

*Capturing Liquid Motion
the Art & Science
of
Freezing Time*

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**Public Lecture
Boulder Summer School
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imagine

a

faucet

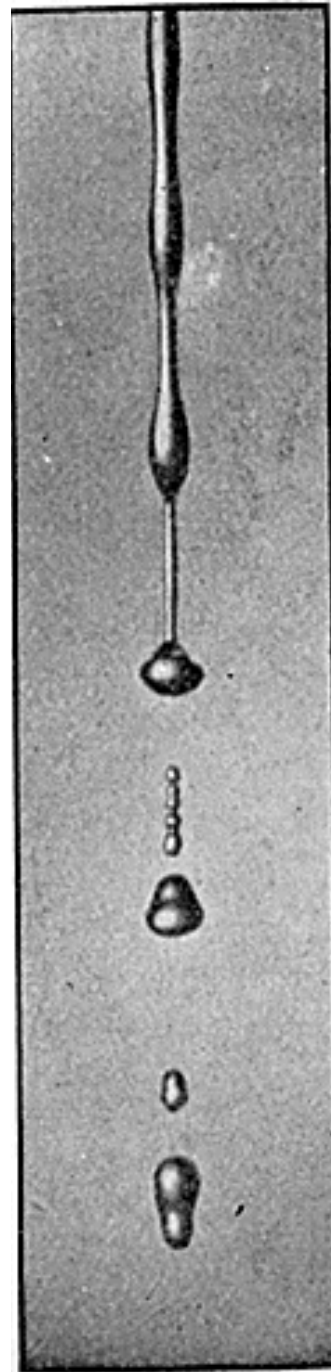
*Dripping faucet
as seen by the naked eye*

