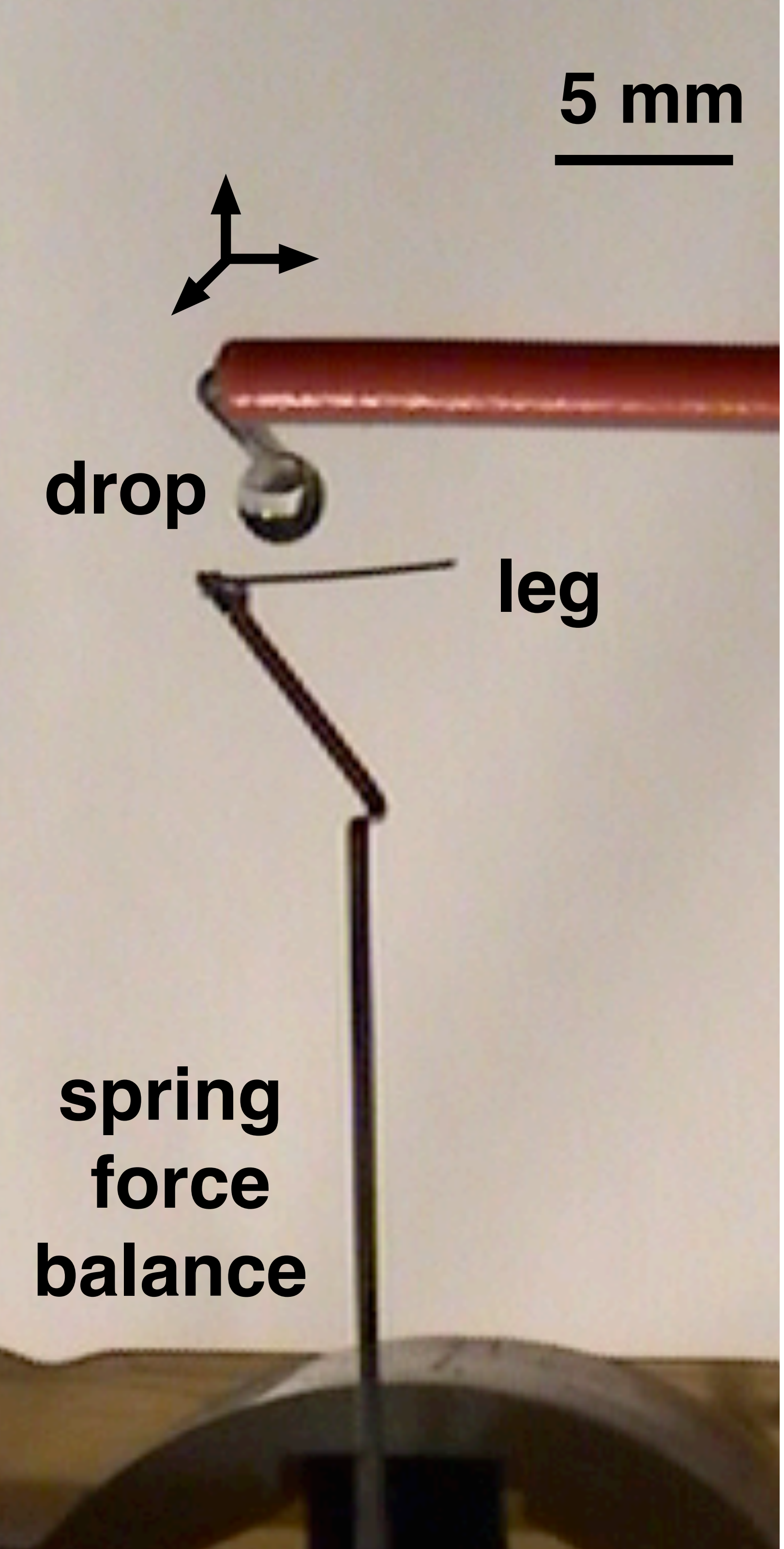
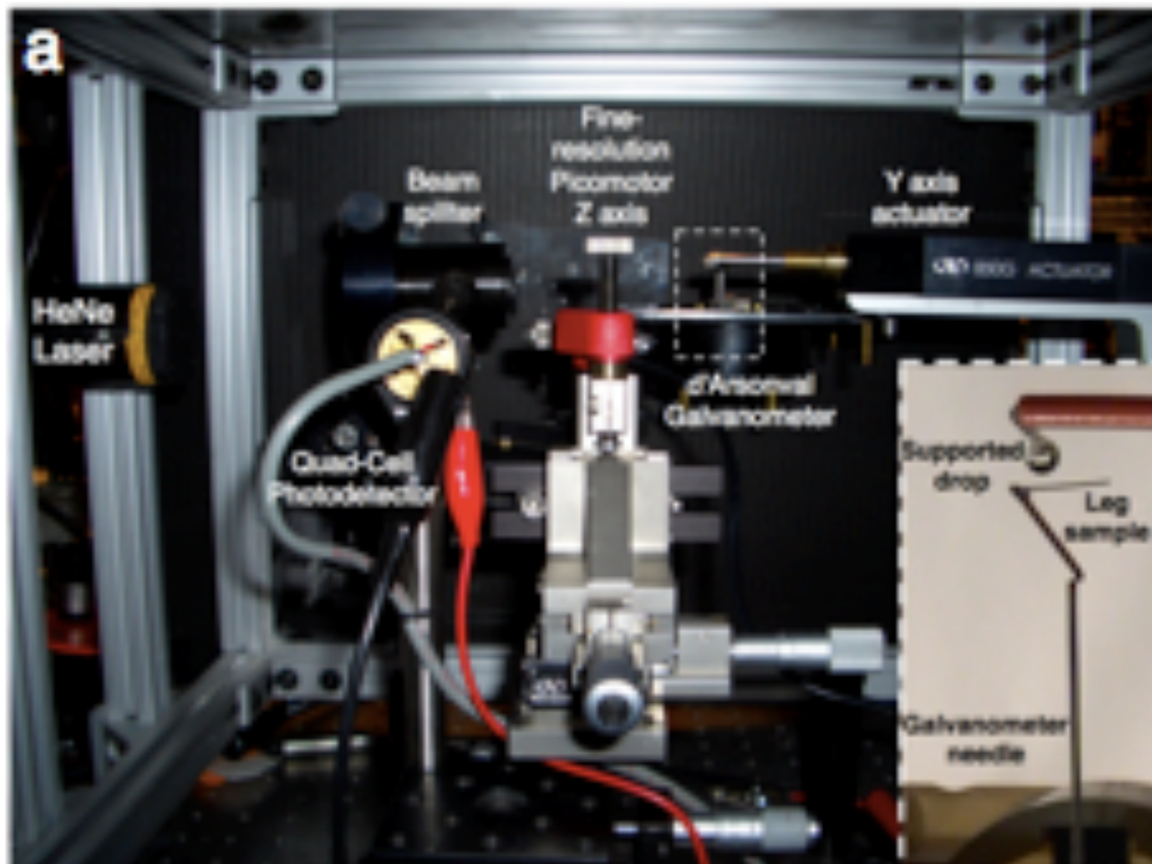
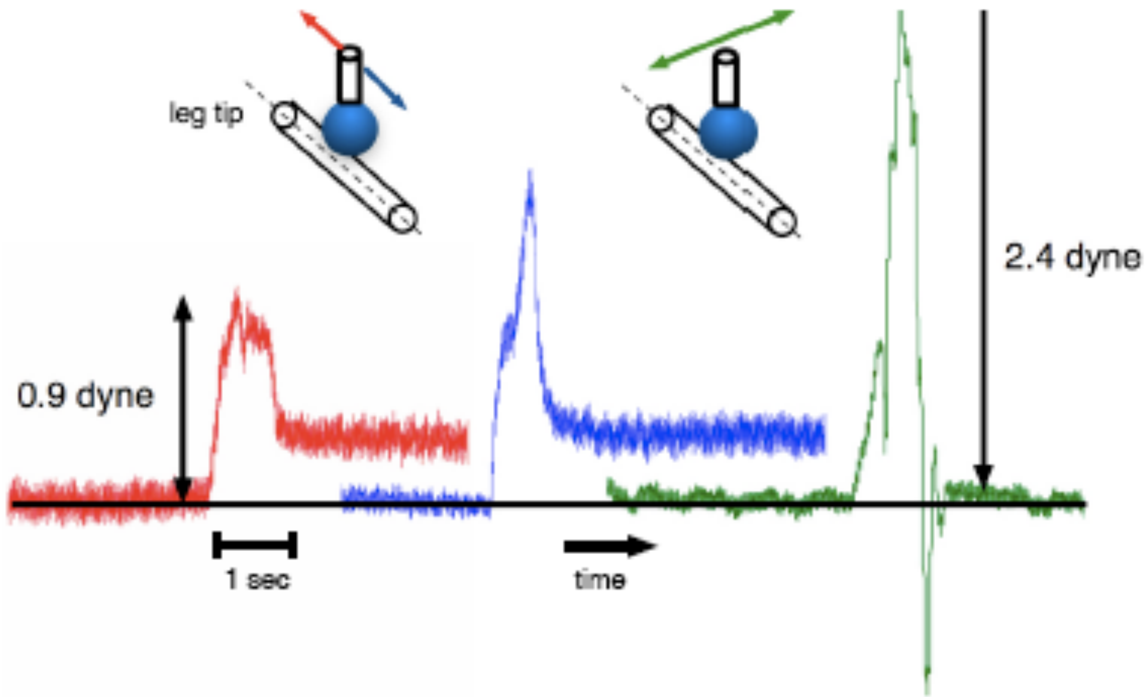
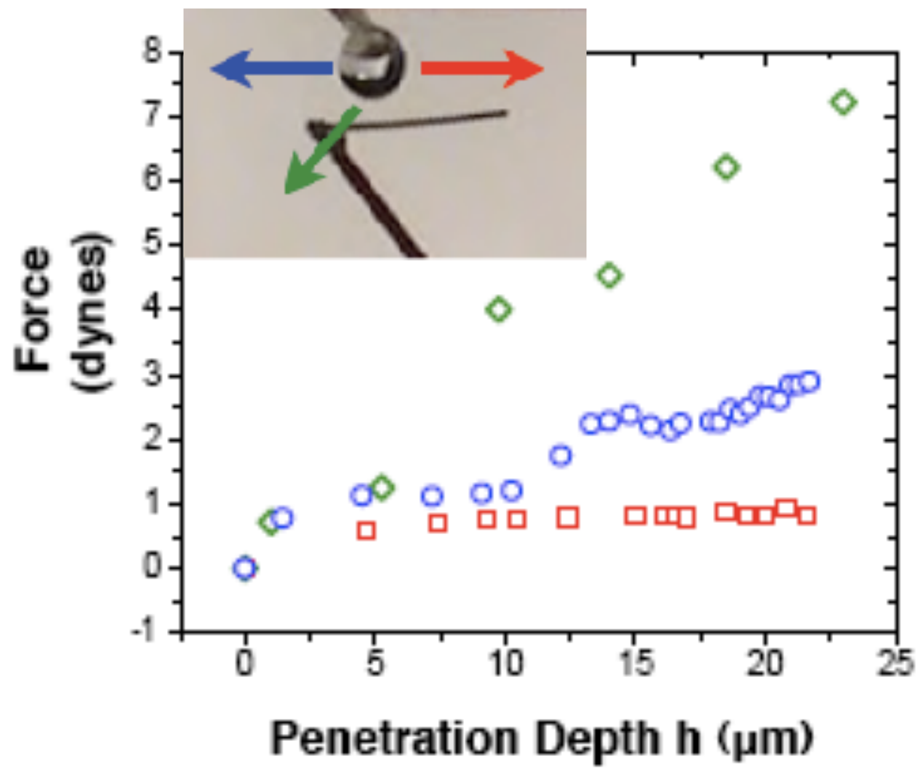


Contact force measurements

- strider leg mounted on spring force balance
- suspended water droplet brushed past leg in 3 principal directions
- Cassie state maintained
- measurements accurate to 0.1 dynes





