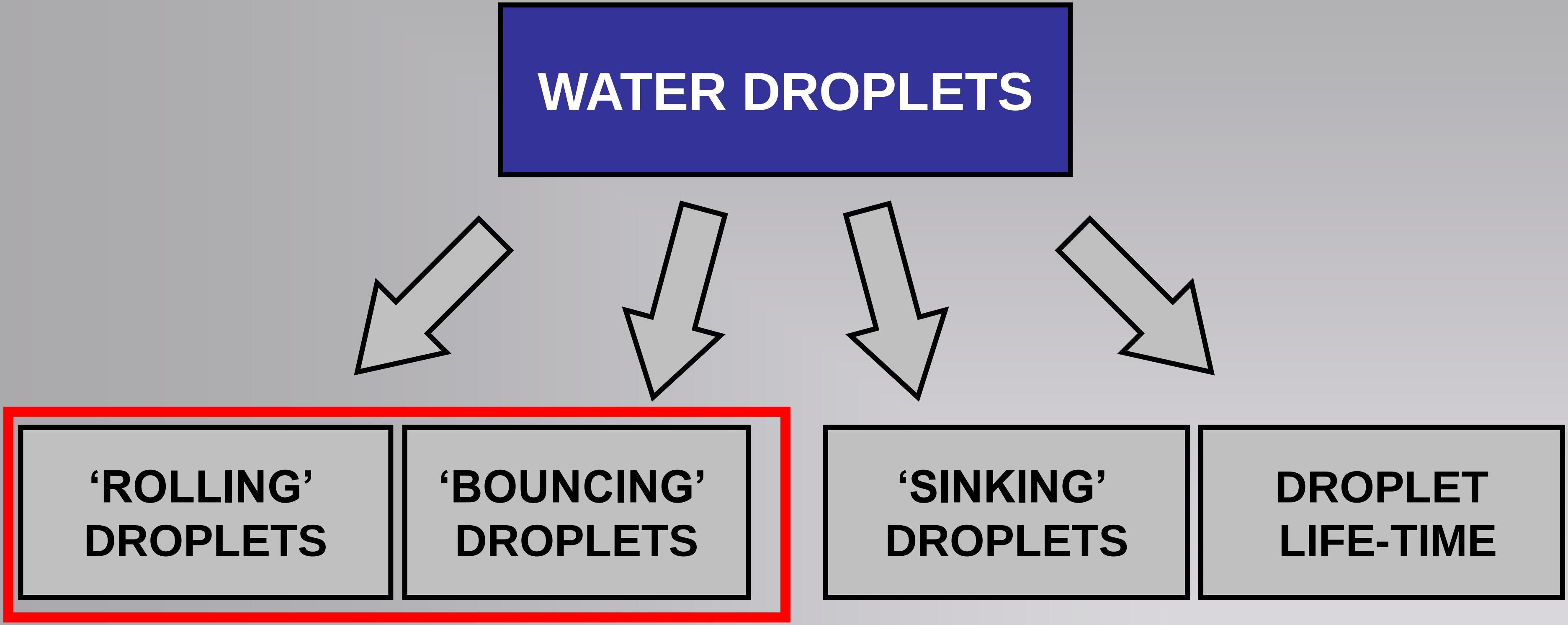
11. Water droplets

If a stream of water droplets is directed at a small angle to the surface of water in a container, droplets may bounce off the surface and roll across it before merging with the body of water. In some cases the droplets rest on the surface for a significant length of time. They can even sink before merging. Investigate these phenomena.