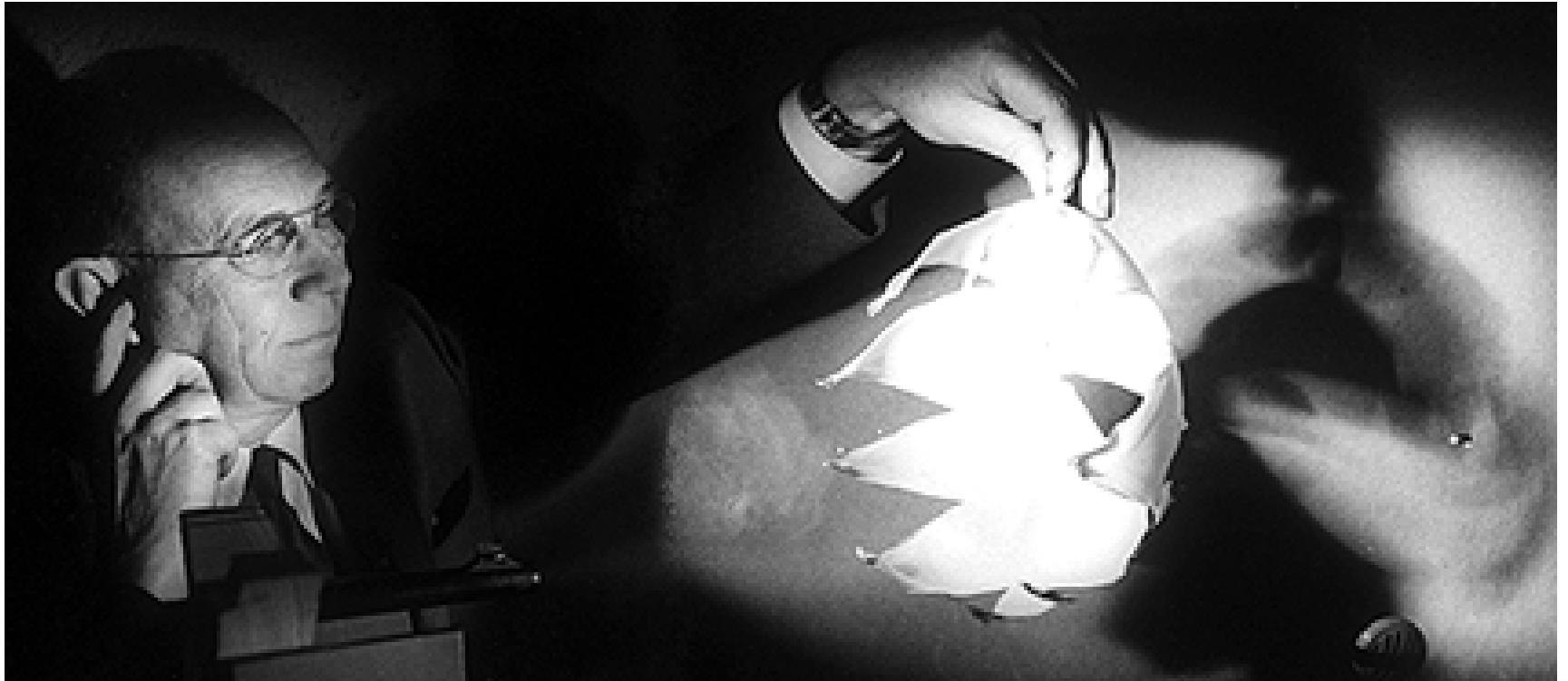


*Water stream
breaking up into
droplets*

*1890's
Lord Rayleigh*

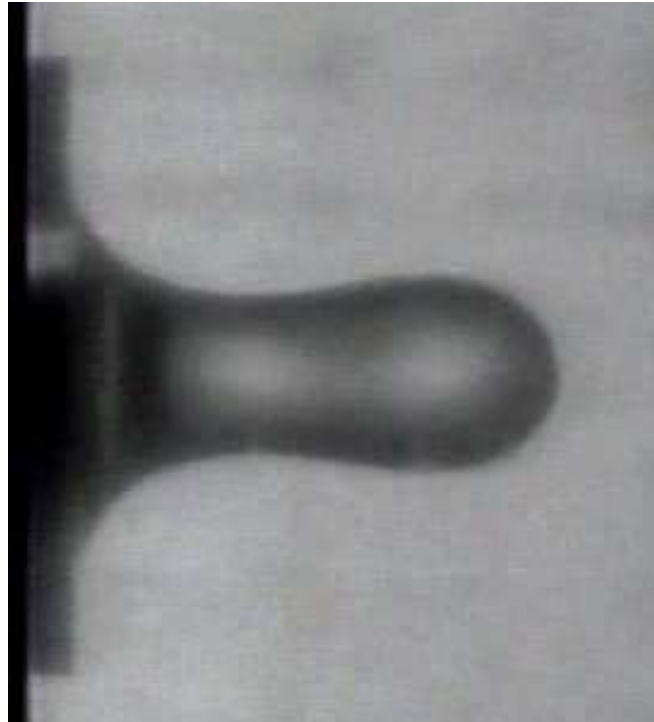
electric spark





Harold Edgerton, M.I.T.
Self Portrait with Balloon and Bullet
1957

*A water drop falling from a nozzle
30 s of video time = 3/100th of a second*



up \longrightarrow down

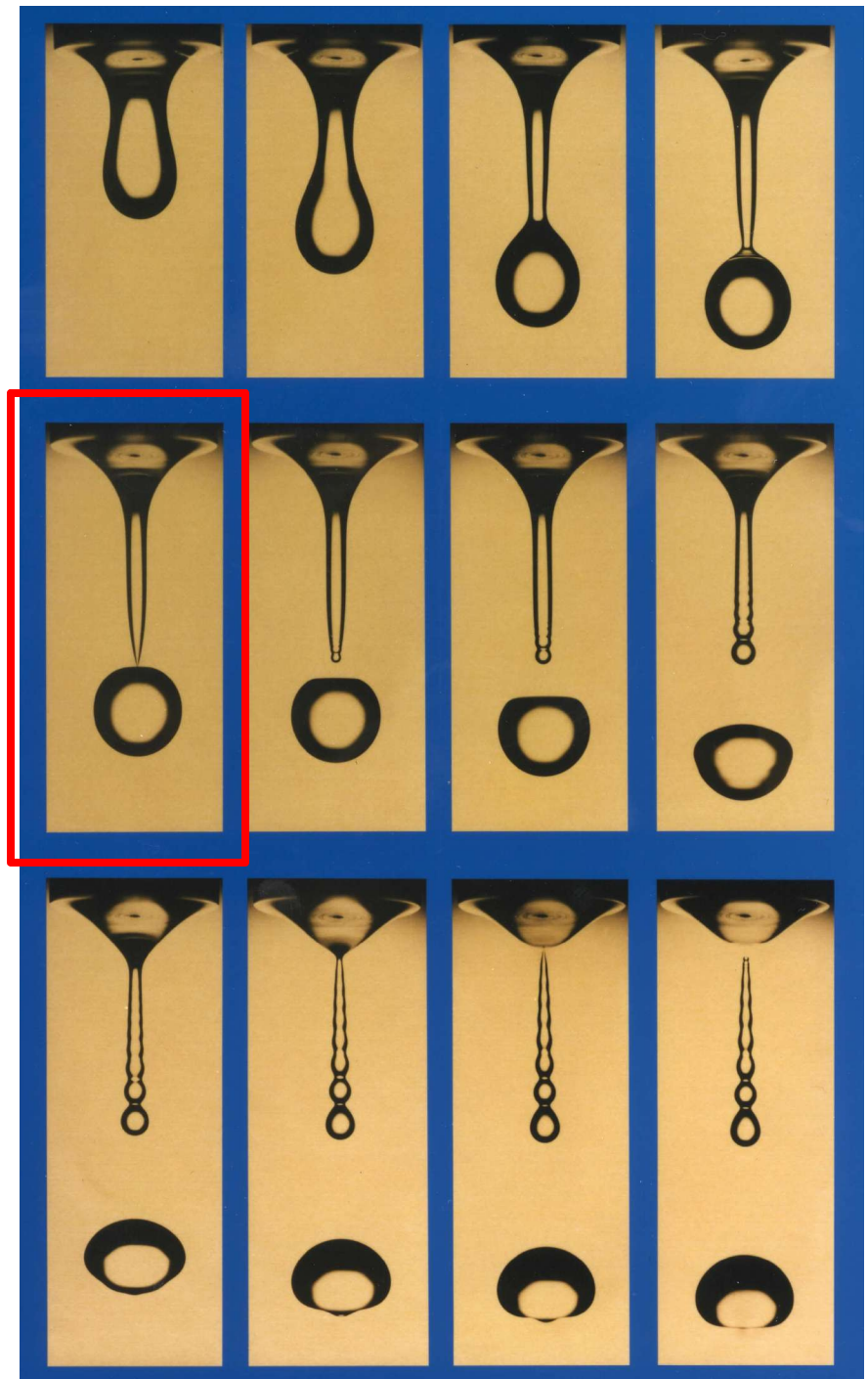
Shi & Nagel
1994

*One drip
of
a water drop*

*sharpens to a
point*

*entire sequence
= 3/100th second*

Shi & Nagel
1994



Surface tension
the elastic skin of water

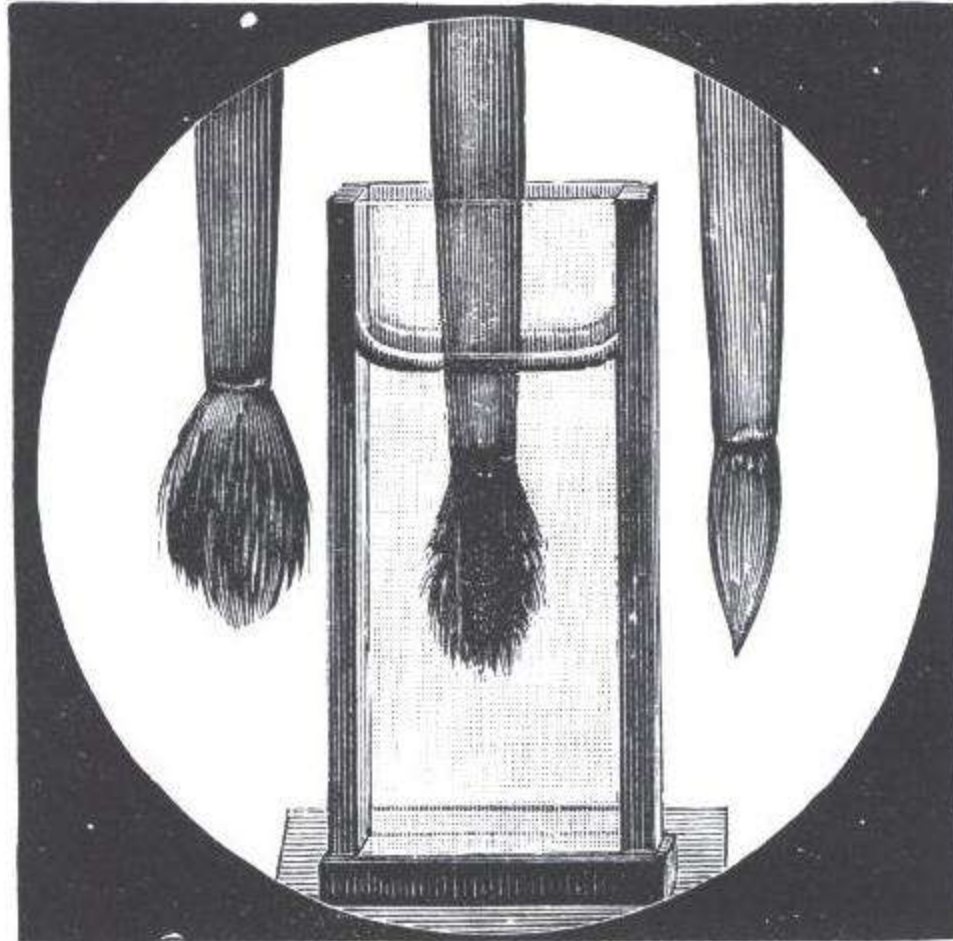
A small insect can stand, and even walk, on water because of surface tension.



Photo by Wilma Keidel

H. H. Dixon 1880's

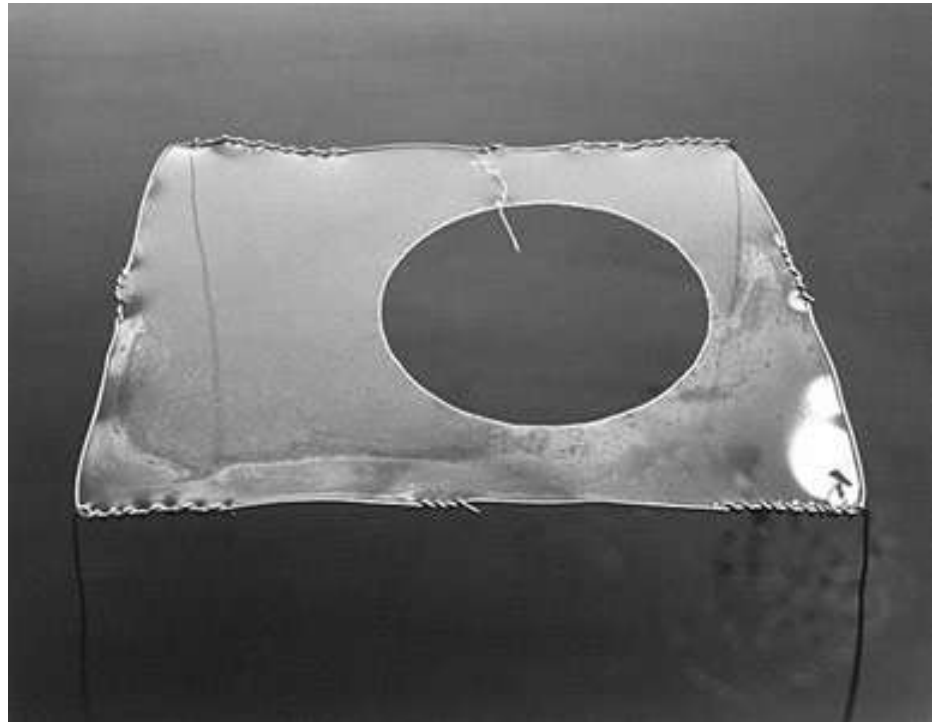
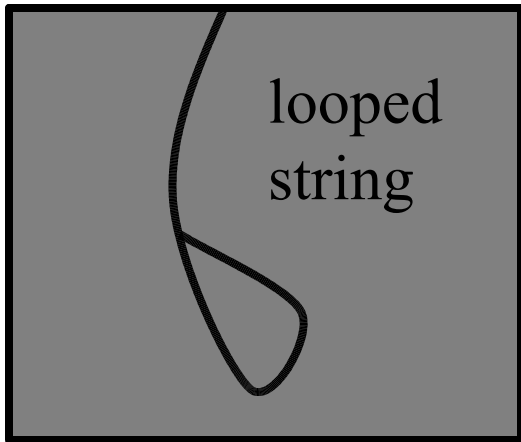
*Surface tension at the air-water surface
causes hairs of a wet brush to cling together*



C. V. Boys
1895

*Surface tension pulls an opening
into a perfect circle*

soap film
on wire frame



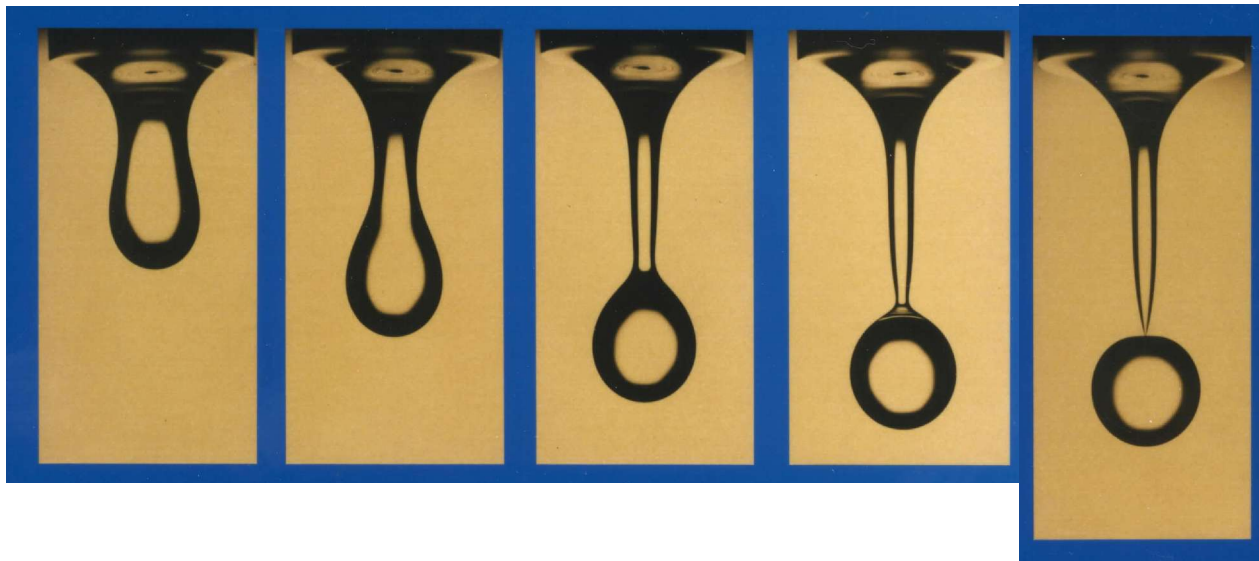
David Goldes *Soap & Water*
Yossi Milo Gallery, 2004

*Surface tension acts to makes
the space enclosed as large as possible
and
the space outside of it as small as possible*