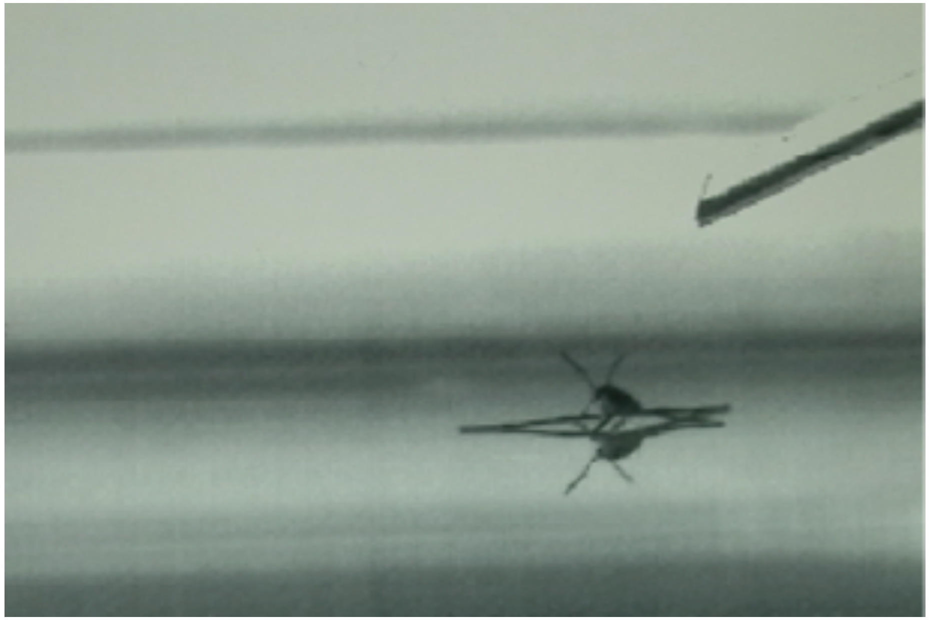


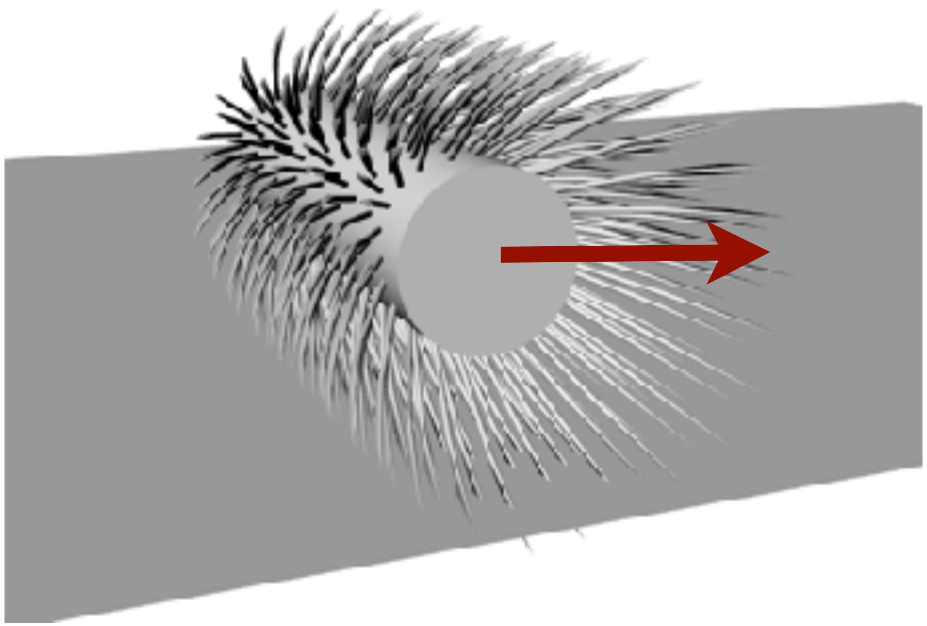
Inferences

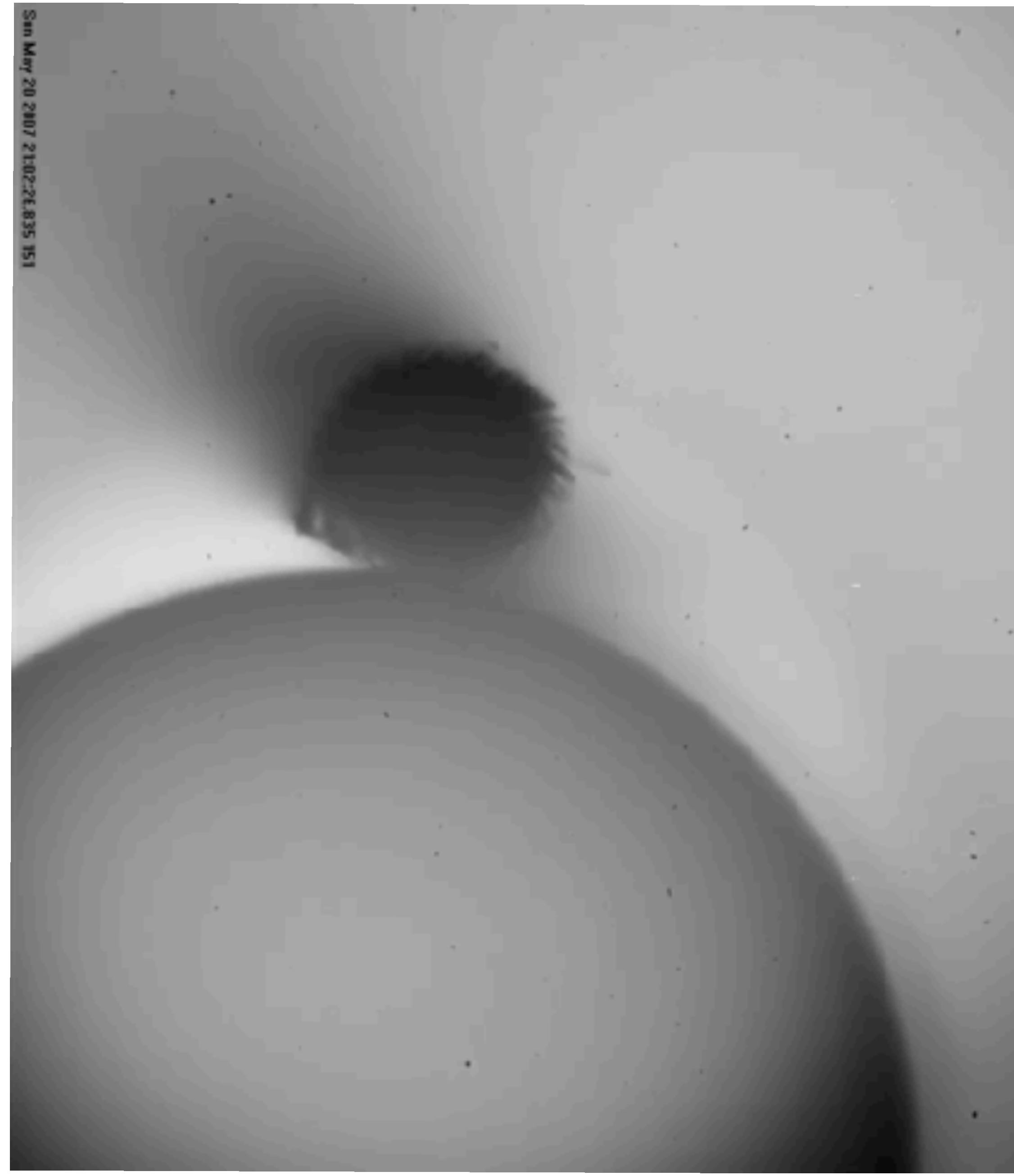
- contact forces depend on penetration depth of hairs, speed
- force/length resisting motion perpendicular, parallel (against the grain) and parallel (with the grain)

4 : 2 : 1

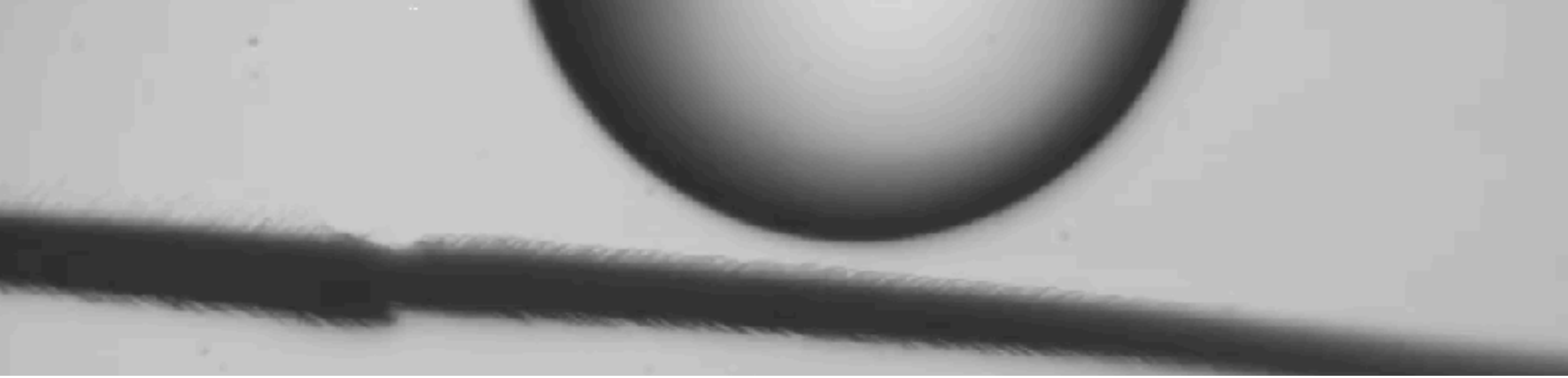
The dynamic interaction between insect cuticle and an interface







Large contact forces generated by brushing the surface.

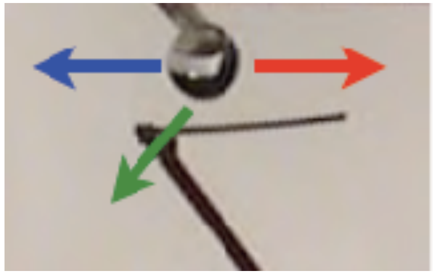


Flexible hair generates unidirectional adhesion:

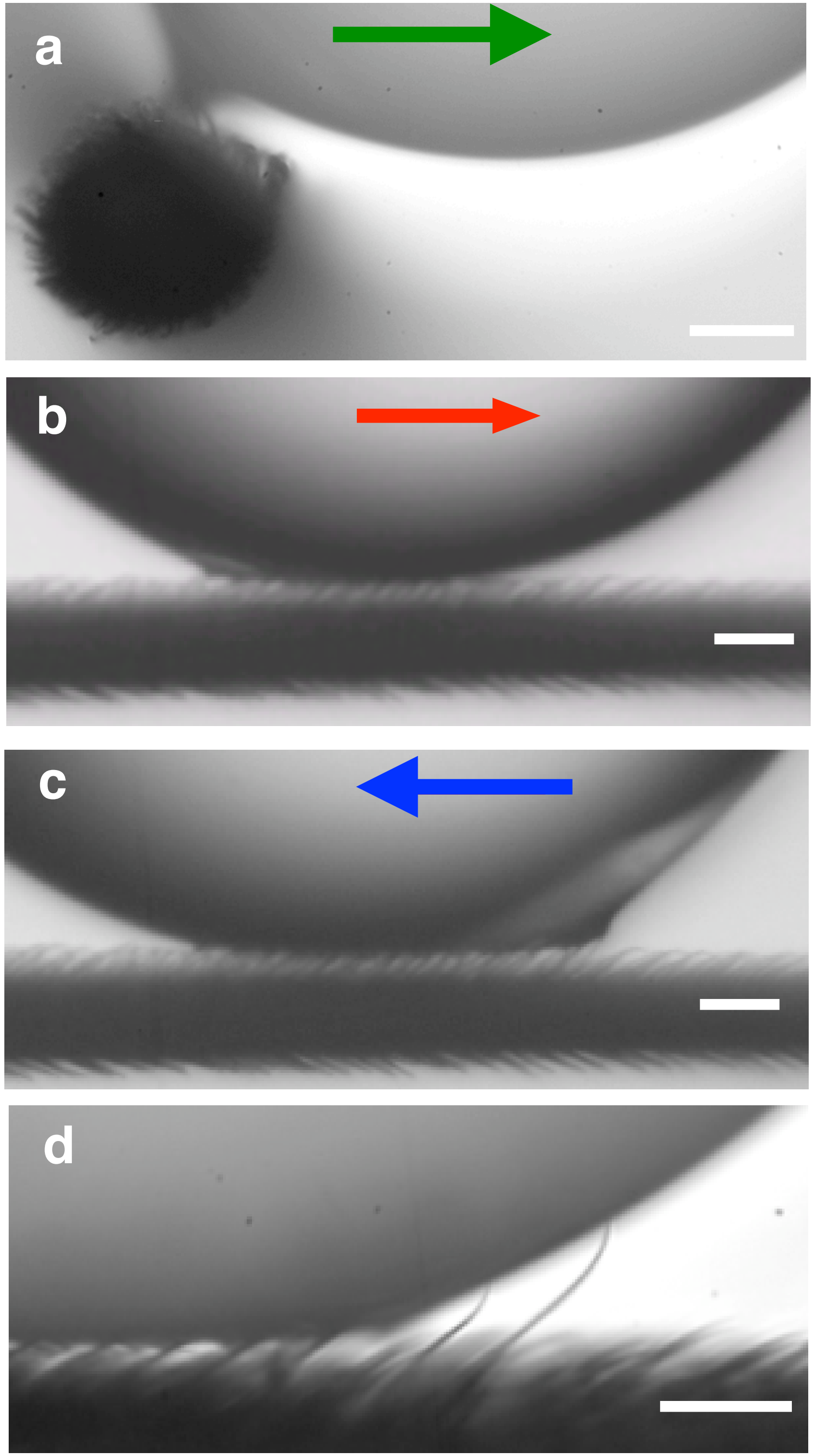
leg
tip

Directional anisotropy apparent

- large drop distortions for motion perpendicular to leg



- drop snagged by flexible hairs as it moves against the grain



[redacted]

Summary

A. By virtue of its tilted hair geometry, the strider leg exhibits directional adhesion: drop moves with greatest difficulty perpendicular to leg

Rationalizes the form of their rowing stroke

- leg strike perpendicular to direction of motion maximizes contact force
- leg glides freely, releases free surface when aligned with direction of motion

  - leg acts like a skate blade

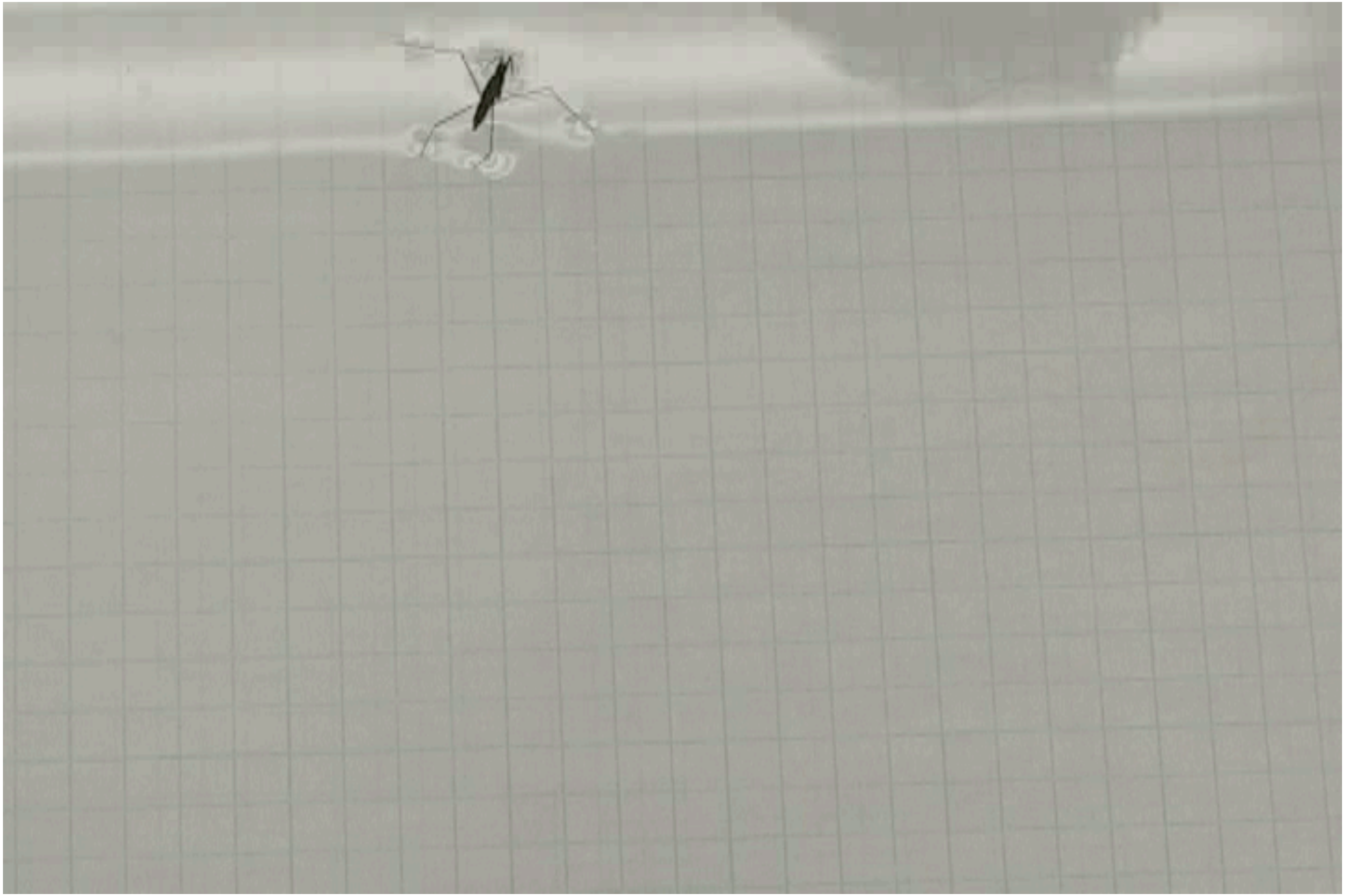
B. By virtue of the hair's flexibility, the leg exhibits unidirectional adhesion: drop moves most easily towards leg tip

  - leg acts like a traditional cross-country ski

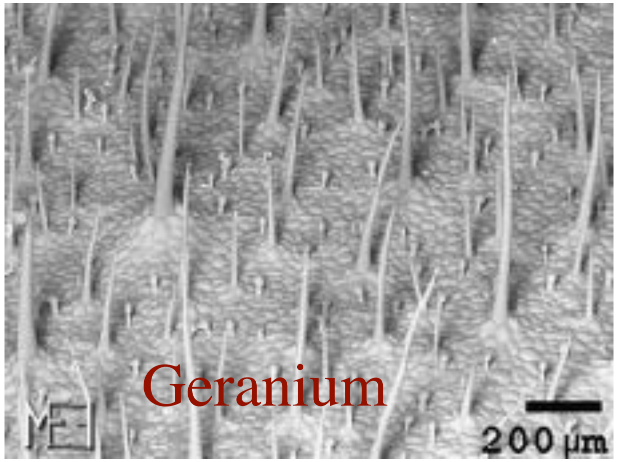
Rationalizes their peculiar response to wind

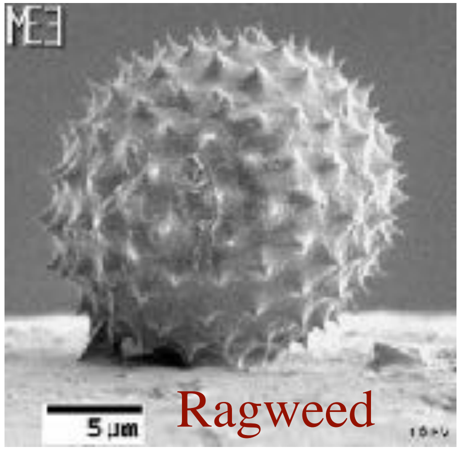
- strider anchors by extending its driving legs perpendicular to wind
- dead strider in a headwind turns to glide in the direction of the wind

