacial properties. *Langmuir* **12**, 4116-4124.

Related publications

Atreya, S. and P.H. Steen, "Stability analyses of long liquid bridges in the presence of gravity and flow," Proc. Roy. Soc. A. 458, 2645-2669 (2002).

Robinson, N.D., and P.H. Steen. "Observations of singularity formation during capillary collapse and bubble pinch-off of a soap-film bridge", J. Colloid Int. Sci. 241, 448-458 (2001).

Bhandar, A.S., M.J. Vogel and P.H. Steen (2004) "Energy landscapes and bi-stability to finite-amplitude disturbances for the capillary bridge", to appear, Phys. Fluids.

Nitsche, M. and P.H. Steen (2004) "Numerical simulations of inviscid capillary pinchoff", to appear, J. Comp. Phys.

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