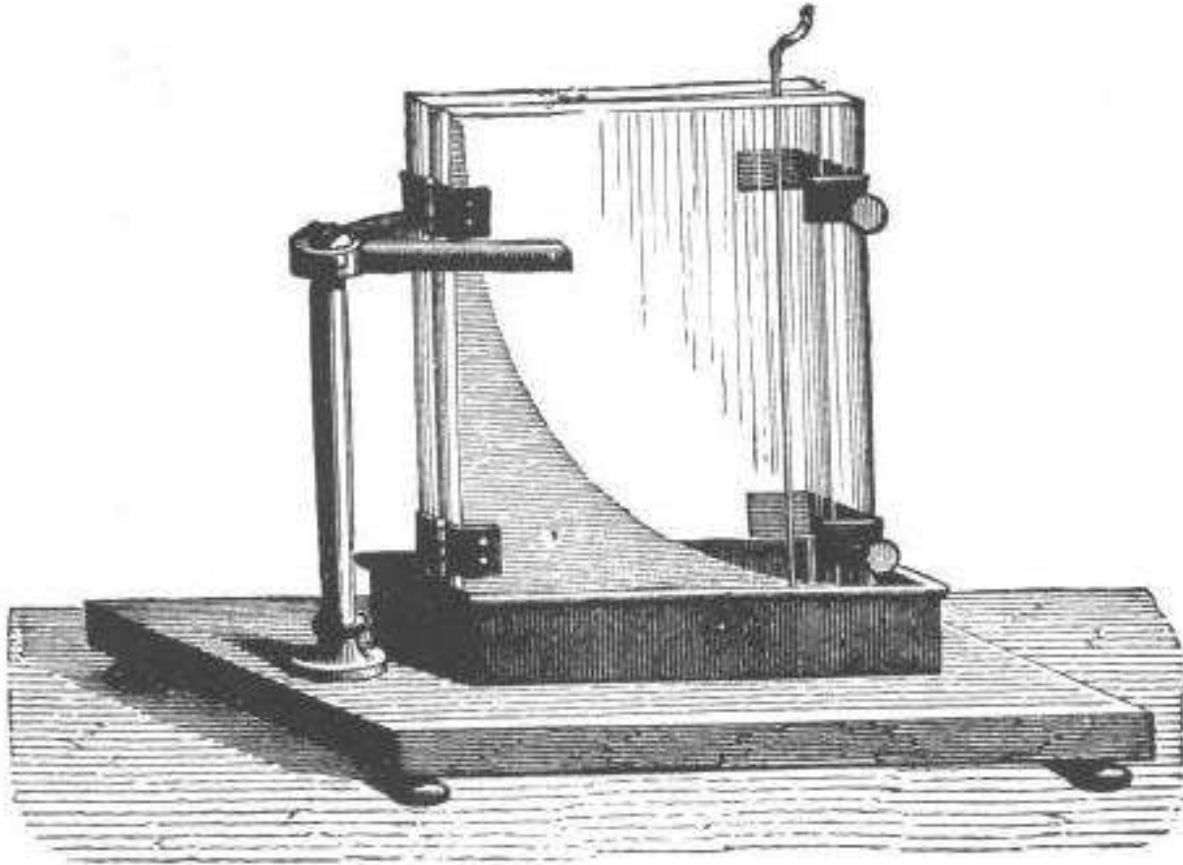


Surface tension causes drop to fall

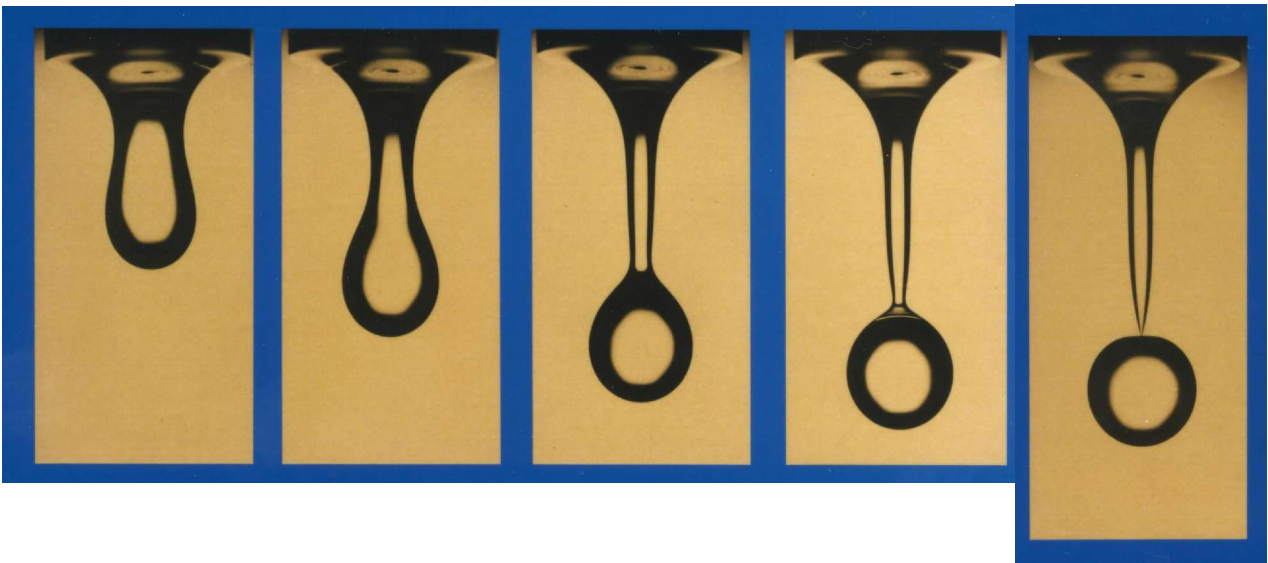
Why does the neck sharpen to a point?



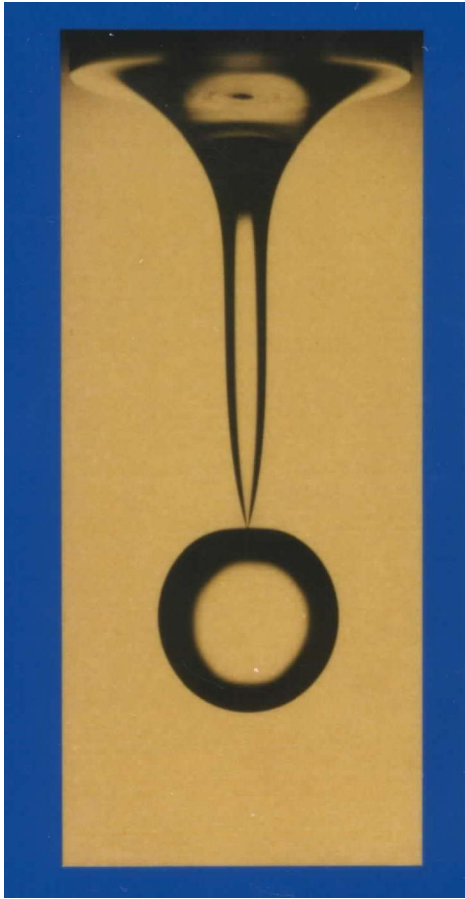
Surface tension pulls liquid in a narrow gap upwards against its own weight



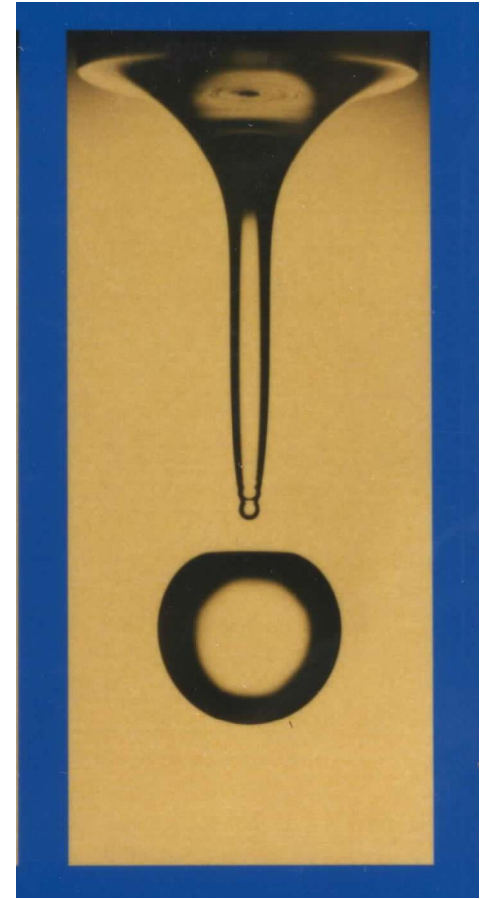
Force grows unbounded as gap narrows



**S
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?**



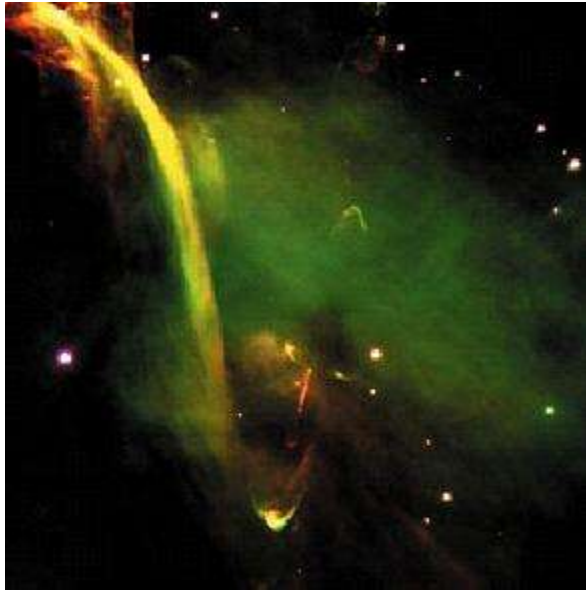
S
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Matter is made up of molecules

Singularity formation in other contexts

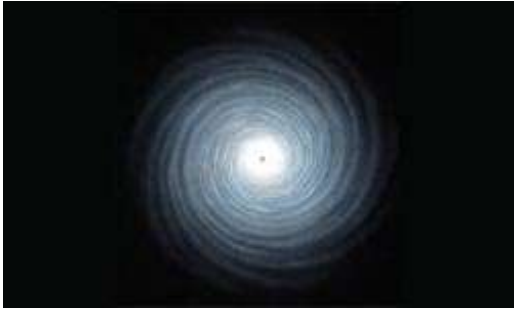
collapse of giant molecular
cloud into a protostar



formation of a black hole
due to gravitational collapse



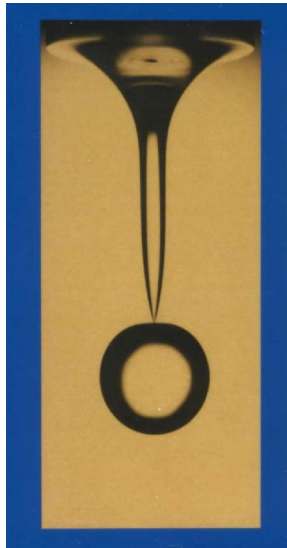
Black hole: information loss paradox



*Does the universe lose
all information about
what fell into a black hole?*

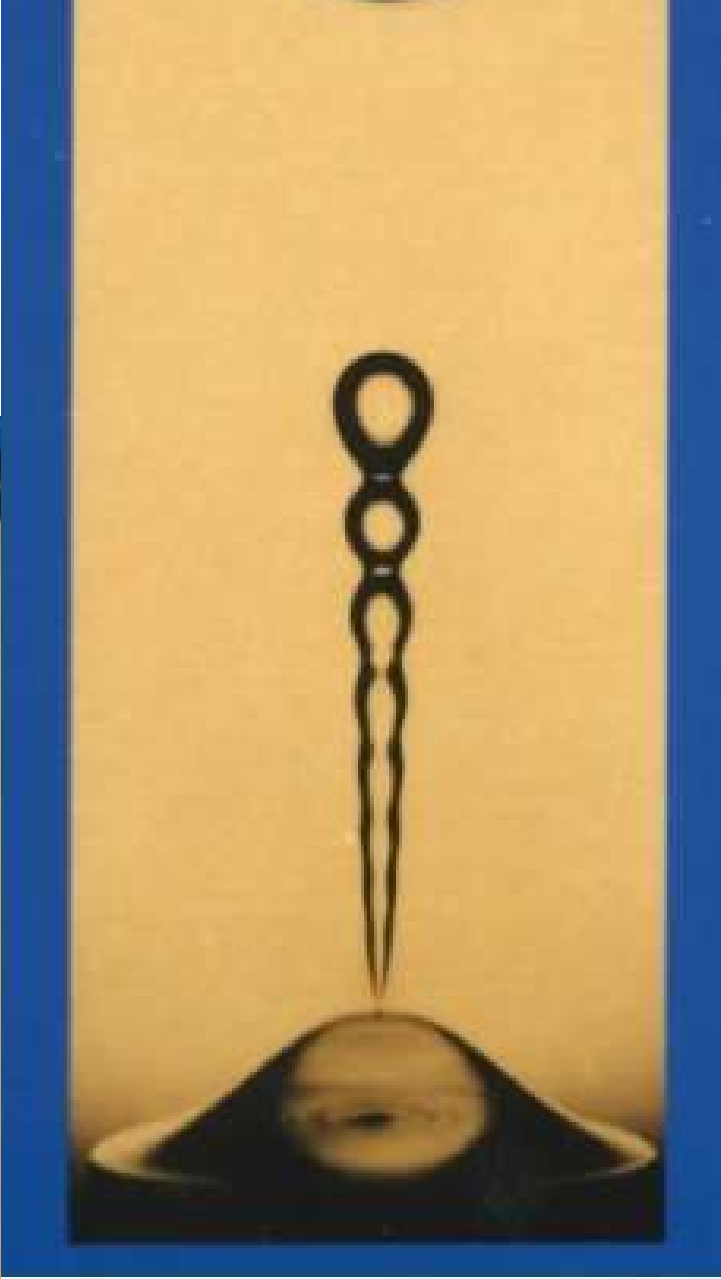
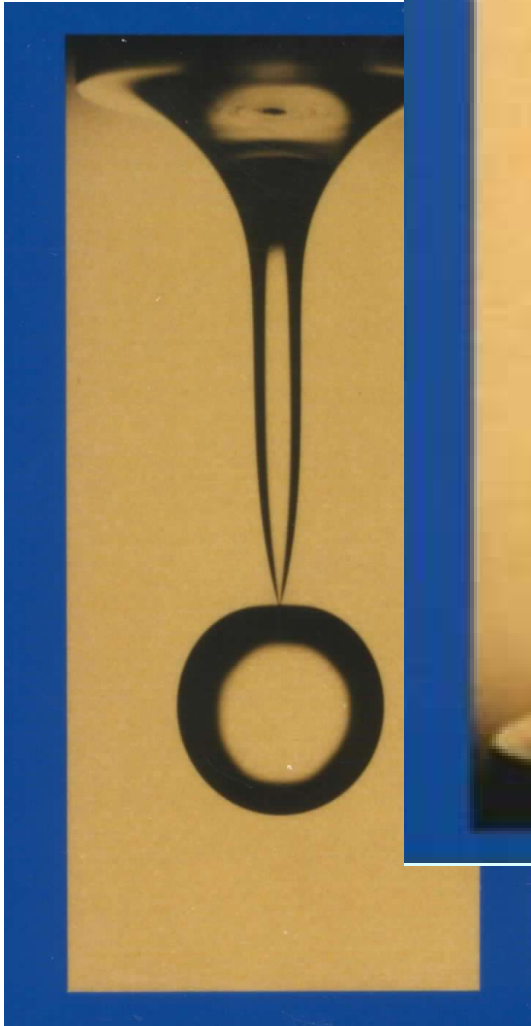
What is remembered?