Unidirectional adhesion: causes (dead) strider to glide aligned with the wind



Plants are bumpy: isotropic roughness provides water-repellency

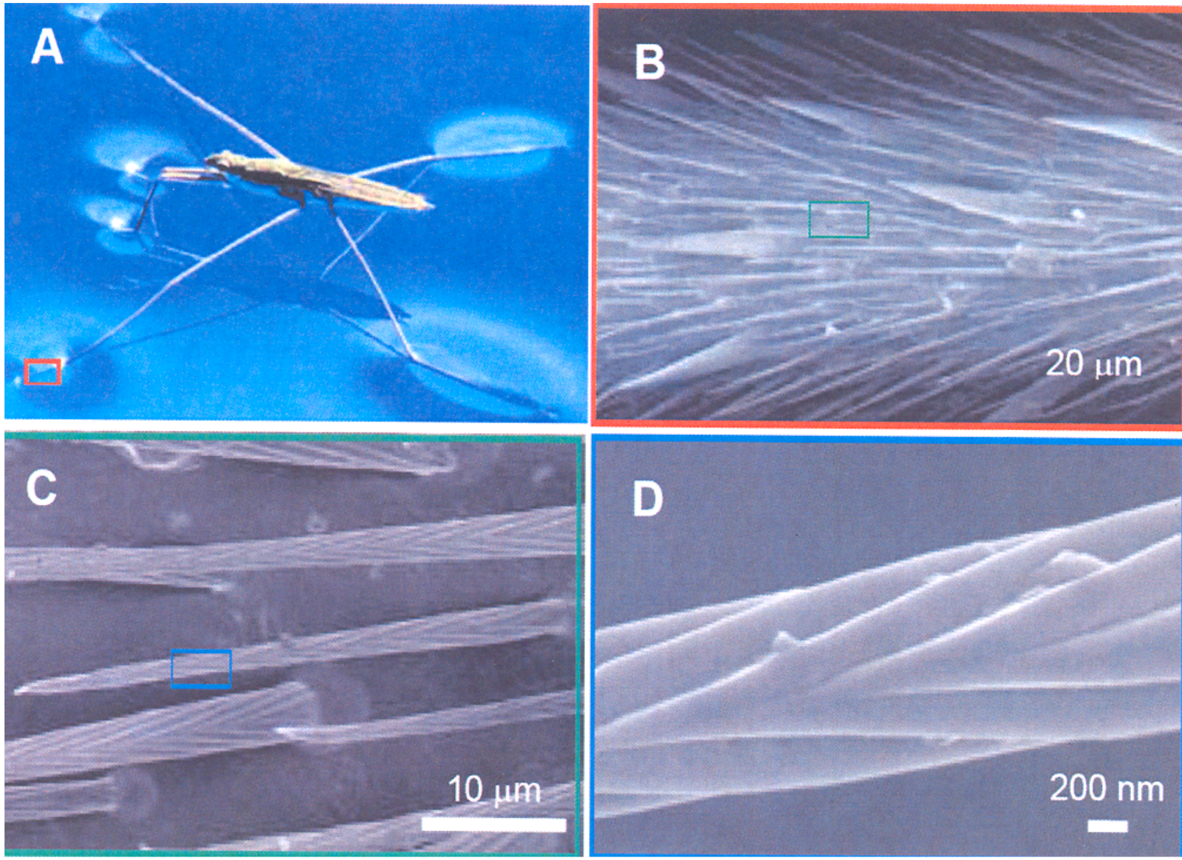




Water-walking bugs are hairy

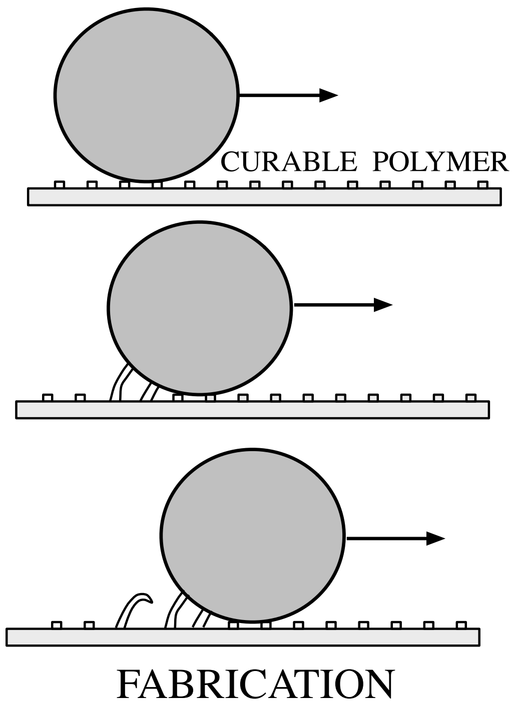
- roughness provides water-repellency
- driving leg exhibits unidirectional adhesion
- anisotropic roughness facilitates **propulsion**

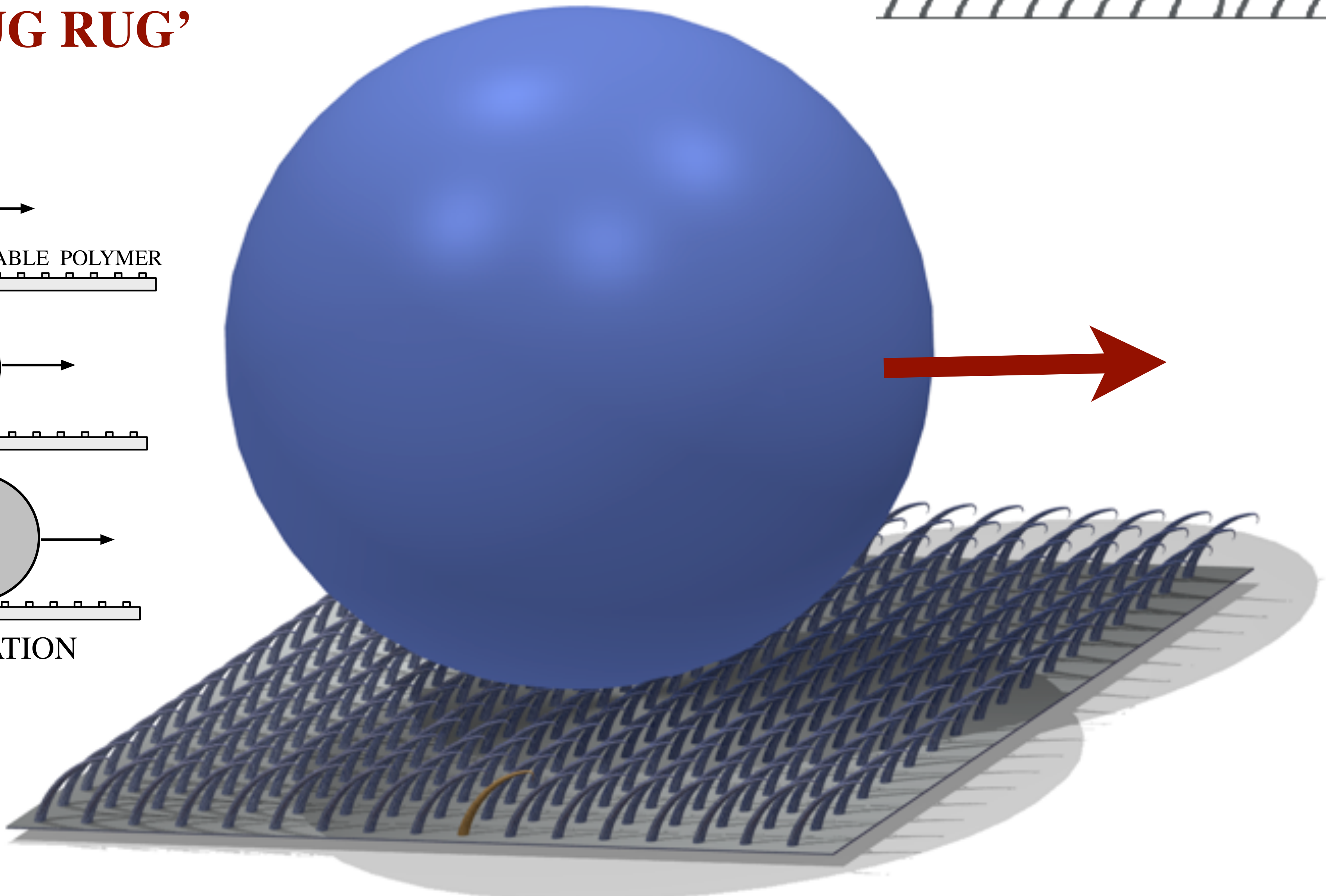
(Prakash & Bush 2010)



Biomimetic unidirectional surface

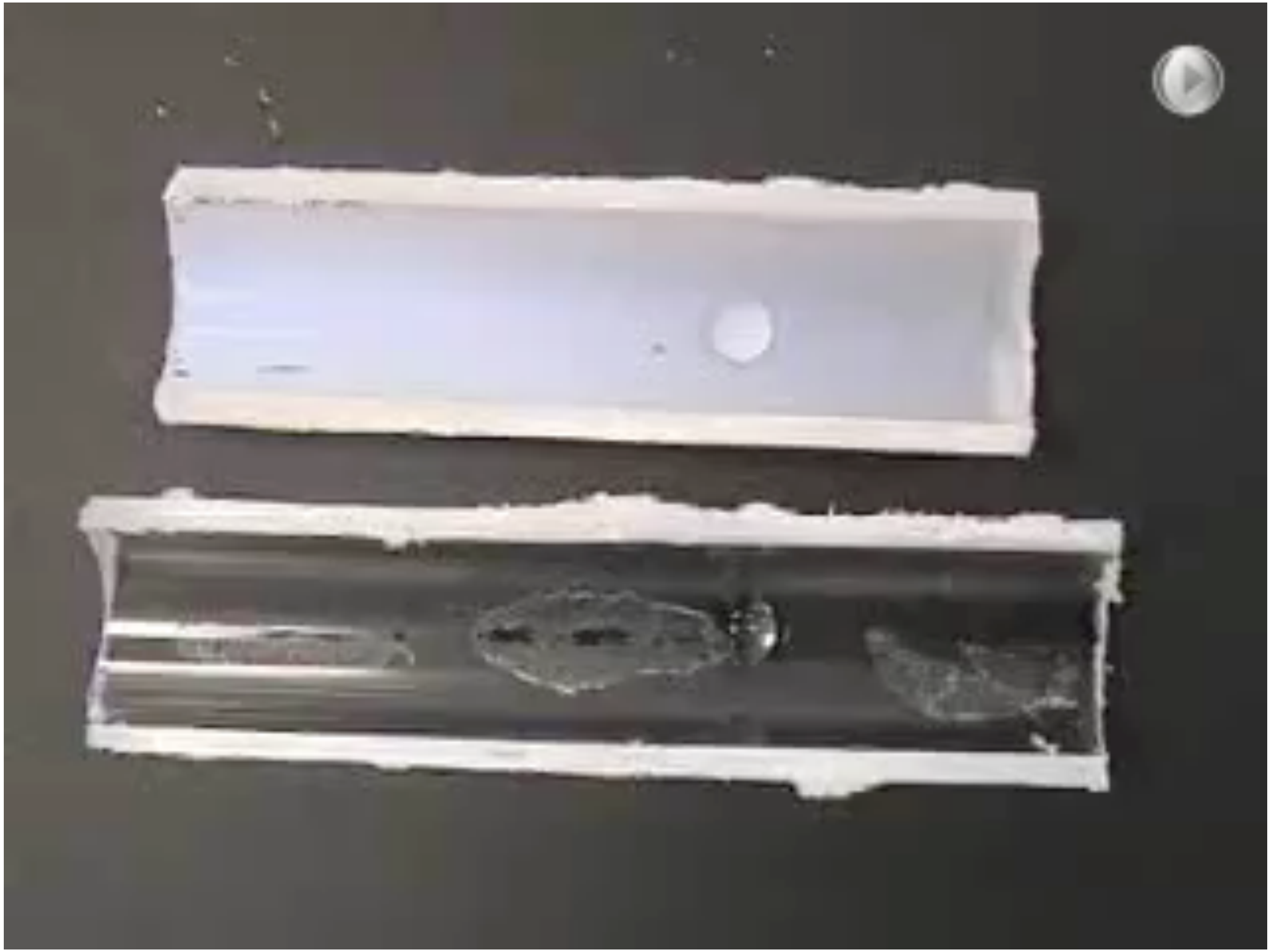
`THE BUG RUG'





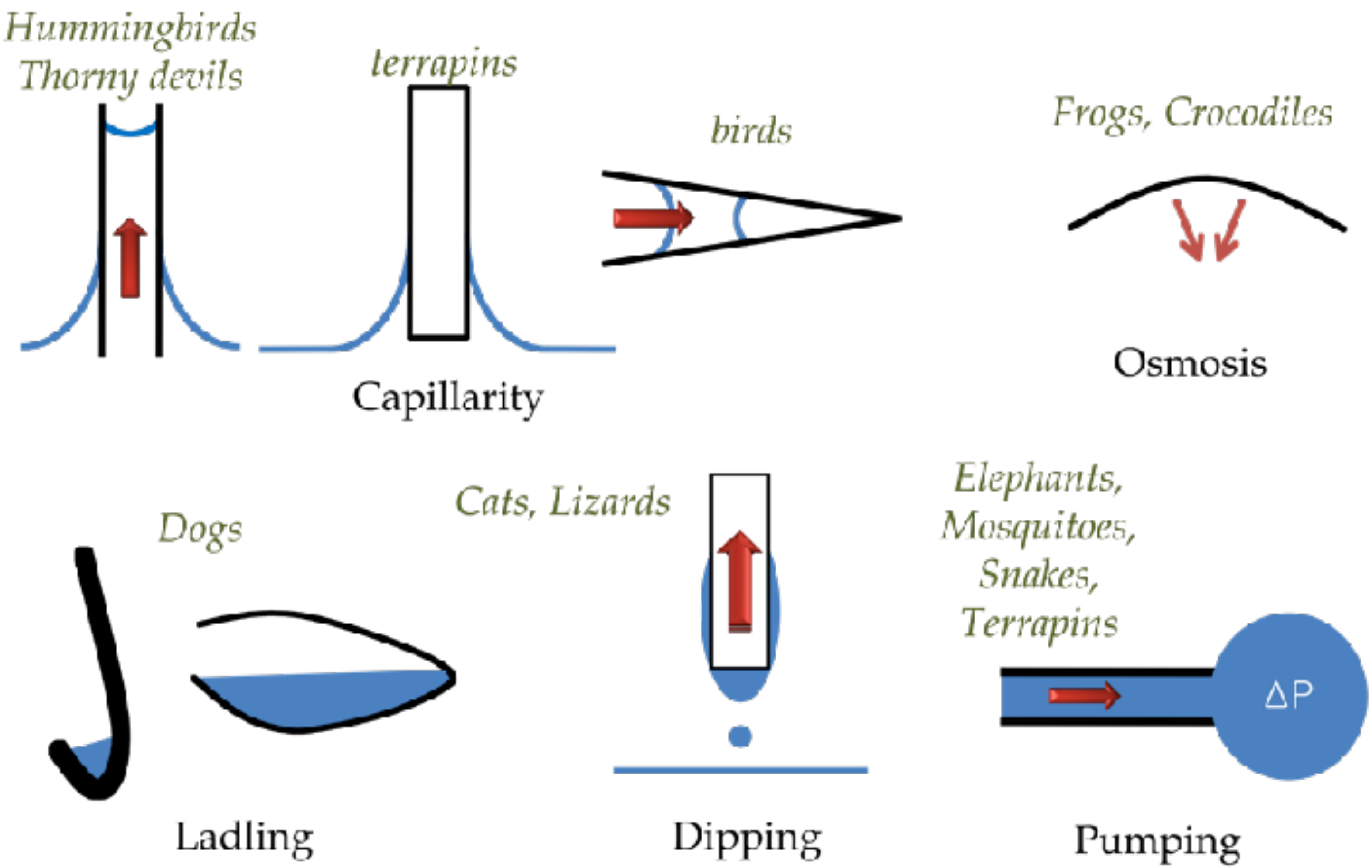
- permits drop motion in only one direction
- applications in directional draining, microfluidics