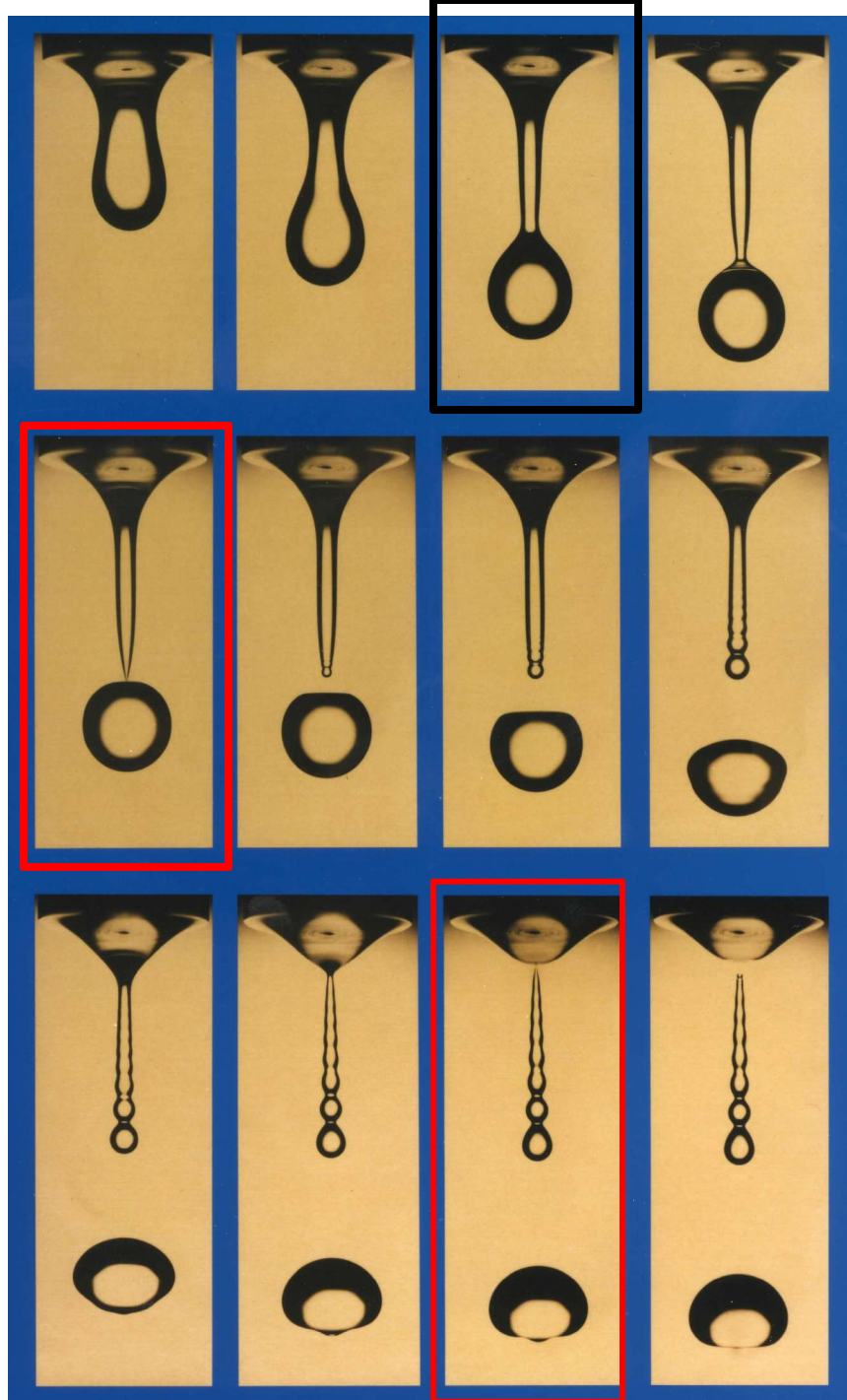
Drop Break-Up: Memory vs Amnesia



*Does liquid motion
near break-up remember
how the break-up began?*

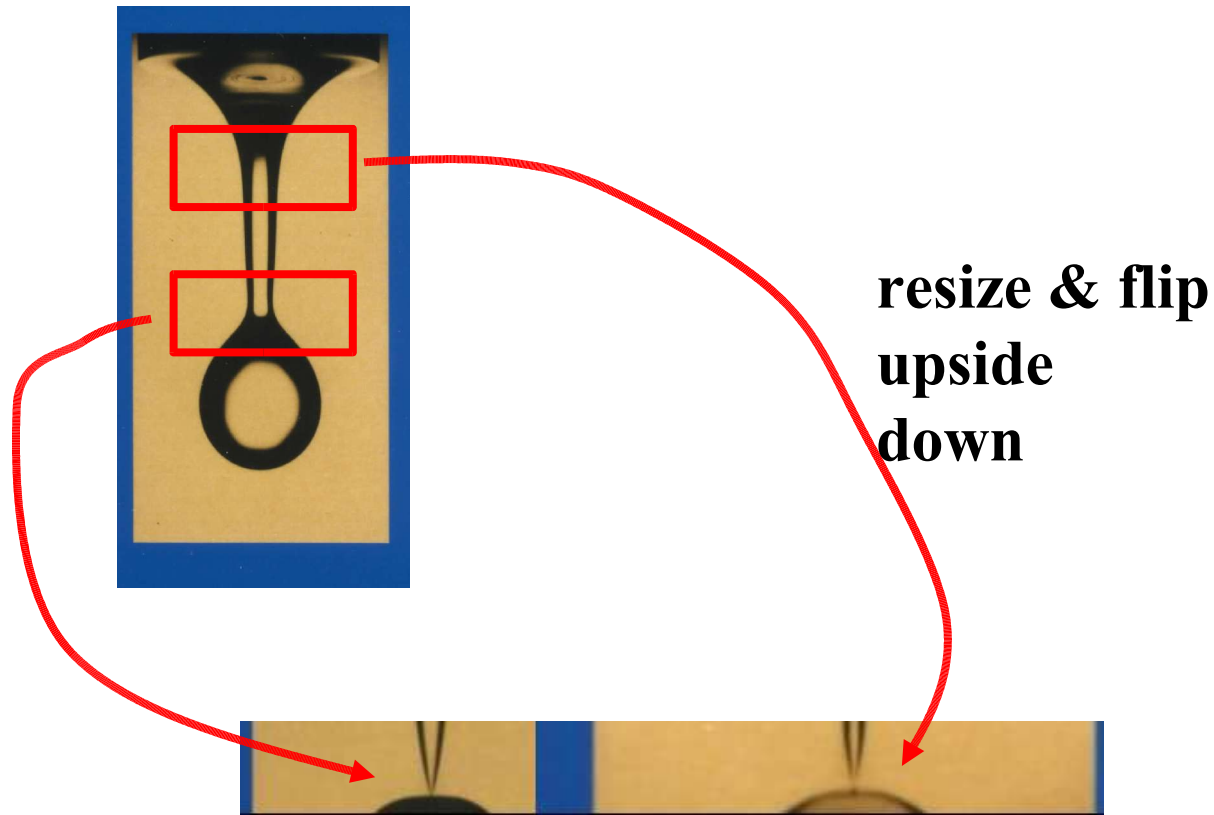






Amnesia in drop break-up

Different initial shape → Same break-up shape



No Memory

*Does break-up **always** forget its beginning?*

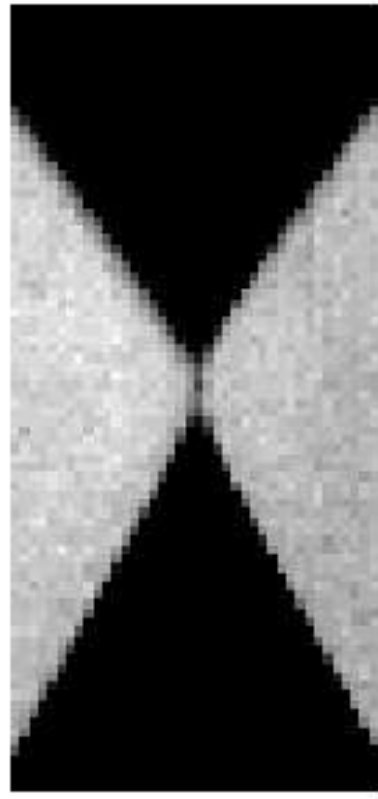
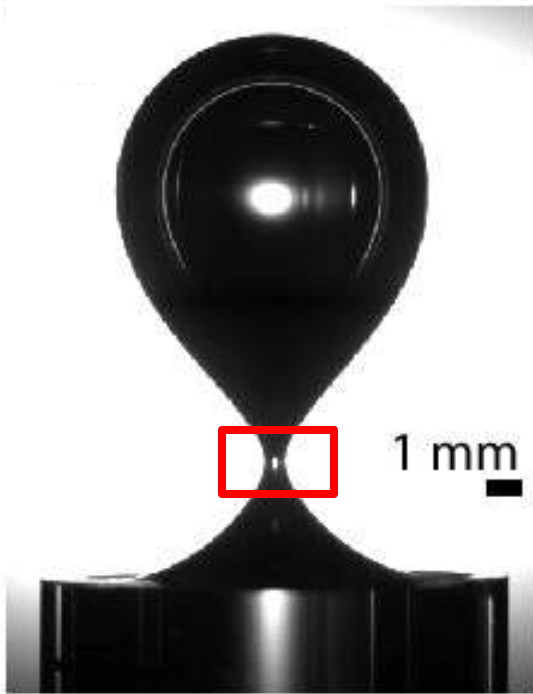
Turn singularity inside-out
Break-up of an air bubble in water



8 mm

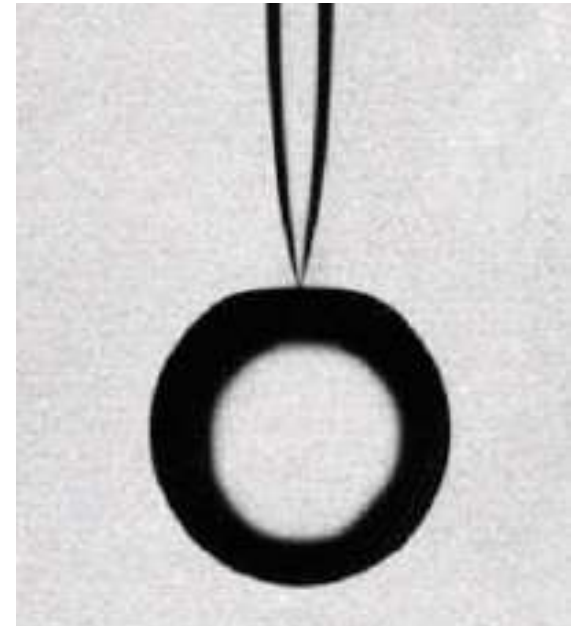
Keim & Nagel, 2005

A different singularity



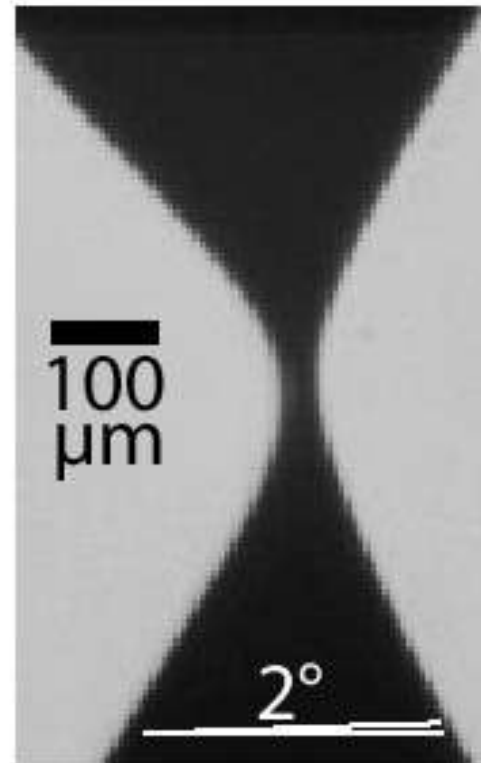
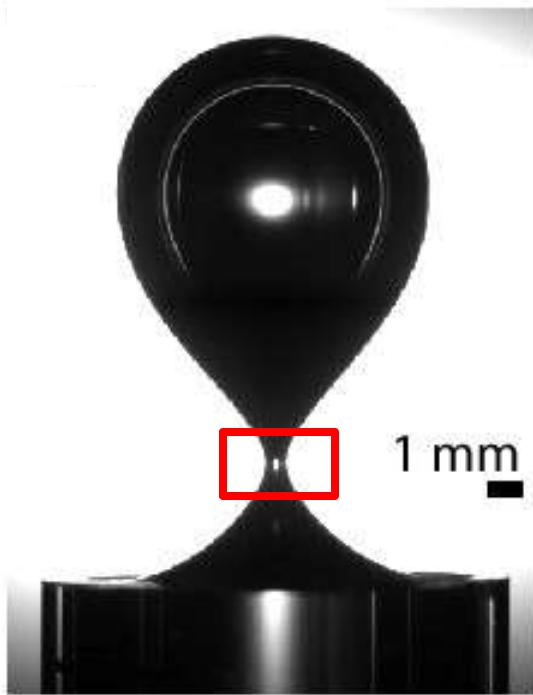
0.4 mm

air in water

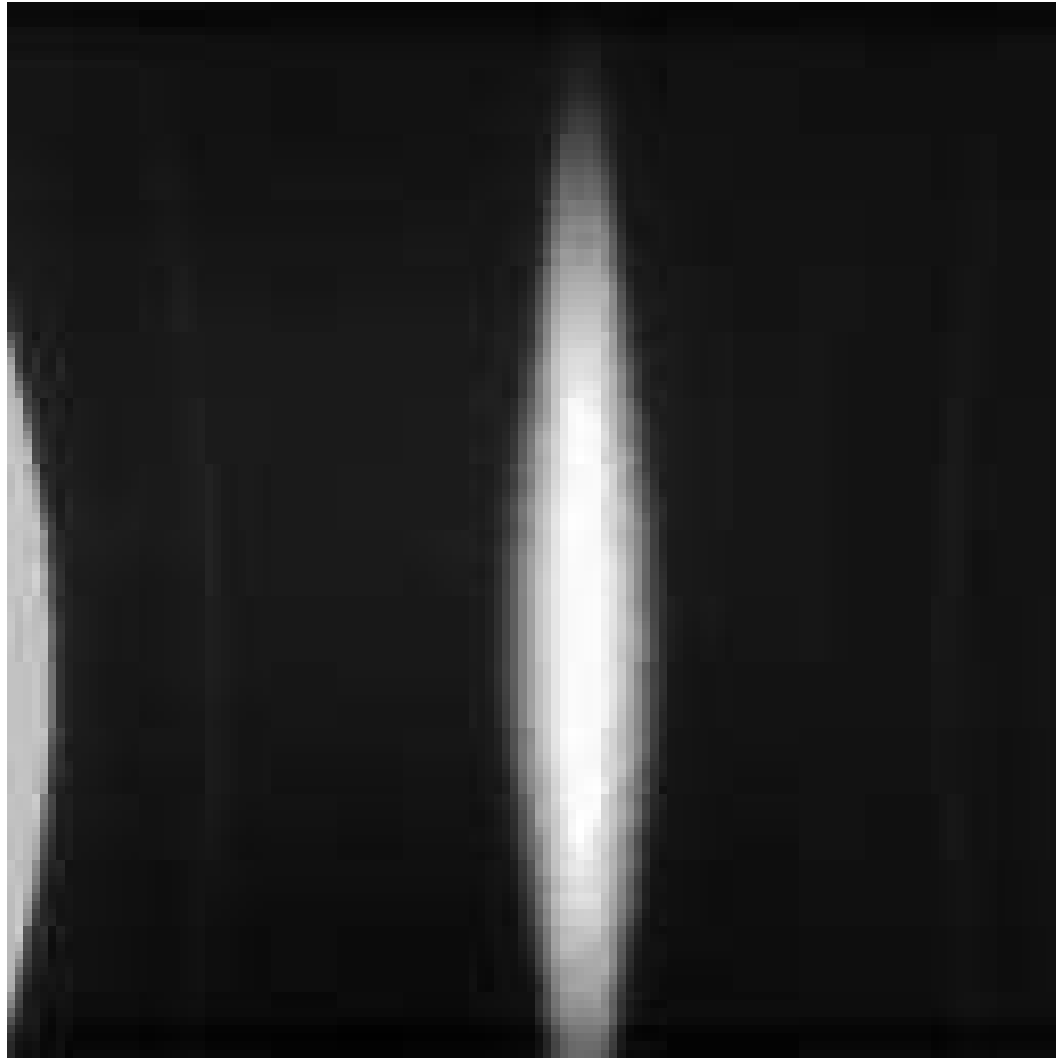


water in air

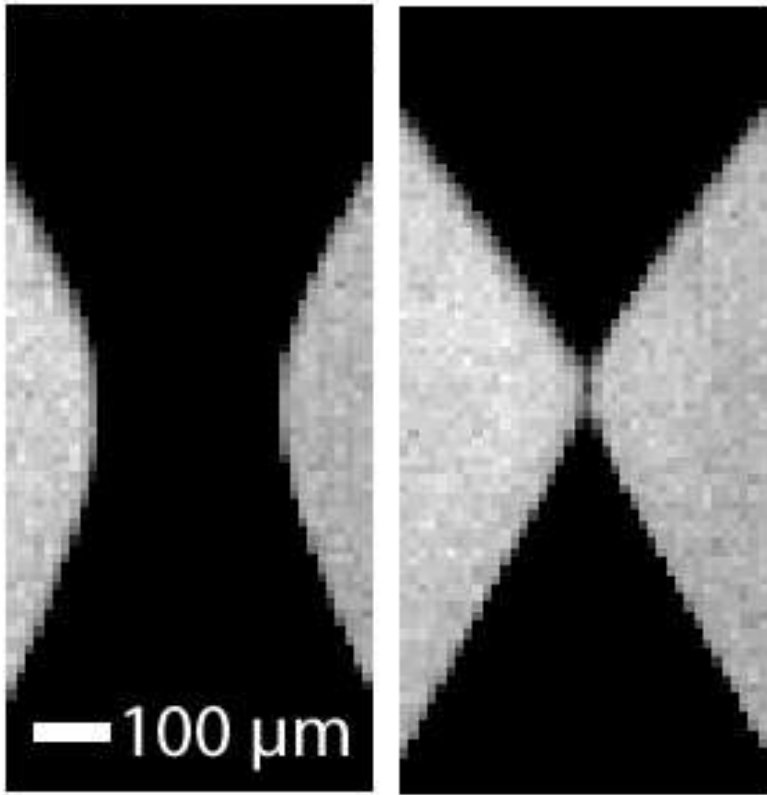
*A slight change in the initial shape
(tilt nozzle 2 degrees)*