Vibration-induced motion on a directional surface




Drinking strategies in nature
with Wonjung Kim

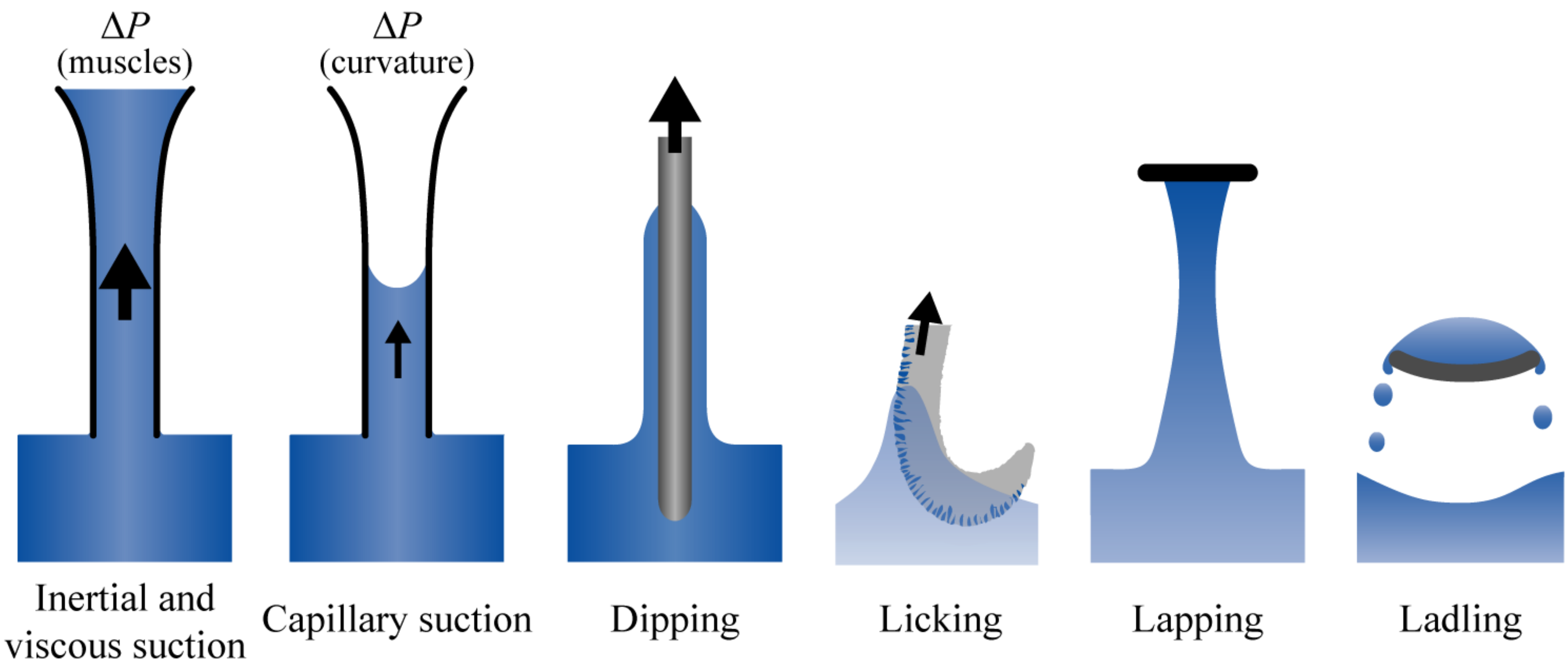
Some drinking strategies in nature



Goal: classify and rationalize all drinking styles

Various drinking techniques in nature

Classification according to dominant driving and resistive forces



Scales of forces in drinking

Scales of forces in drinking

fluid properties (ρ, μ), flow speed (u), mouth size (L), applied pressure (ΔP), and gravitational acceleration (g)

$F_{pressure} \sim \Delta P\, L^2$

$F_{inertia} \sim \rho u^2 L^2$

$F_{viscous} \sim \mu u L$

$F_{gravity} \sim \rho g L^3$

- $\Delta P_{muscle} \sim 10$ kPa
- $\Delta P_{curvature} \sim \sigma / L$

$F_{max} \sim l^2$, $\Delta P_{max} \sim F_{max} / l^2 \sim l^0$

e.g., 10 kPa for mosquitoes, humans, and elephants

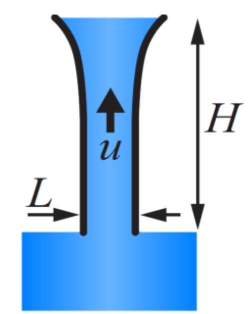
Relative magnitudes of hydrodynamic forces

$Bo = \rho g L^2 / \sigma$ ~ curvature to hydrostatic pressure

$Re = \rho u L / \mu$ ~ inertia to viscous forces

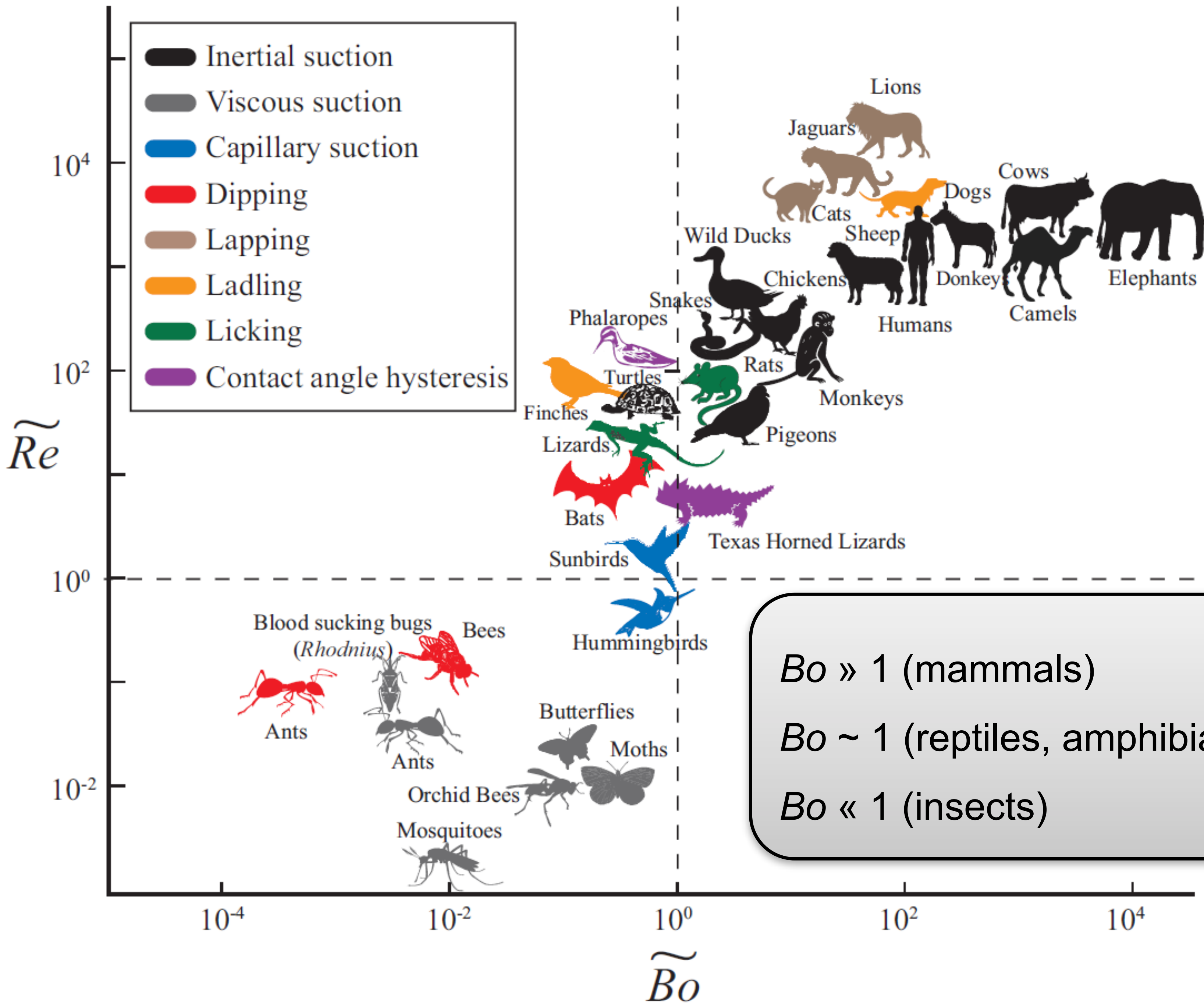
$\tilde{Bo} = \rho g L^2 / \sigma \cdot (H/L)$

$\tilde{Re} = \rho u L / \cdot (L/H)$



Assessment of these dimensionless numbers → dominant forces in drinking

Re and *Bo* in drinking of various creatures



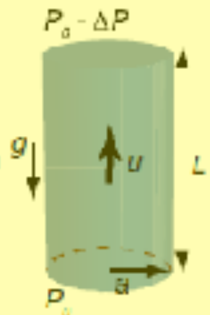
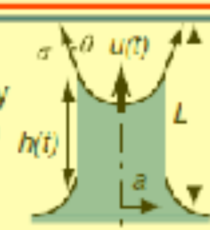
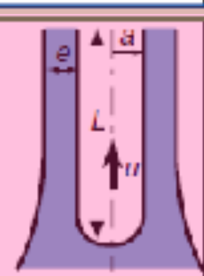
Bo » 1 (mammals)

Bo ~ 1 (reptiles, amphibians, birds)

Bo « 1 (insects)

Nectar drinking (with Wonjung Kim, Tristan Gilet)

- simple models allow for rationalization of optimal sugar concentration

Mechanism	Name	Genus	Optimal (%)
Active Suction 	Ants	*Atta* (5)	30
		Camponotus (5)	40
	Bees	*Euglossa* (18)	35
	Butterflies	*Agraulis* (12)	40
		Phoebis (12)	35
		Speyeria (24)	35
		Thymelicus (2)	40
		Vanessa (25)	40
	Moths	*Pseudaletia* (2)	40
		Macroglossum (26)	35
		Manduca (27)	30
Capillary Suction 	Humming-birds	*Sciasphorus* (16)	35-45
		Selasphorus (28)	
	Honey-eaters	*Anthochaera* (29)	50
		Phylidonyris (29)	40
		Acanthorhynchus (29)	30
	Sunbirds	*Cinnyris* (30)	30
Viscous Dipping 	Ants	*Pachycondyla* (5)	50
		Rhytidoponera (5)	50
	Bees	*Bombus* (8)	55
		Apis (9)	55
		Melipona (9)	60
	Bats	*Glossophaga* (31)	60

Suction

Dipping

- optimal S minimizes energy flux with constant power output

Namib Desert Beetle: drinking via refrigeration-free condensation

- the desert beetle has hydrophylic bumps to which 5 micron scale fog droplets stick, then grow by accretion until rolling through hydrophobic valleys and into their mouths

Parker & Lawrence (2001)

- inspired the development of superplastics for water gathering in the 3rd World

Zhai et al. (2006)

Capillary feeding in shorebirds

with Manu Prakash, David Quere, in *Science*

The Phalarope

- spinning motion sweeps preys to surface, like tea leaves in a swirling cup

Rubega (1997)

- capillary feeding used by a variety of shorebirds
- an intermediate step in evolution of filter-feeding

Question: how do they intake water?

Possibilities

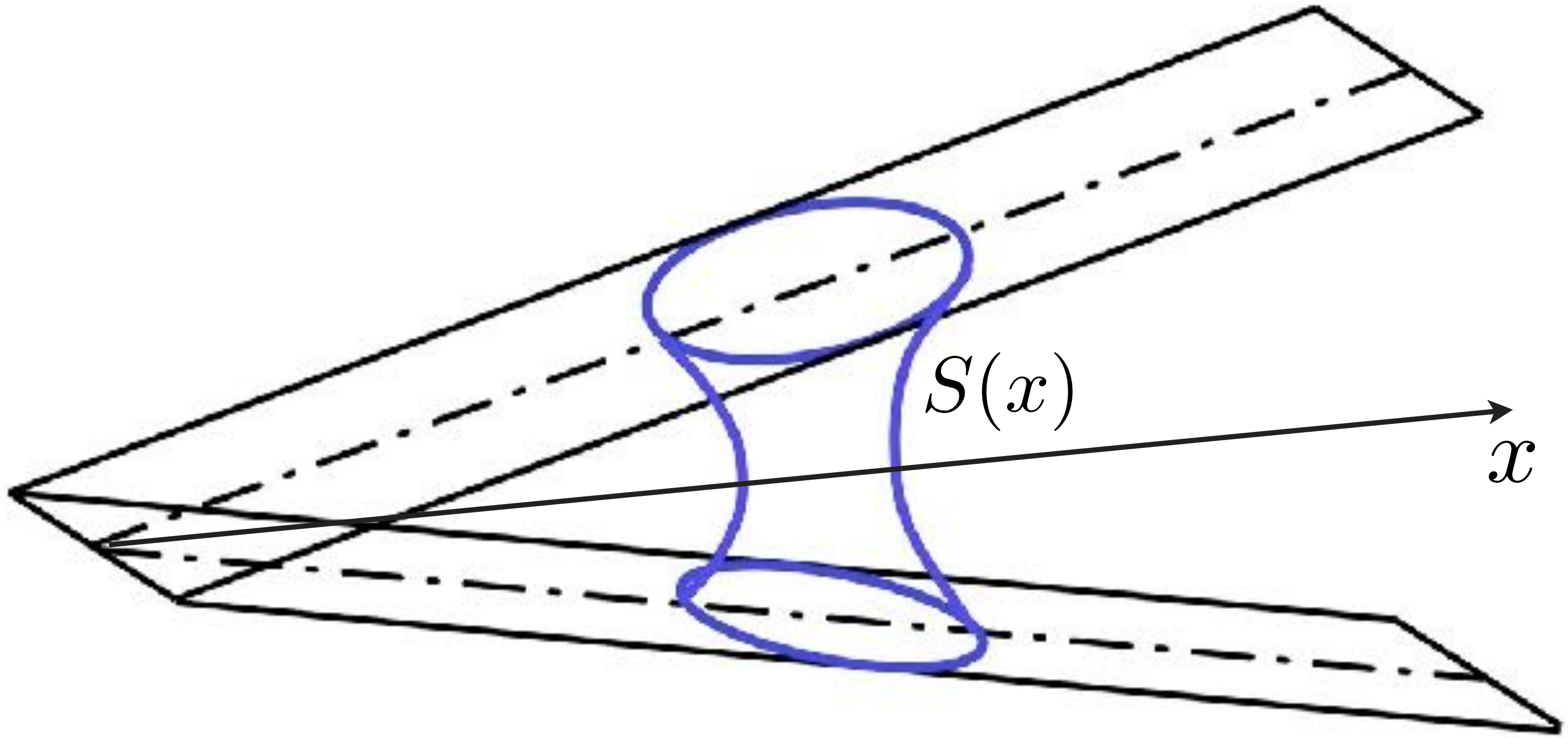
- suction: precluded by beak geometry
- gravity: requires head tilting
- capillarity

Observations

Rubega & Obst, 1993. Surface-tension feeding in phalaropes: a novel feeding mechanism, *The Auk*, **110**, 169-178.