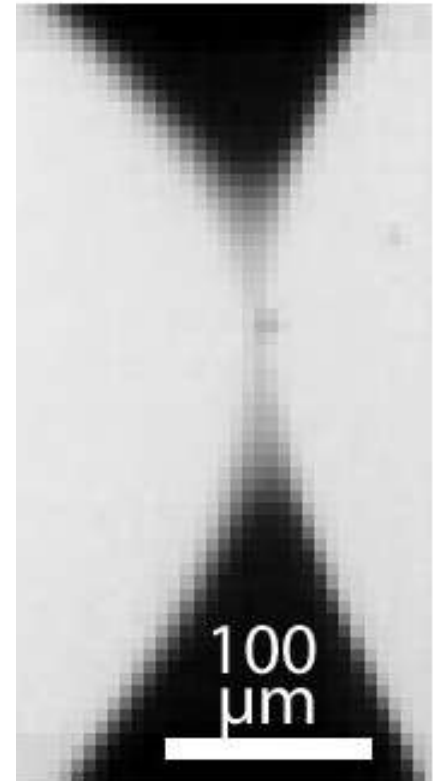
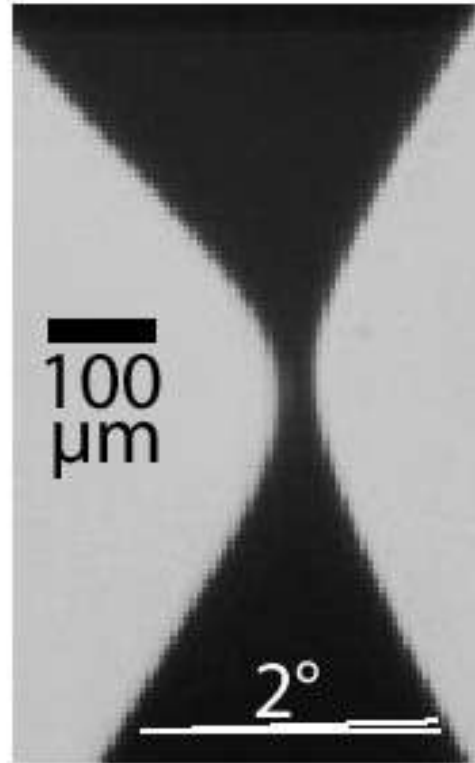
Bubble break-up from a tilted nozzle



*Memory in bubble break-up
slight changes in beginning are remembered*



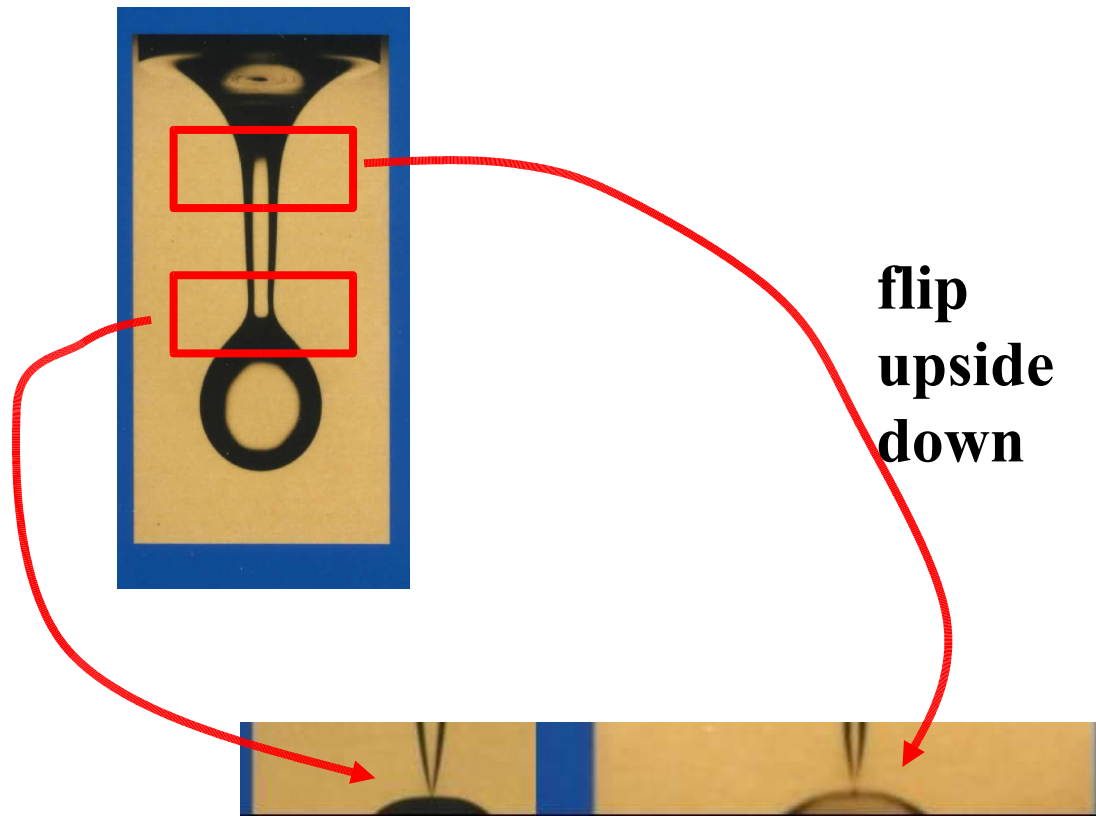
“level”



tilted

Amnesia in drop break-up

Different initial shape → Same break-up shape



No Memory

Two kinds of break-up singularities:

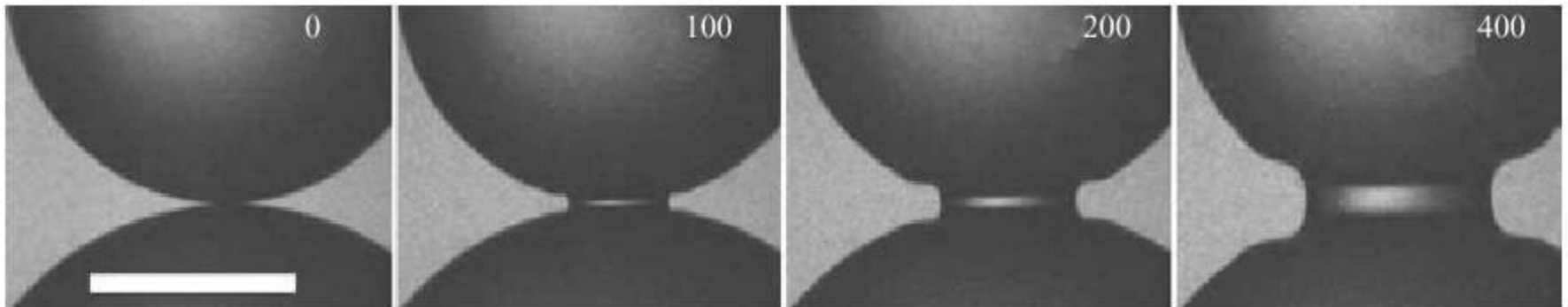
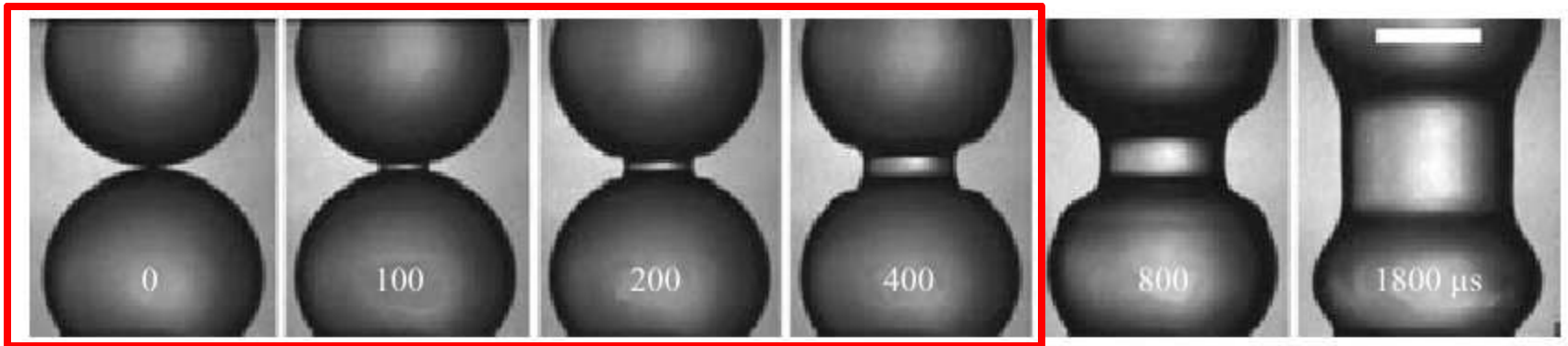
complete amnesia

“complete” memory

Every topology change on a liquid surface involves the formation of a singularity