- some shorebirds use capillary forces to draw water into their mouths
- plankton withdrawn from drop, then water expelled
- drops move at high speed ~ 30-50 cm/s
- pecking rates ~ 10 Hz; 2-3 mandibular spreading events per cycle

Toy Model: Catenoid between inclined plates



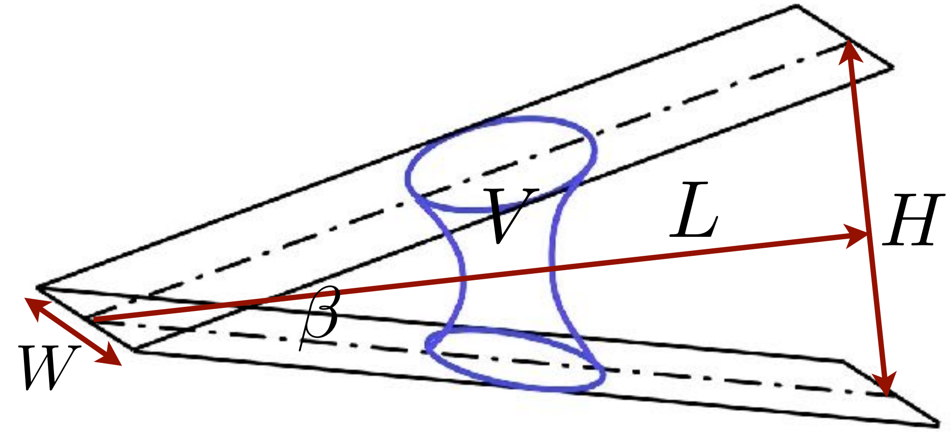
- neglect the influence of gravity
- isolate the influence of surface tension

Propulsive force:

$$F_c(x) \; = \; \sigma \, \frac{dS(x)}{dx}$$

Criterion for drop motion

$$V > \frac{2\pi}{3} W^2 H$$



Criterion for drop stability

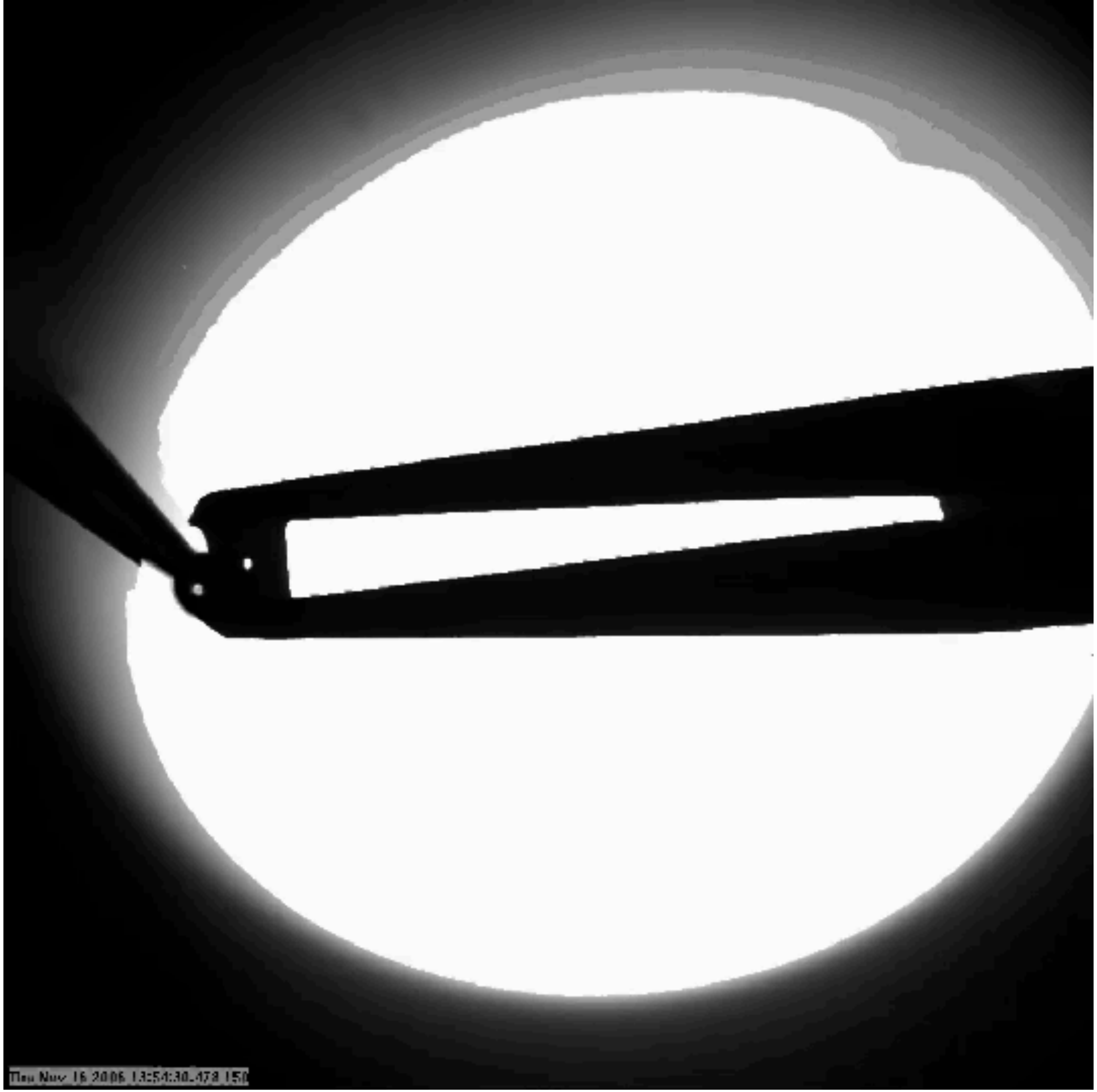
$$V > \frac{H^3}{\pi}$$

- these criteria may be satisfied simultaneously provided

$$\frac{H}{W} > \sqrt{2\pi} \longrightarrow \boxed{\frac{L}{W} \tan\frac{\beta}{2} > \sqrt{2\pi}}$$

→ a meaningful constraint on the morphology of bird beaks?

- 5 cS silicon oil on stainless steel

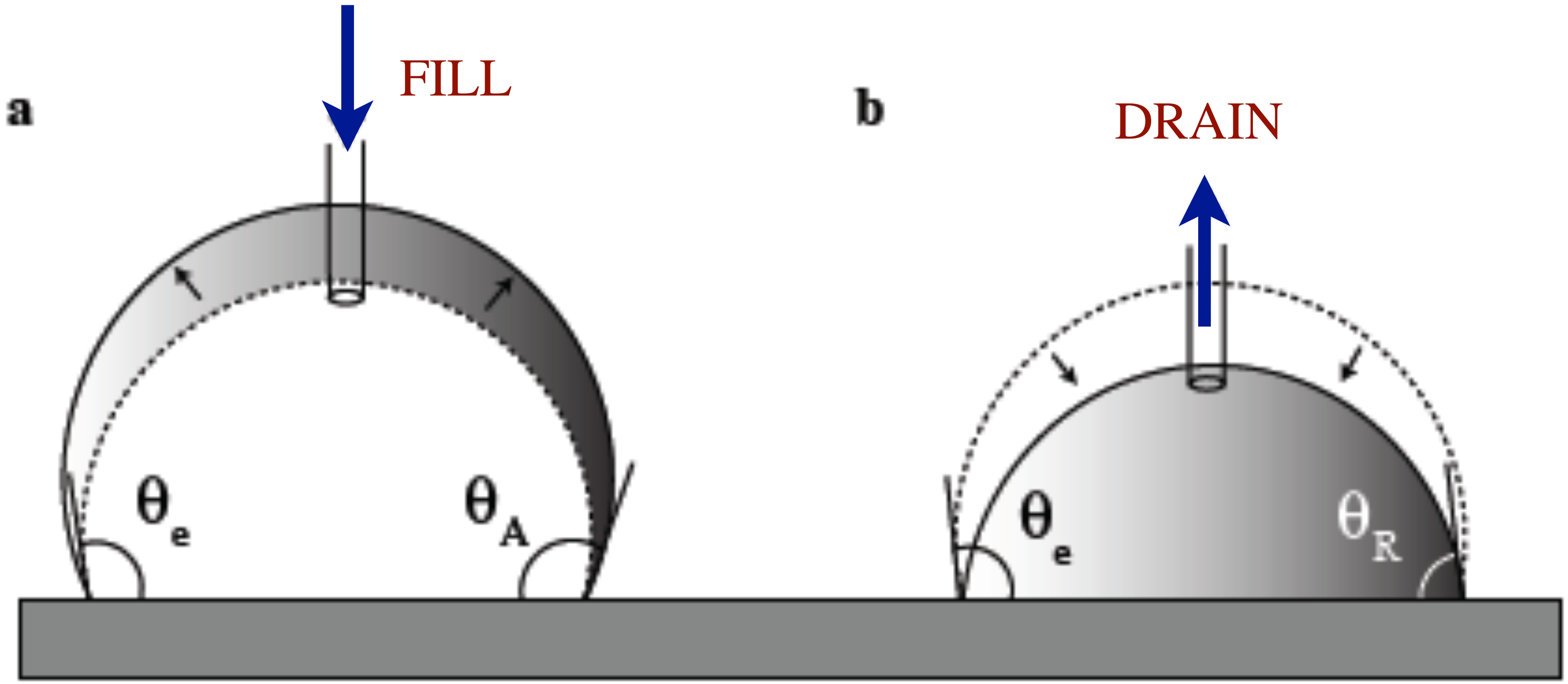


- water drop pinned by contact line

Contact angle hysteresis

Static contact angle is not uniquely θ_e

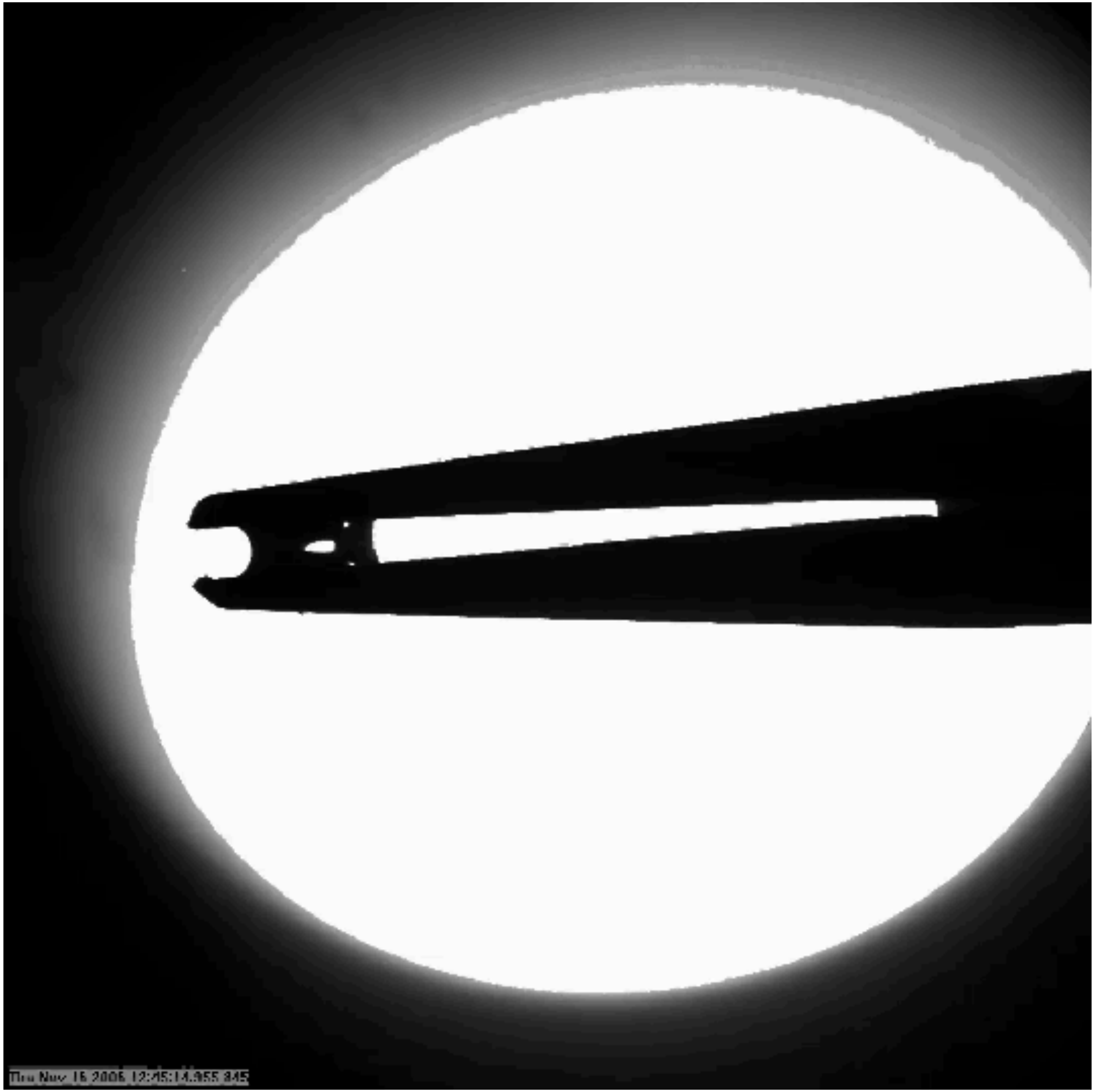
Reality: drop is stable over a range of $\theta_r < \theta < \theta_a$



FORCE of ADHESION resists drop motion

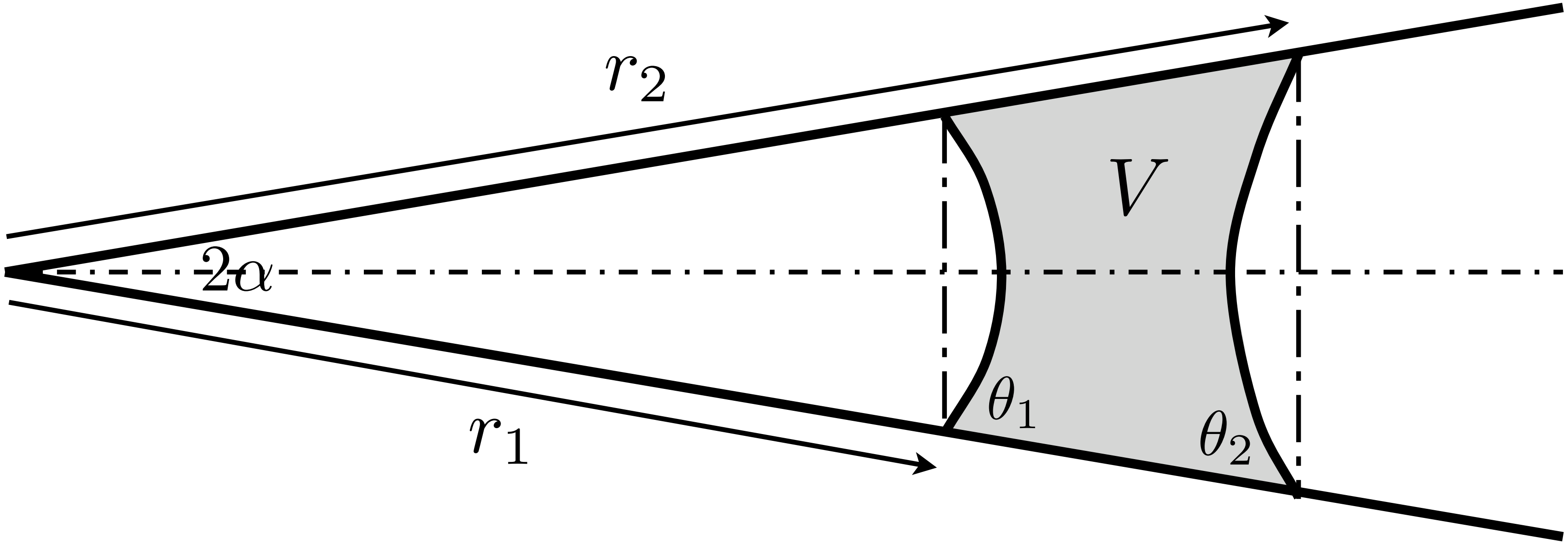
increases with $\Delta\theta = \theta_a - \theta_r$

Origins: advancing contact lines pinned on surface irregularities



- water drop freed to move by oscillating boundaries

Capillary ratcheting: the non-wetting beak (2D)



Bounds on static contact angles: $\theta_a > (\theta_1, \theta_2) > \theta_r$

Lateral force balance on static drop: $\theta_1 - \theta_2 \;=\; 2\alpha$

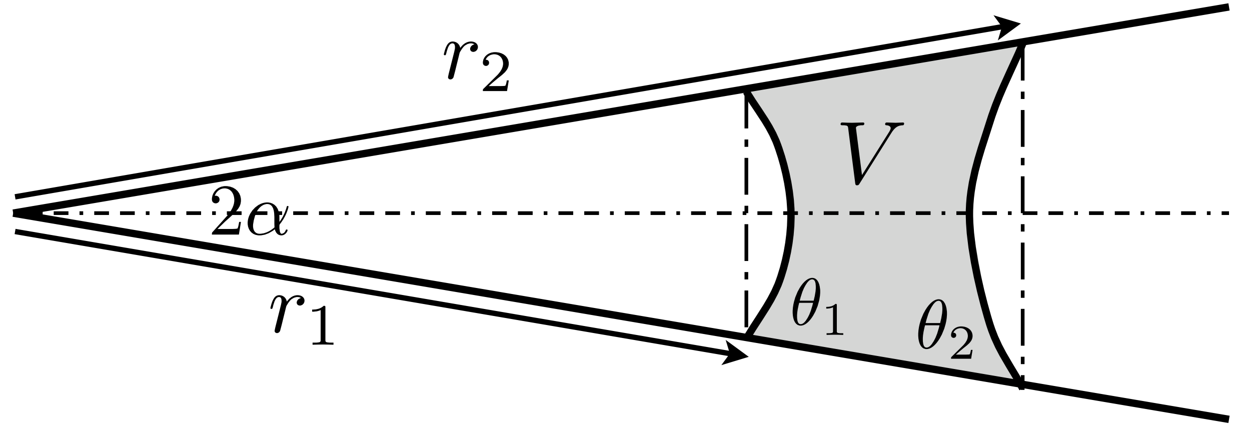
Continuity:
$$\frac{V - \frac{1}{2}(r_2^2 - r_1^2)\sin 2\alpha}{(r_1^2 + r_2^2)\sin^2\alpha}\cos^2 x \;=\; \frac{\pi}{2} - x - \frac{1}{2}\sin x$$

where $x = \theta_1 - \alpha = \theta_2 + \alpha$

→ yields (θ_1, θ_2) in terms of (V, r_1, r_2, α)

Force balance requires:

$$\theta_1 - \theta_2 = 2\alpha$$

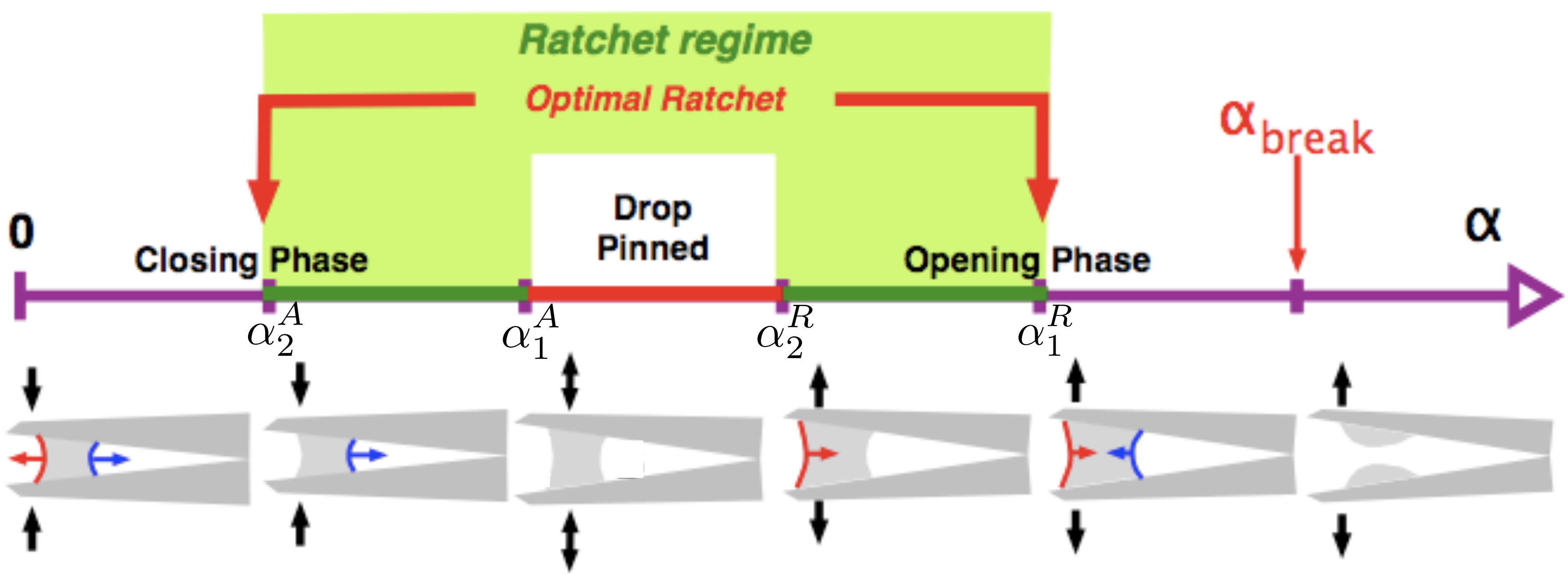


Closure phase: can deduce α_1^A at which $\theta_1 = \theta_A$

α_2^A at which $\theta_2 = \theta_A$

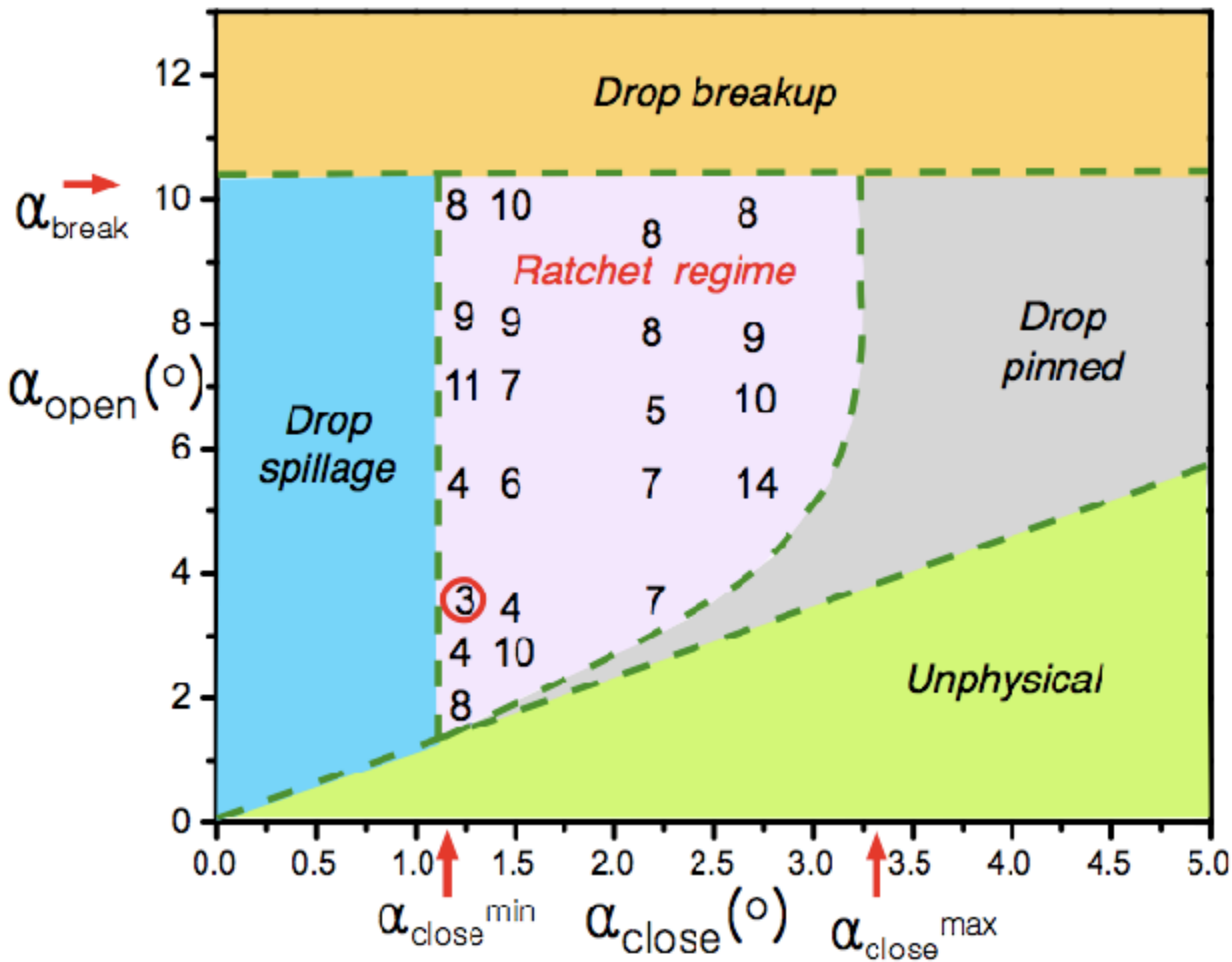
Opening phase: can deduce α_2^R at which $\theta_2 = \theta_R$

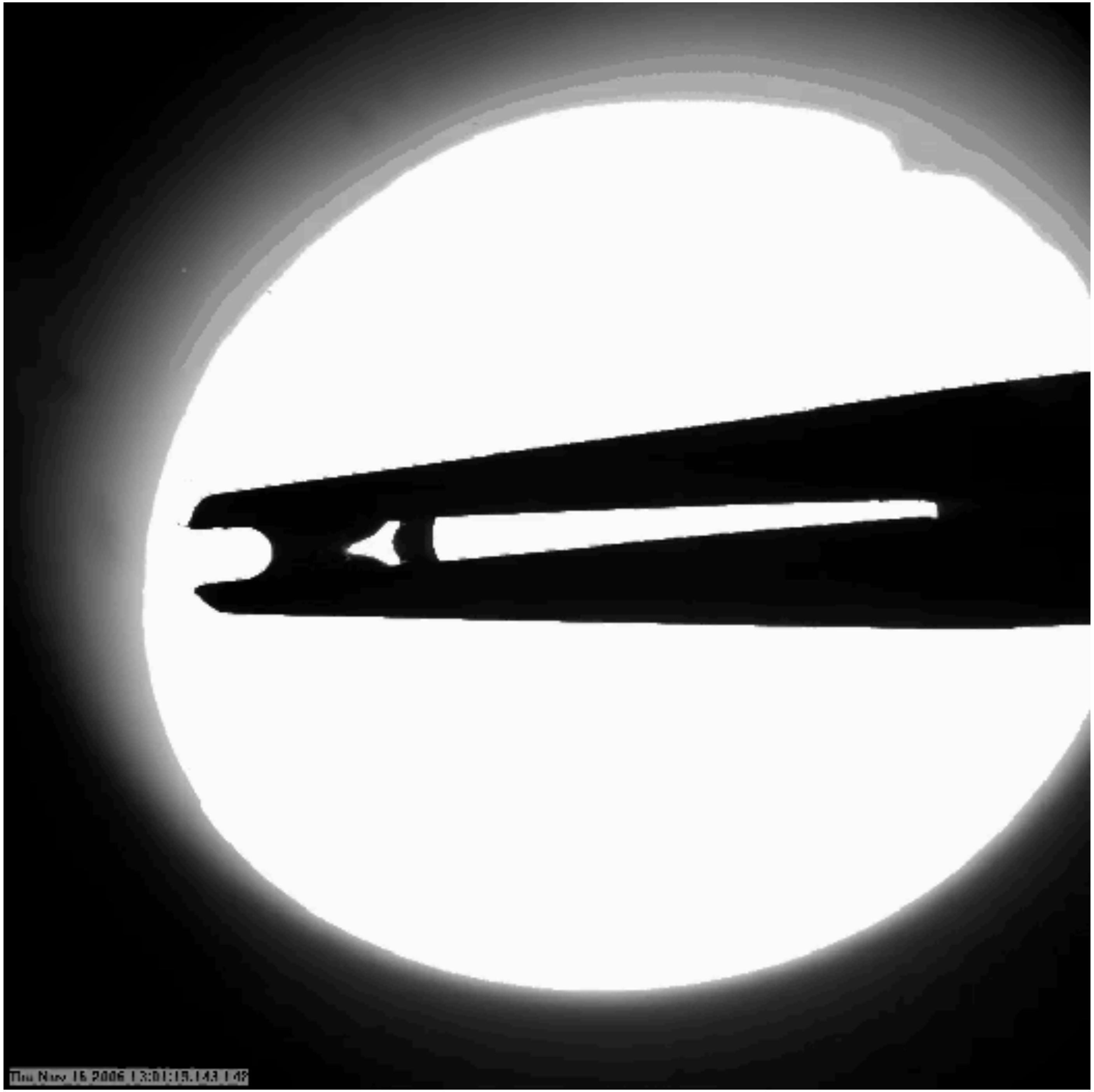
α_1^R at which $\theta_1 = \theta_R$



Tuning the capillary ratchet

- fix drop volume





- the bird beak regime: 2-3 cycles per feeding event

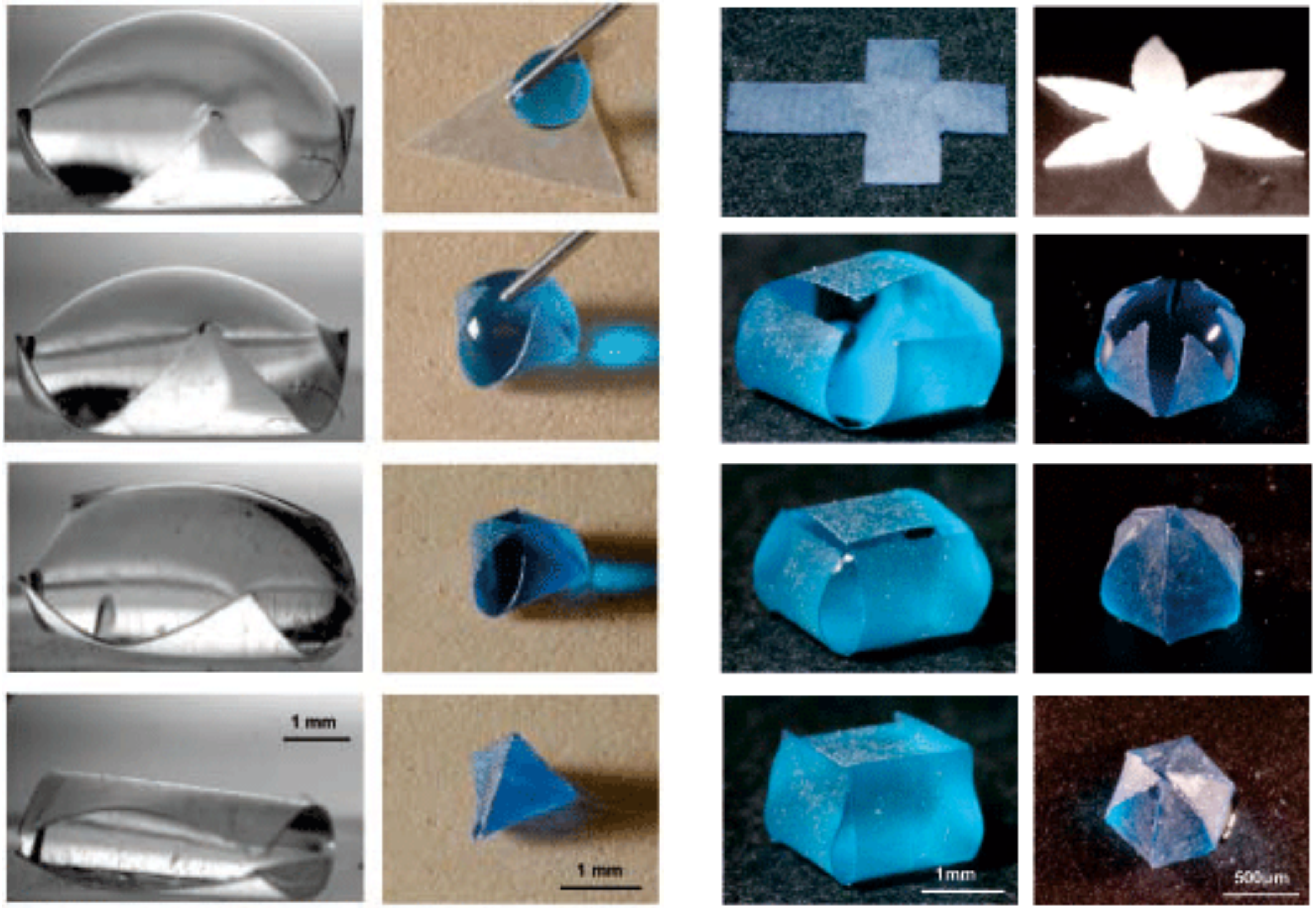
Big picture

- wetting properties of beaks important to shorebirds: effect of oil spills?
- σ - dominated flows to be more prevalent at smaller scales
- similar mechanisms bound to exist in the insect world or elsewhere
- contact angle hysteresis coupled with geometry can drive motion
    - applications: discrete fluid transport in microfluidic devices

Capillary Origami: folding of elastic sheets with surface tension

Py, Reverdy, Roman, Bico, Baroud (2007)