Coalescence

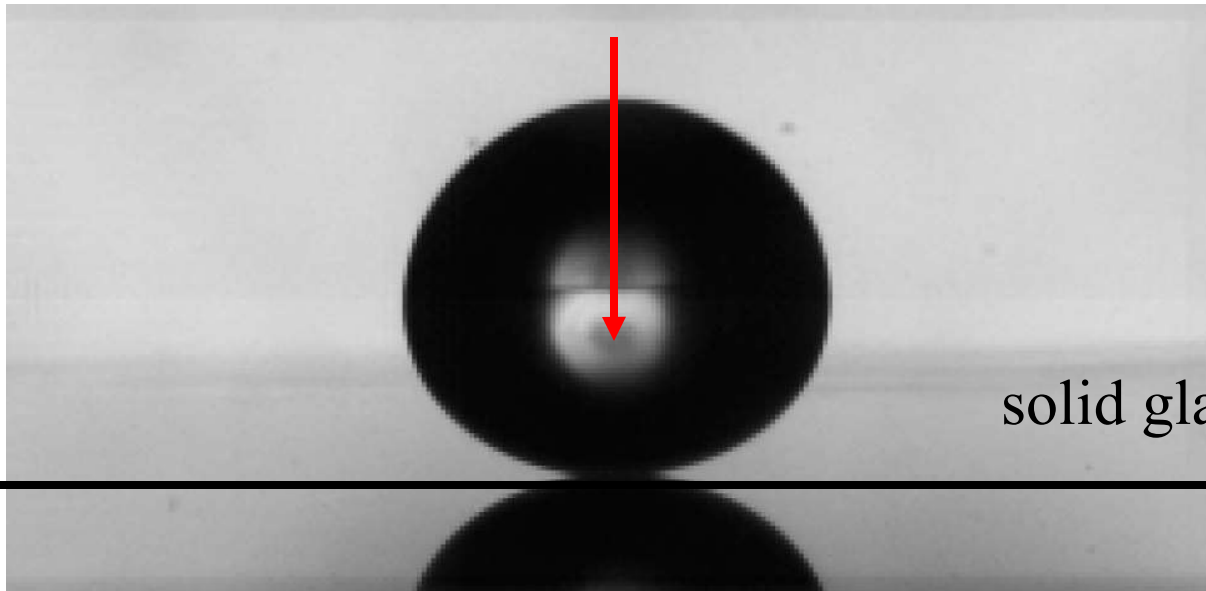
1 mm



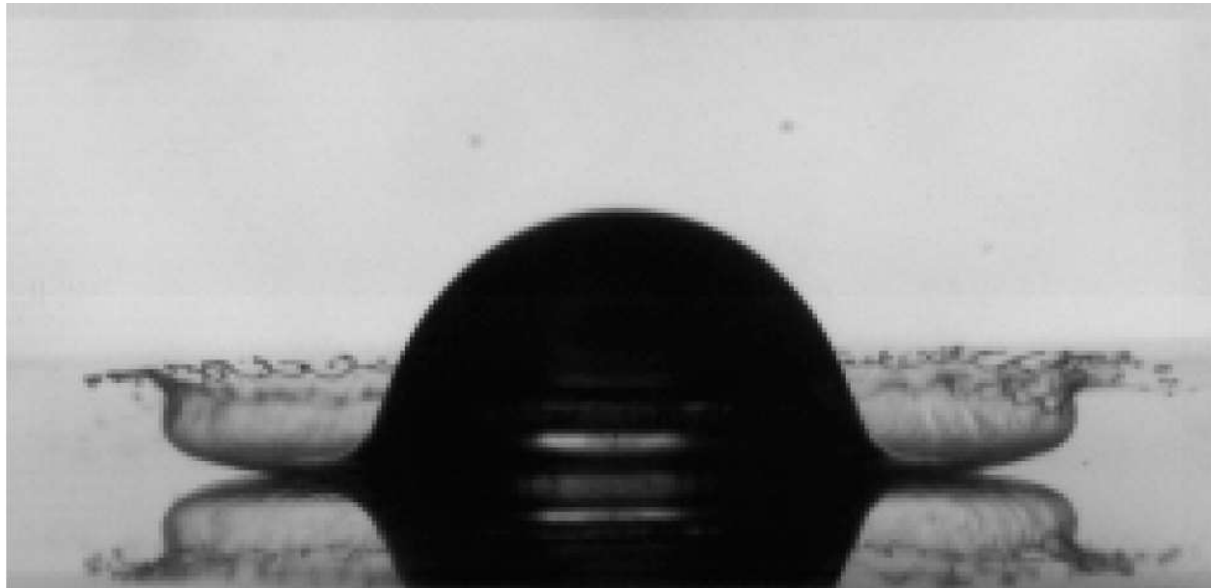
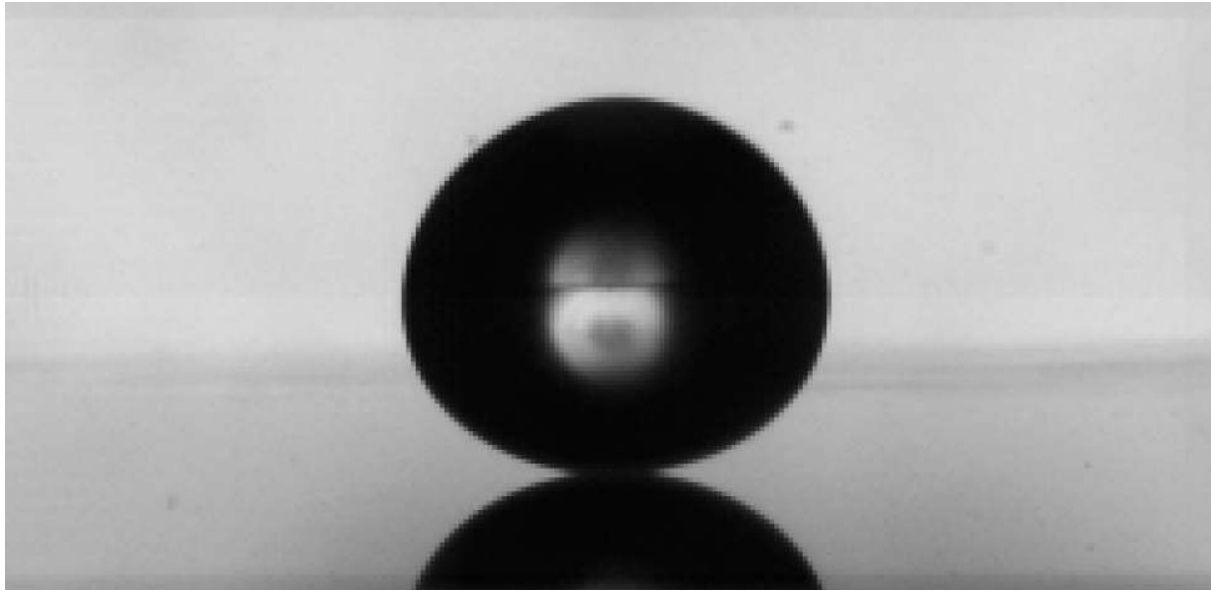
1 mm

Thoroddsen, Takehara & Etoh 2005

Impact is another kind of singularity

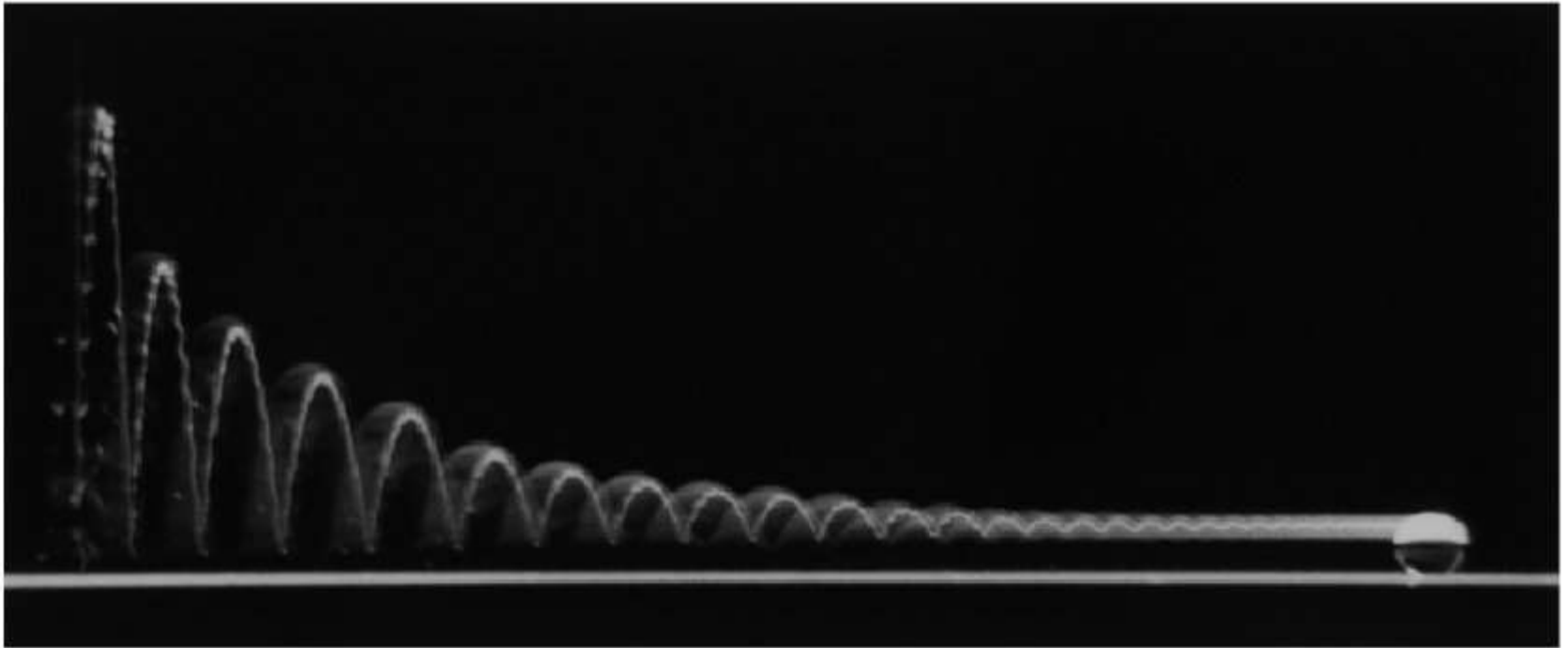


solid glass surface



Splash is NOT caused by surface tension

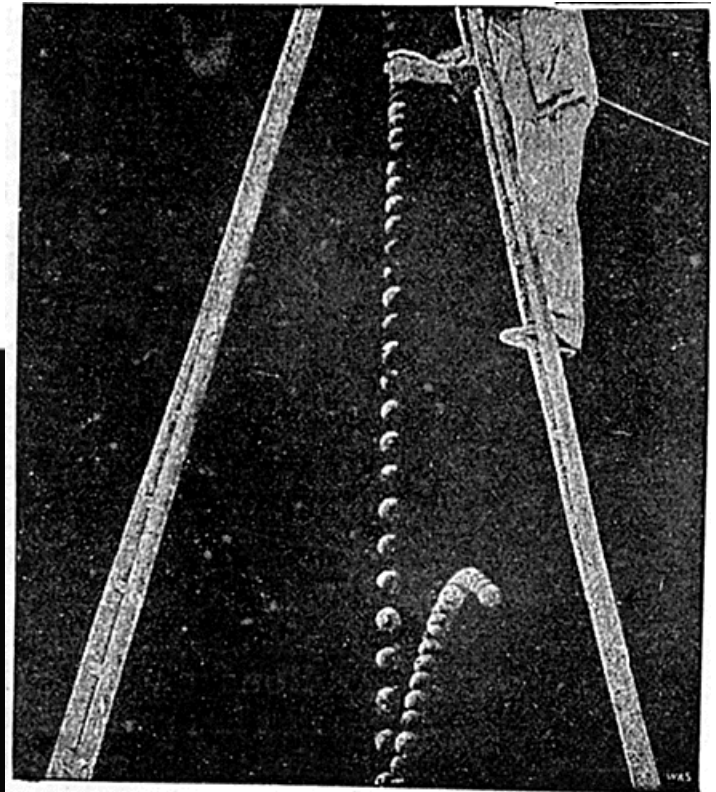
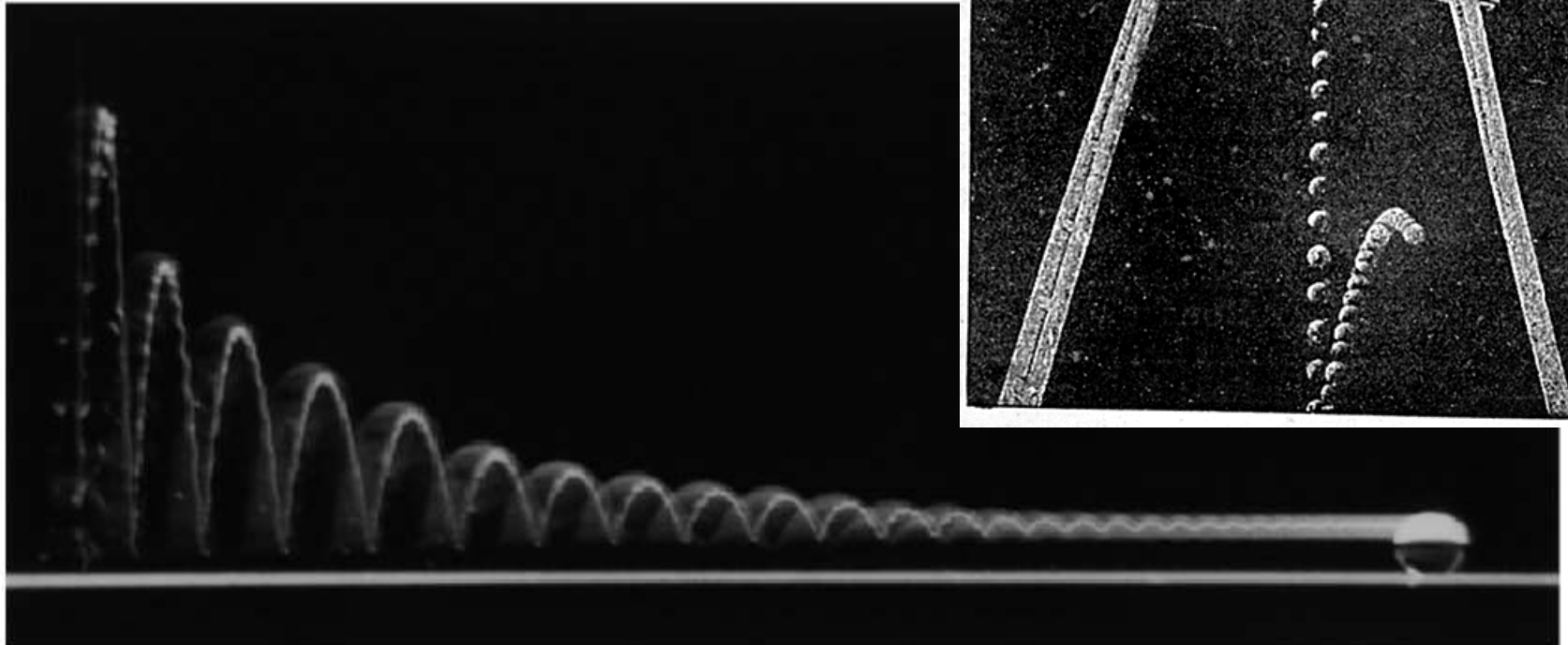
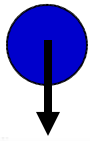
*If surface tension were the dominant effect
a liquid drop should **bounce** on impact*



And it does!