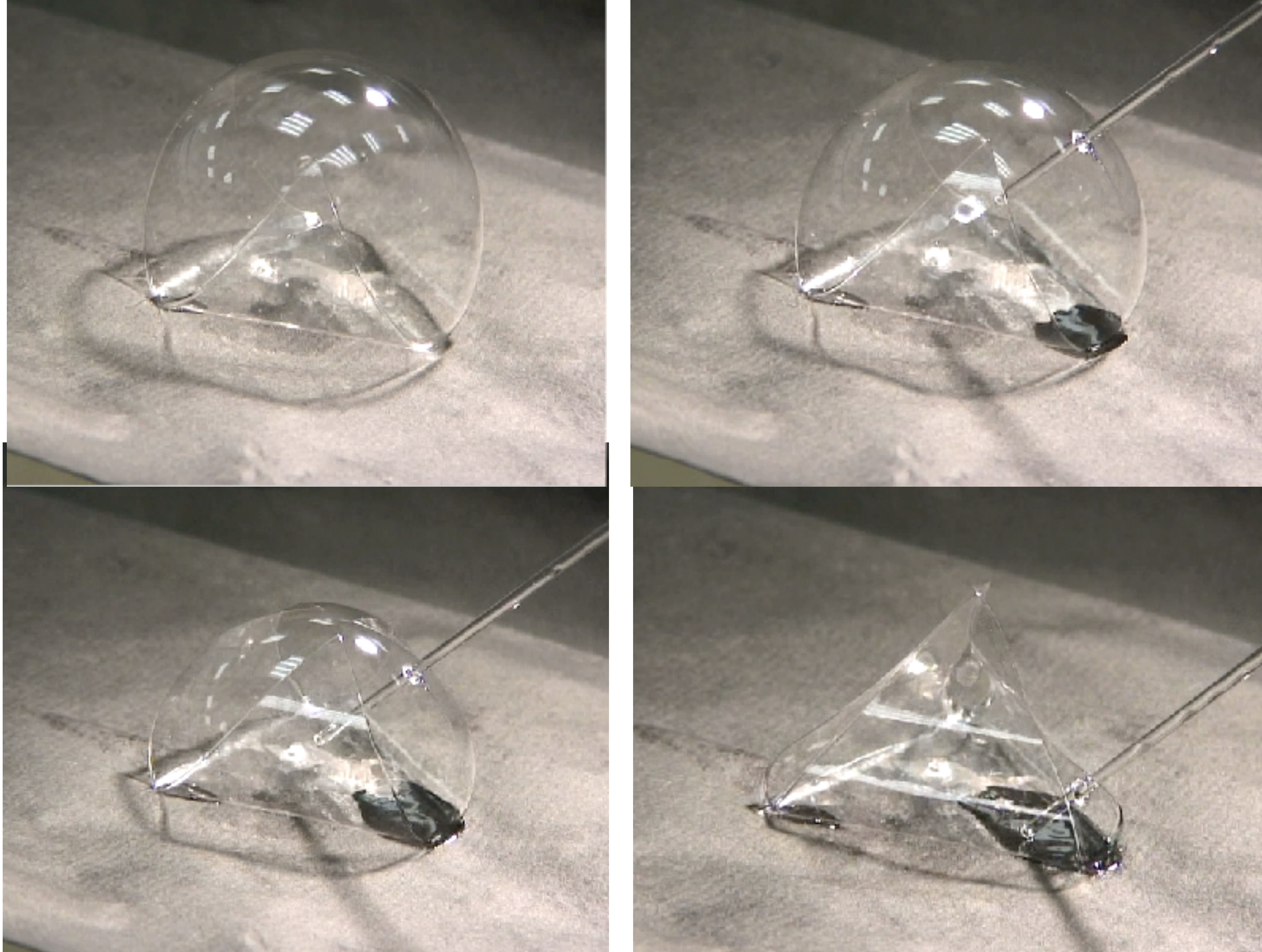
Capillary Origami: folding of elastic sheets with surface tension



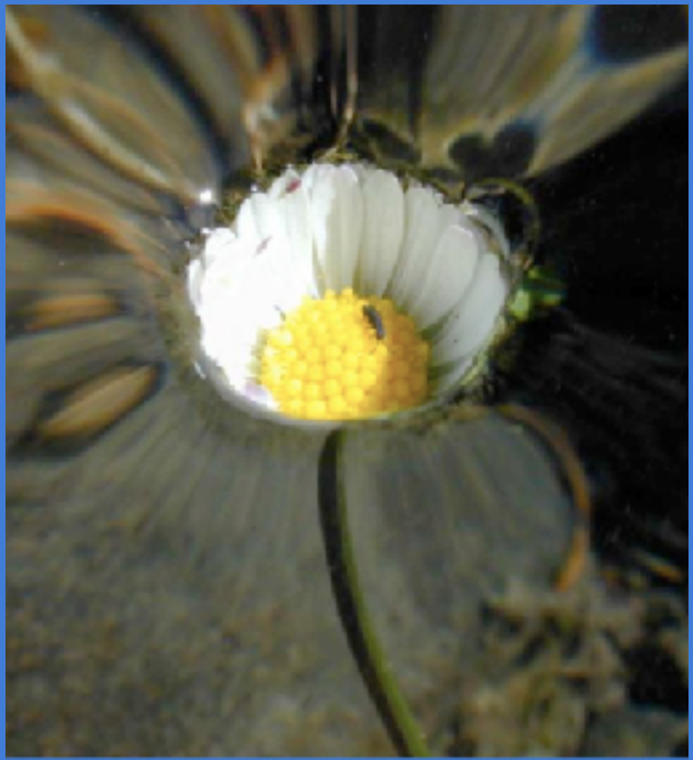
Elastocapillary length:

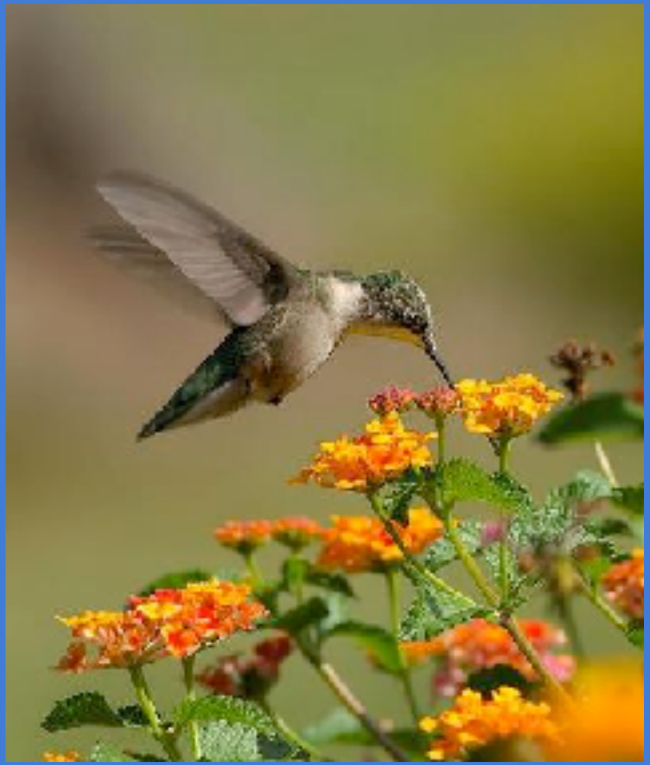
$$\ell_{EC} \sim \left(\frac{Eh^3}{\sigma}\right)^{1/2}$$

Py et al. (2007)



Capillary origami in nature





1. The folding of floating flowers

   - with Pedro Reis, Sunny Jung and Christophe Clanet

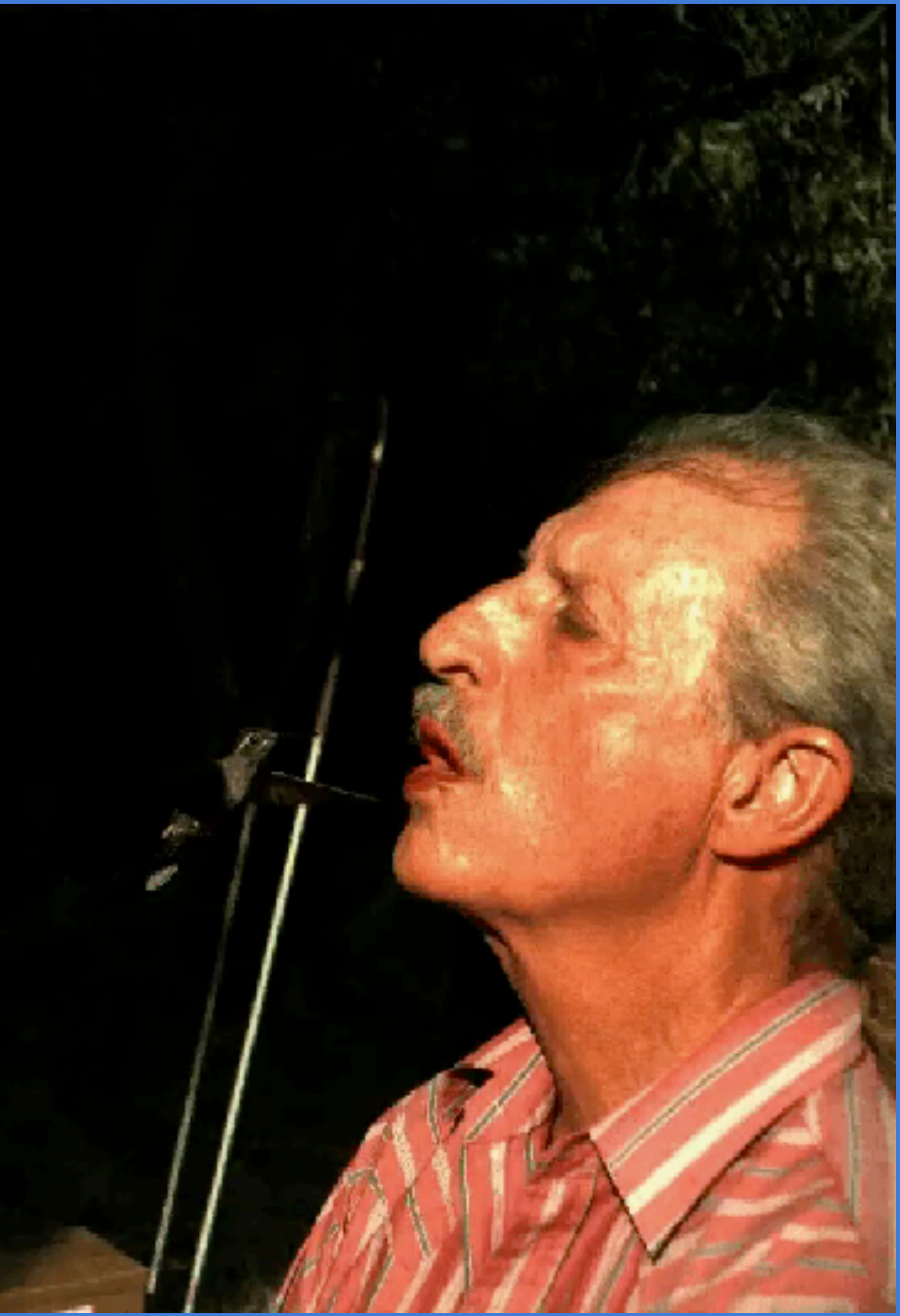
2. Spider capture thread: form and function

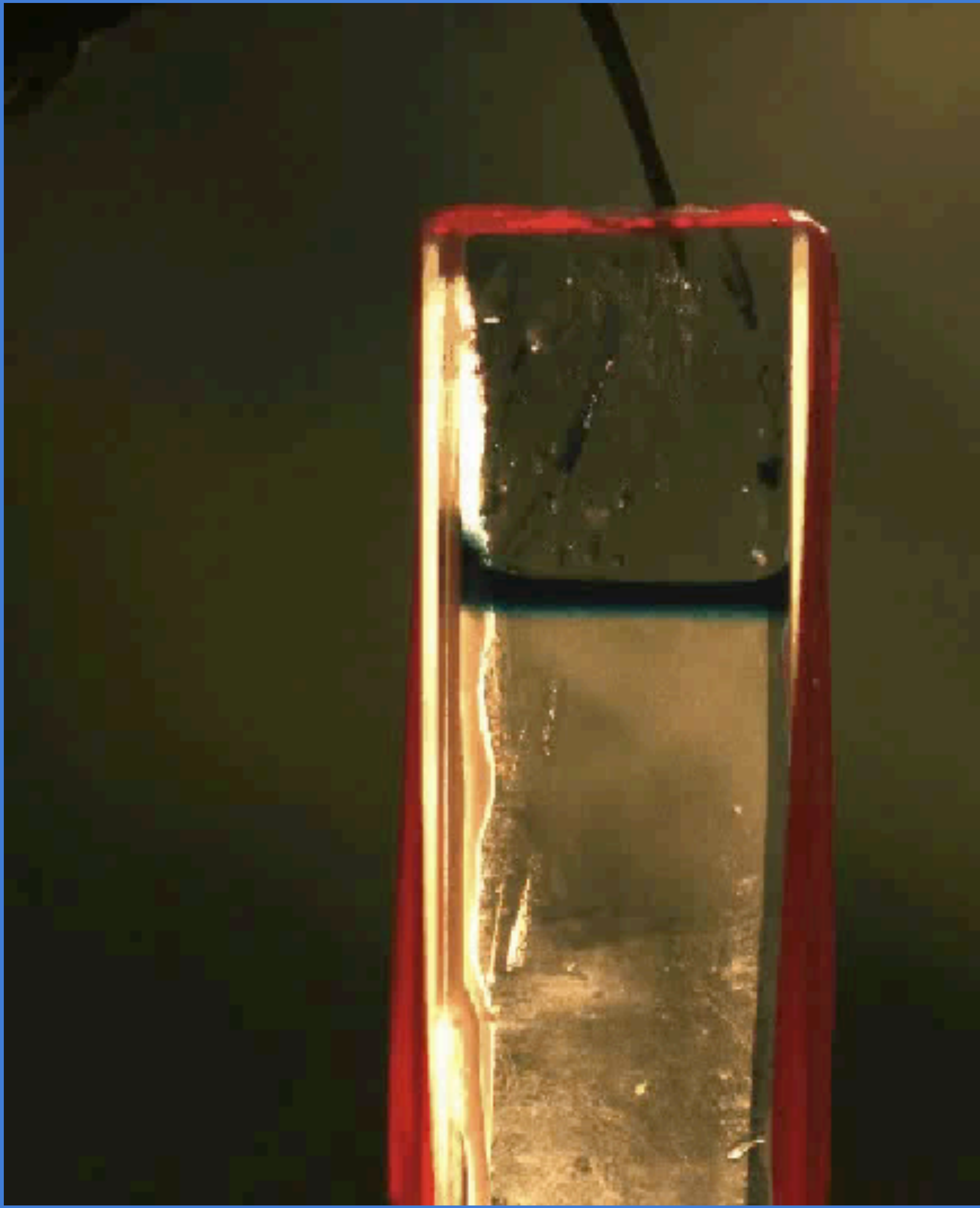
   - with Sunny Jung and Christophe Clanet