*Aside: Drop
bounces better
than a rubber ball*

Wall, 1890's



What does cause a splash?

Two experiments

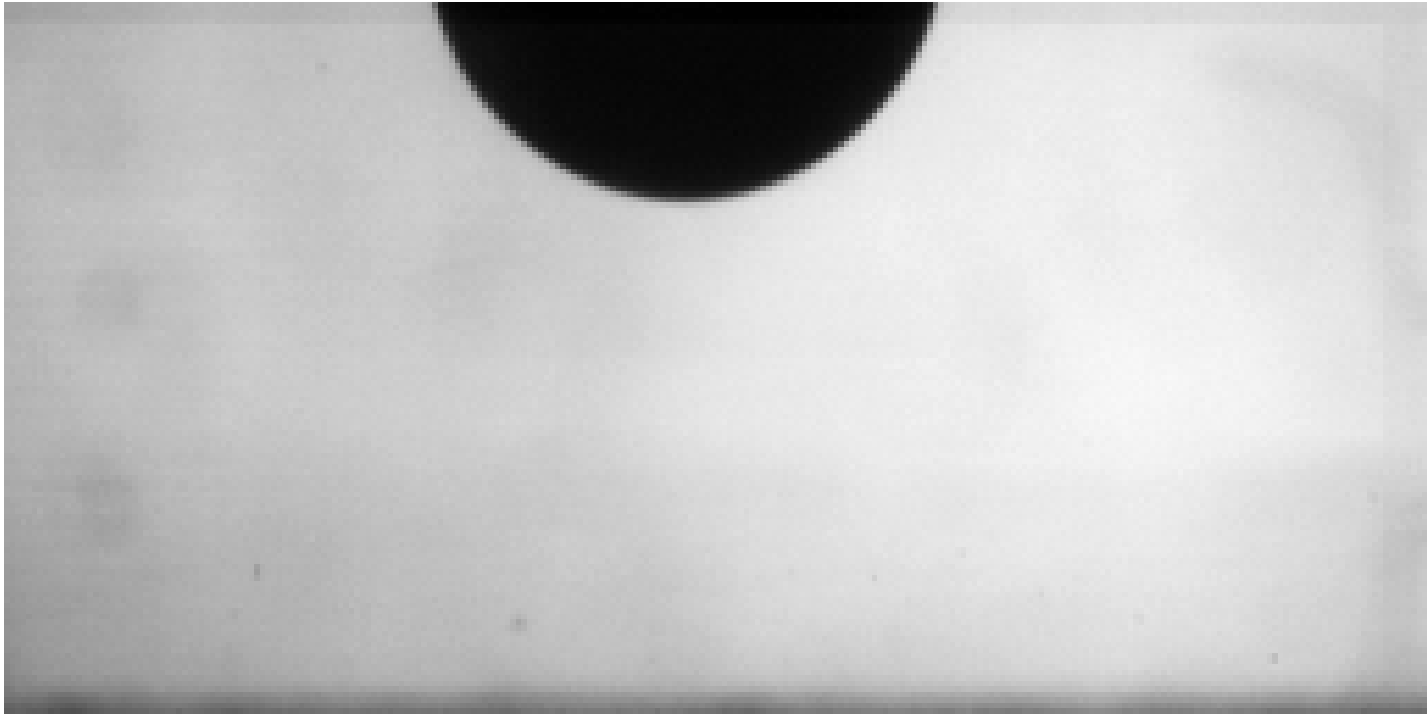
1st Experiment

*Liquid drop hitting dry glass @ 4 m/s
2.5 ms in real time*



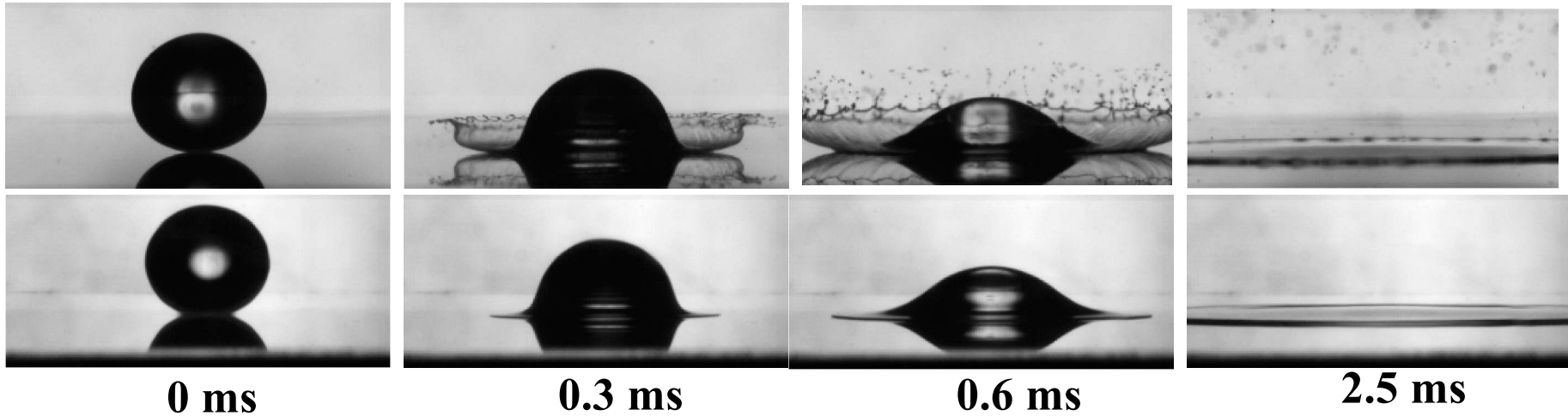
2nd Experiment

*Liquid drop hitting dry glass @ 4 m/s
2.5 ms in real time*



Splash disappears when there is less air

1st experiment **1 atmosphere pressure** **Chicago**



2nd experiment **0.2 atmosphere pressure** **Everest**

How air creates a splash (we think)

*liquid spreads out so rapidly after impact
that air resists as if the air were a solid*

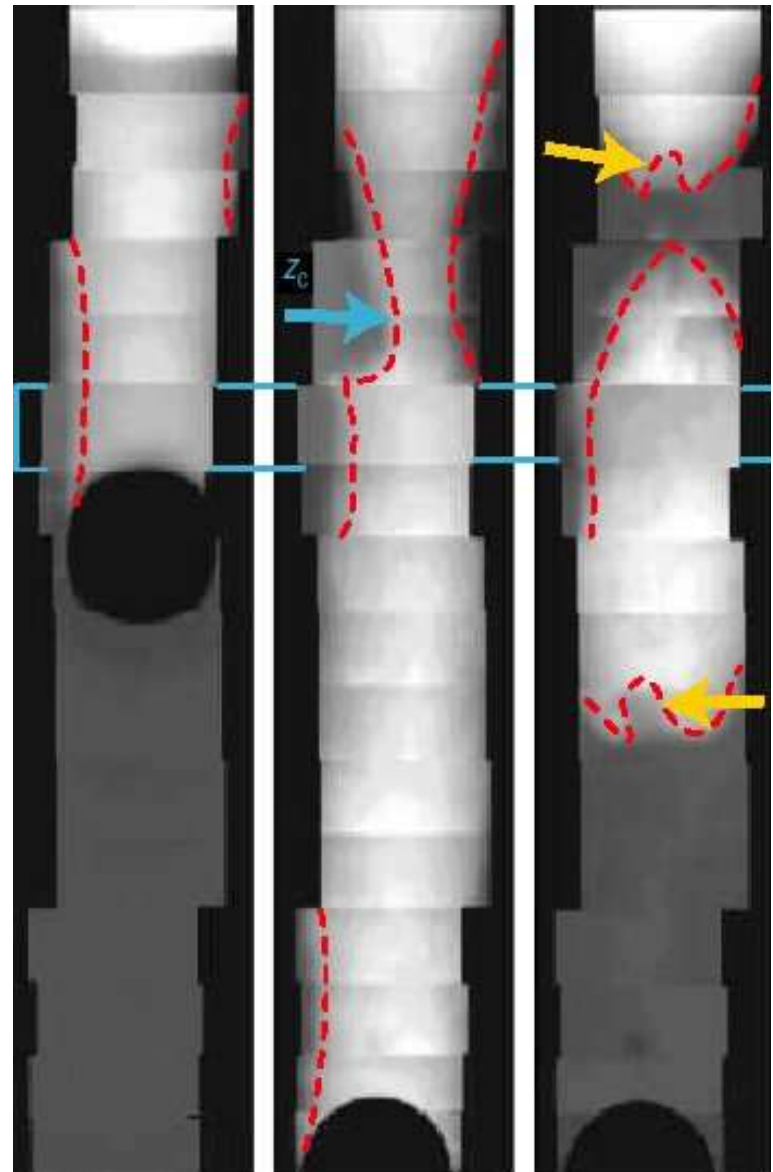


*Material properties can change
dramatically near a singularity*

*Liquid-less
break-up
steel ball
falling into
dry loose sand
@ 2 m/s*



*reconstructed
X-ray
radiographs*



10 ms

70 ms

100 ms

Some examples of singularity formation
dripping faucet
bubble break-up
coalescence
impact

Singularities come in different flavors
memory vs amnesia in break-up
bouncing vs splashing in impact

There are a lot we don't understand!

The End

References

1. C. V. Boys, *Soap Bubbles*, Dover N.Y., 1911
2. J. Ingram, *The Velocity of Honey*, Penguin 2003
3. A. M. Worthington, *A Study of Splashes*, Dover N.Y. 1908
4. H. E. Edgerton, *Exploring the Art & Science of Stopping Time*, M.I.T. press, 2000
6. W. G. Fitzgerald, *Some Curiosities of Modern Photography*, The Strand, 1895

With Thanks To

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