3. The tongue of the hummingbird

   - Wonjung Kim's course project

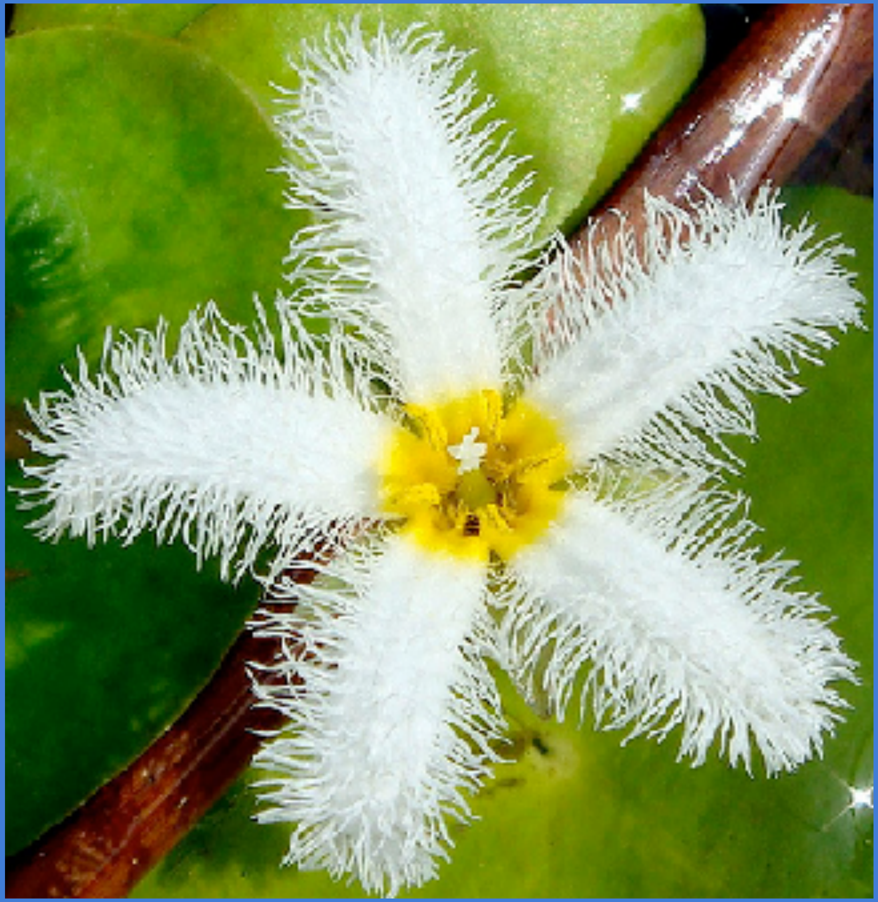
Capillary feeding by the hummingbird





Floating flowers

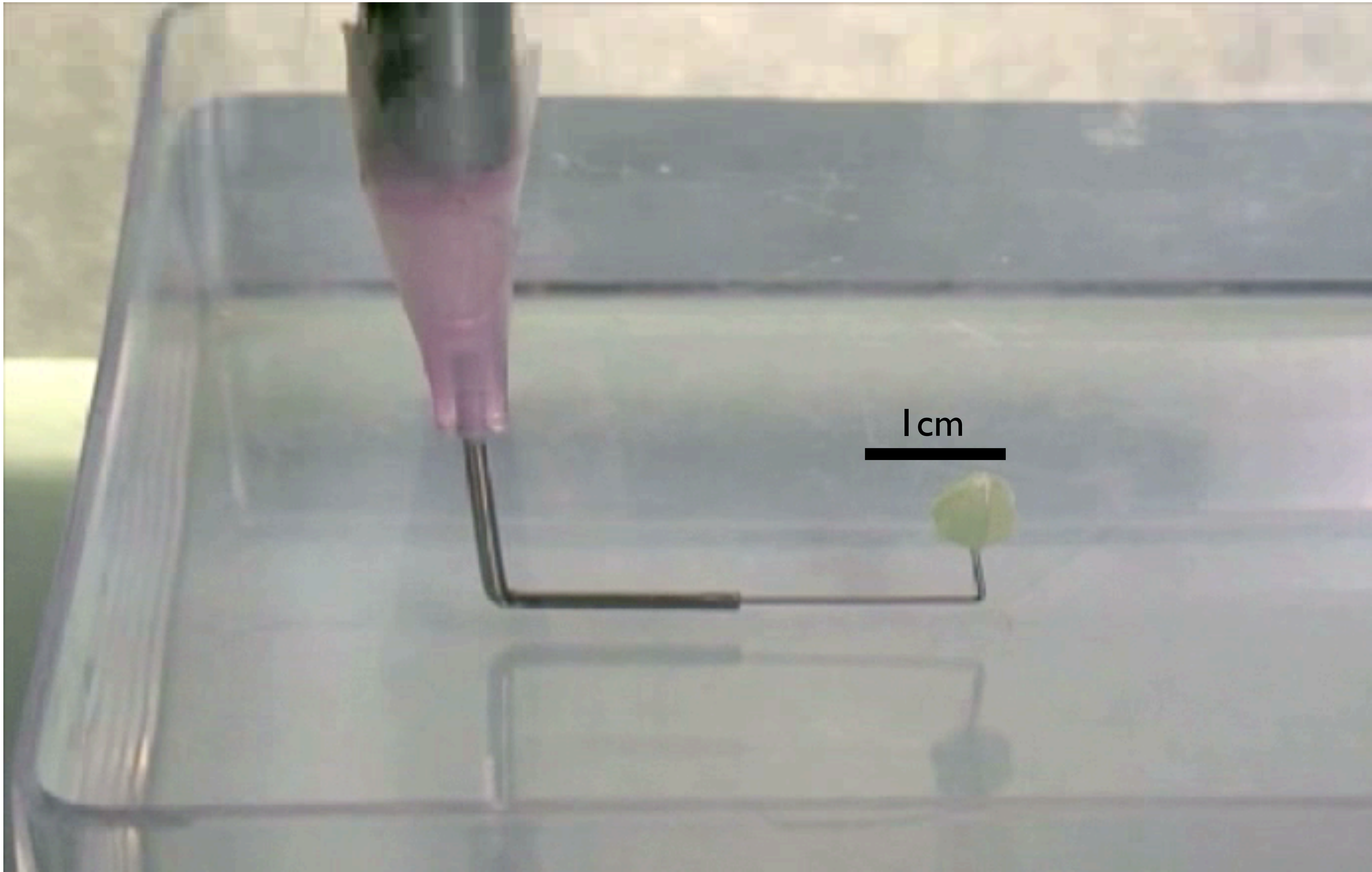
- some anchored flowers avoid flooding by folding



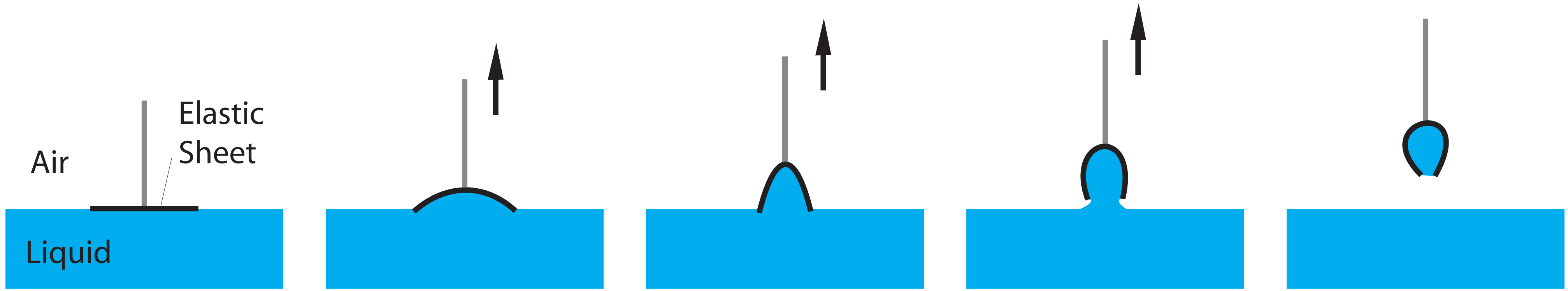
Menyanthaceae
Armstrong, Americ. J. of Bot. (2002)

3D polymer flowers:

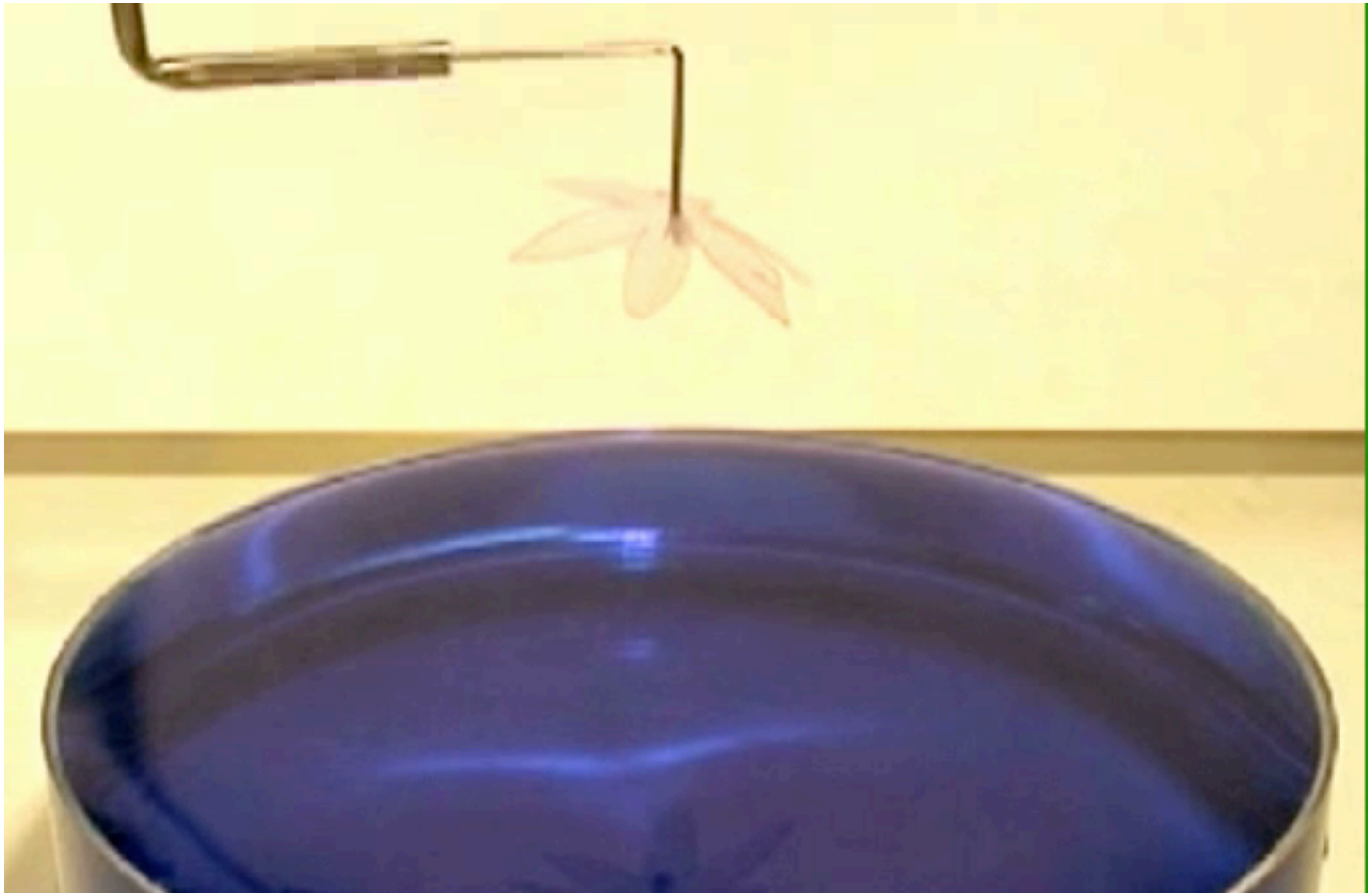
Vinylpolysiloxane (similar to PDMS)
thickness ~ 250µm
size ~ 10mm



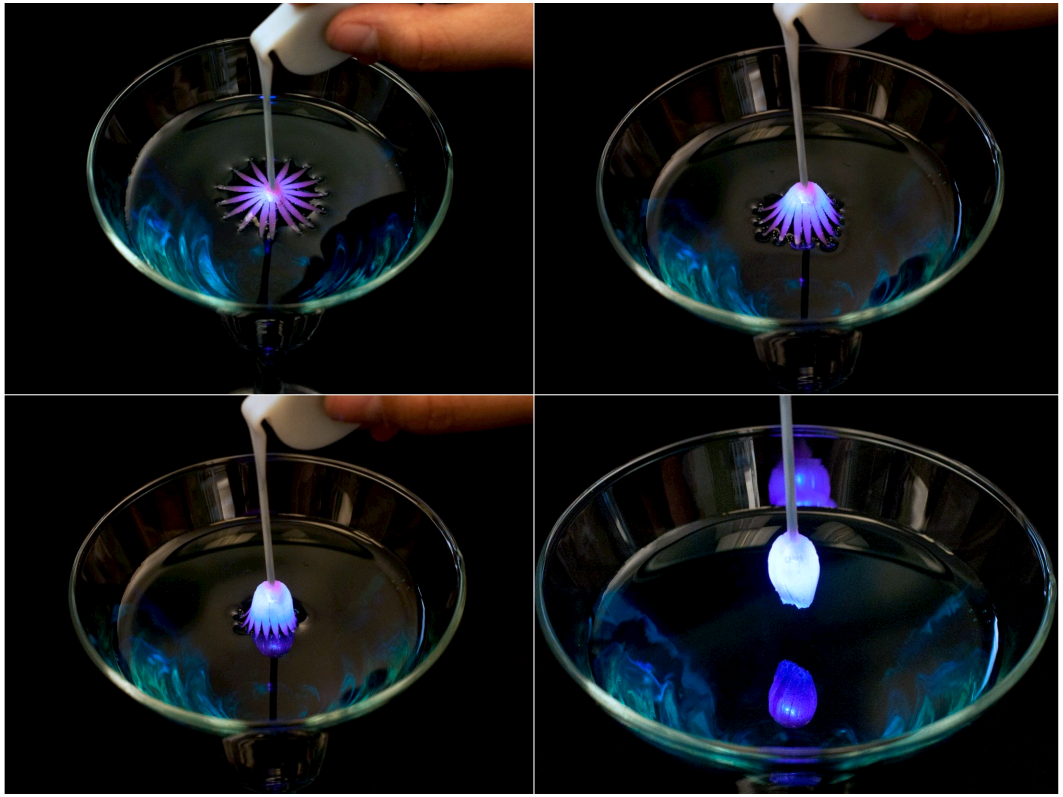
The elastocapillary pipette: grabbing fluid at the interface



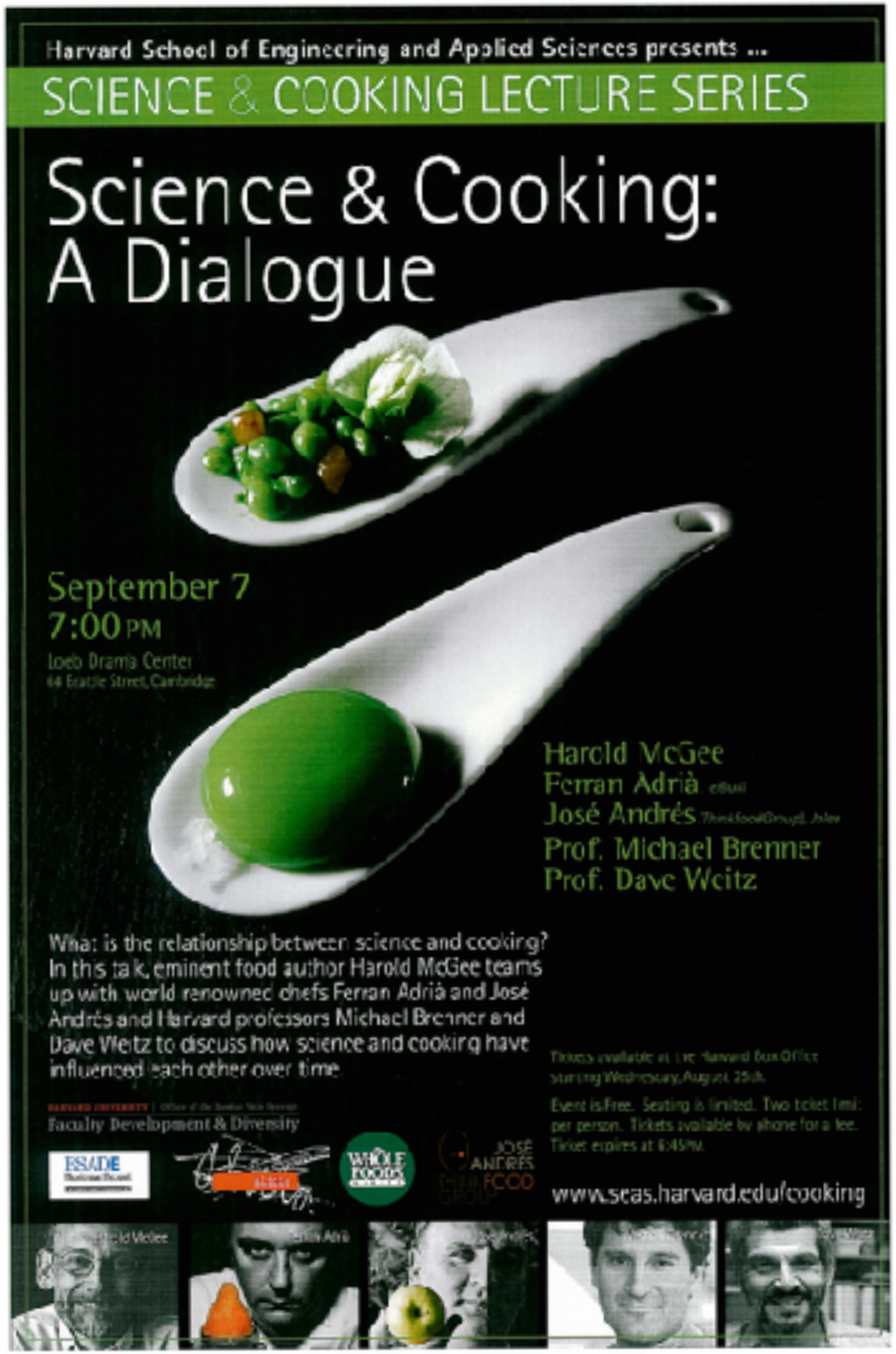
Is this mechanism used somewhere in nature for drinking?



The Floral Pipette



- implemented with Jose Andres' ThinkFood Group for use in Minibar
- flowers used to serve small volumes of palette-cleansing liqueurs
- flowers composed of edible, flavored gels



Jose Andres, ThinkFood Group

World Central Kitchen

“ I was stunned by the perfection of the insects.”

\- Pablo Neruda