PRSENTATION OUTLINE



WATER DROPLETS

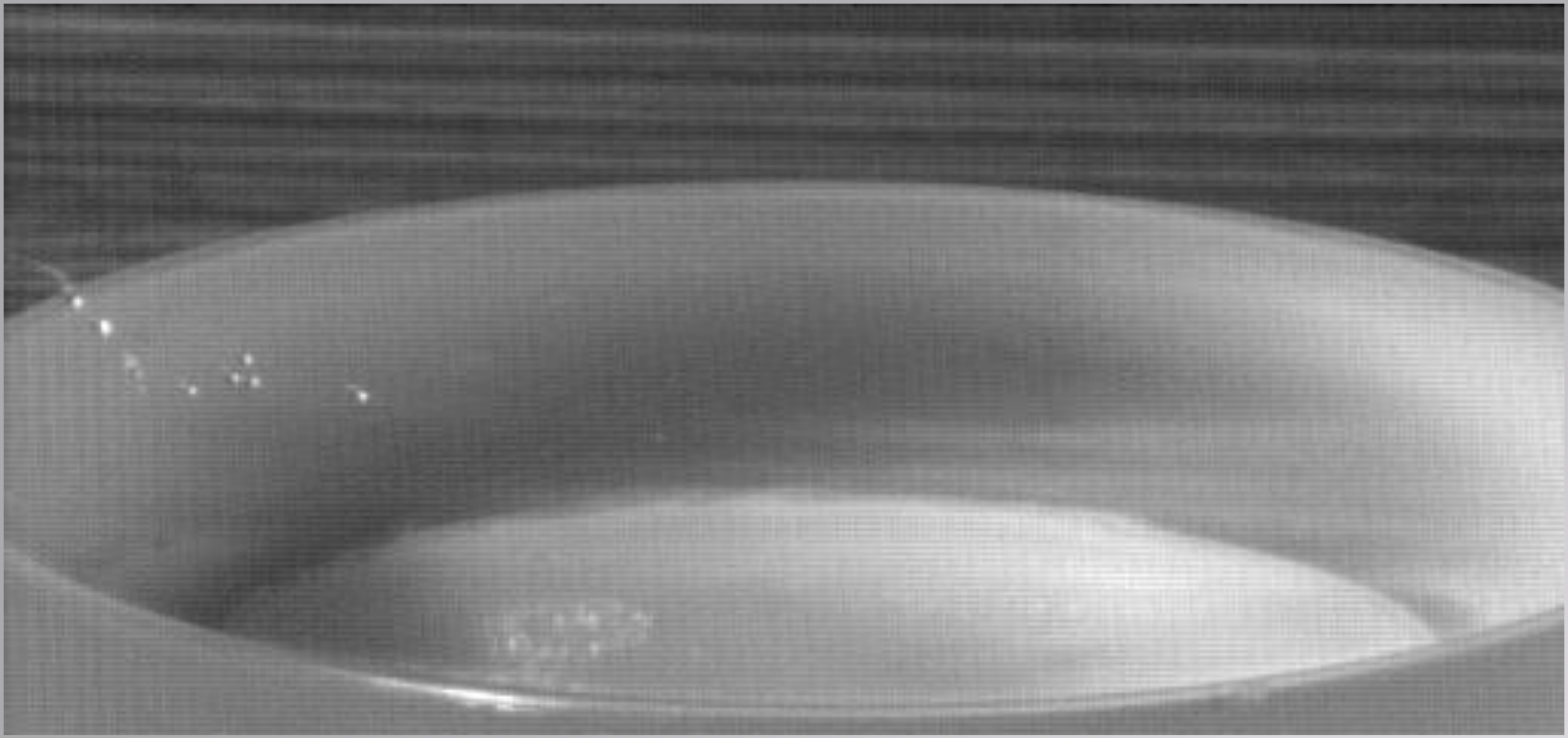
‘ROLLING’ DROPLETS

‘BOUNCING’ DROPLETS

‘SINKING’ DROPLETS

DROPLET LIFE-TIME

DESCRIBED PHENOMENA



EXPERIMENTAL SET – UP

Investigated substances:

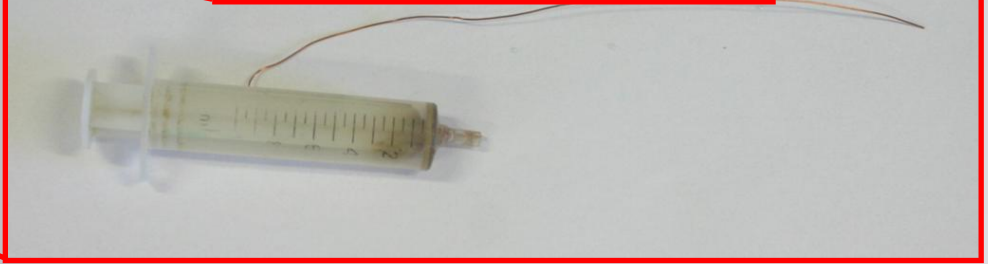
1. Water
2. Water with soap
3. Vegetable oil
4. Ethyl alcohol

Vessels:

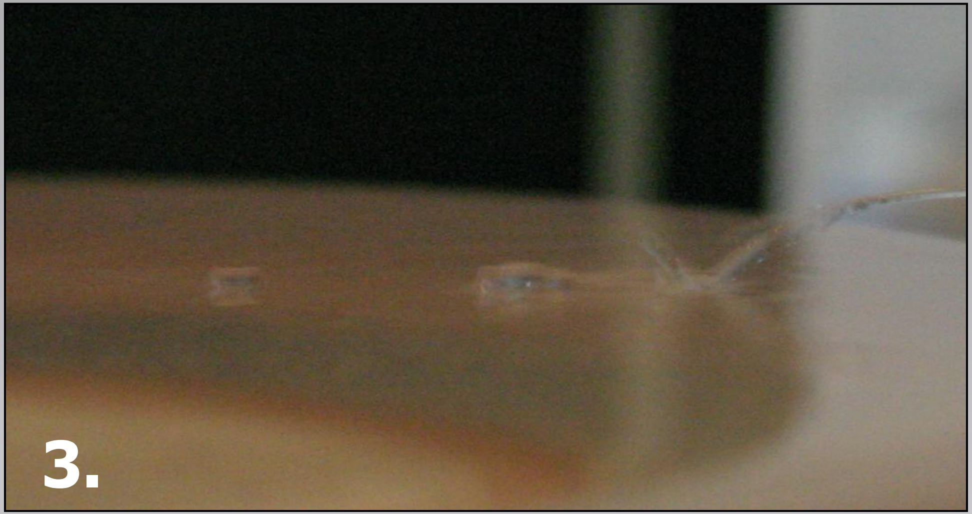
1. Flat disk
2. Bowl
3. Large beaker

Others:

1. Syringe
2. Pipette



ROLLING DROPLETS

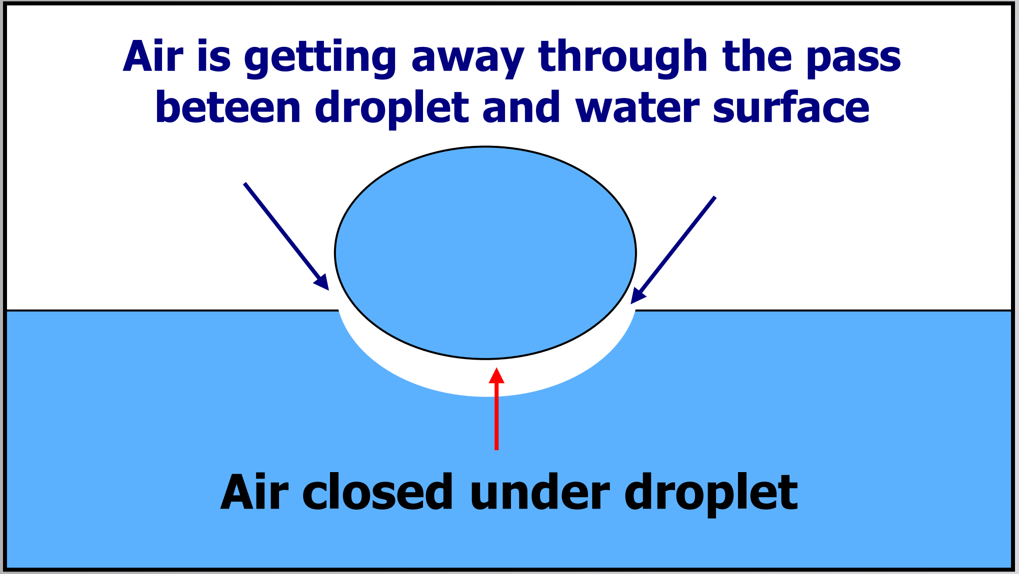


1. **Water with soap**
2. **Vegetable oil**
3. **Water**

ROLLING DROPLETS

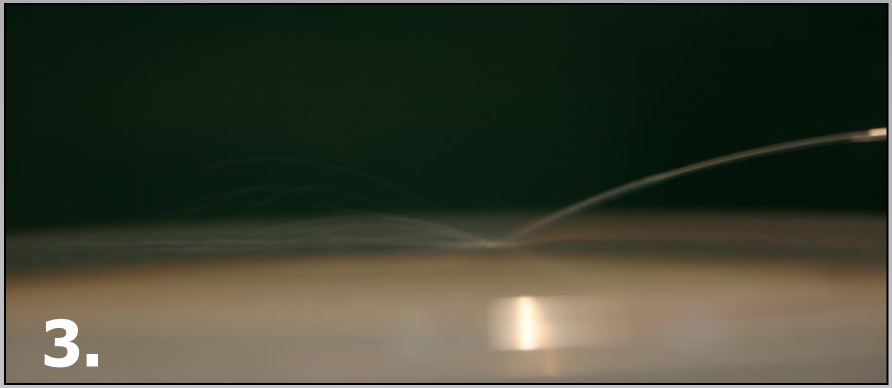
if water molecules inside the droplets have the contact with water molecules in the vessel, the merge occurs

to obtain rolling droplets, there must be the distinct boundary between droplet and water in the vessel

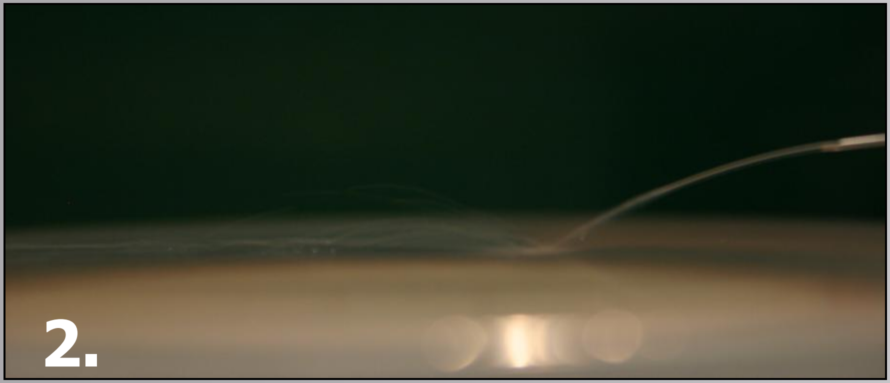


BOUNCING DROPLETS

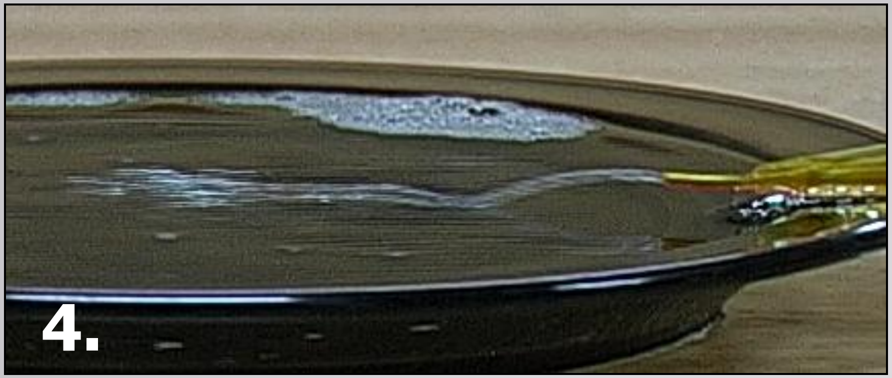
1.



3.



2.



4.

1., 2., 3. water

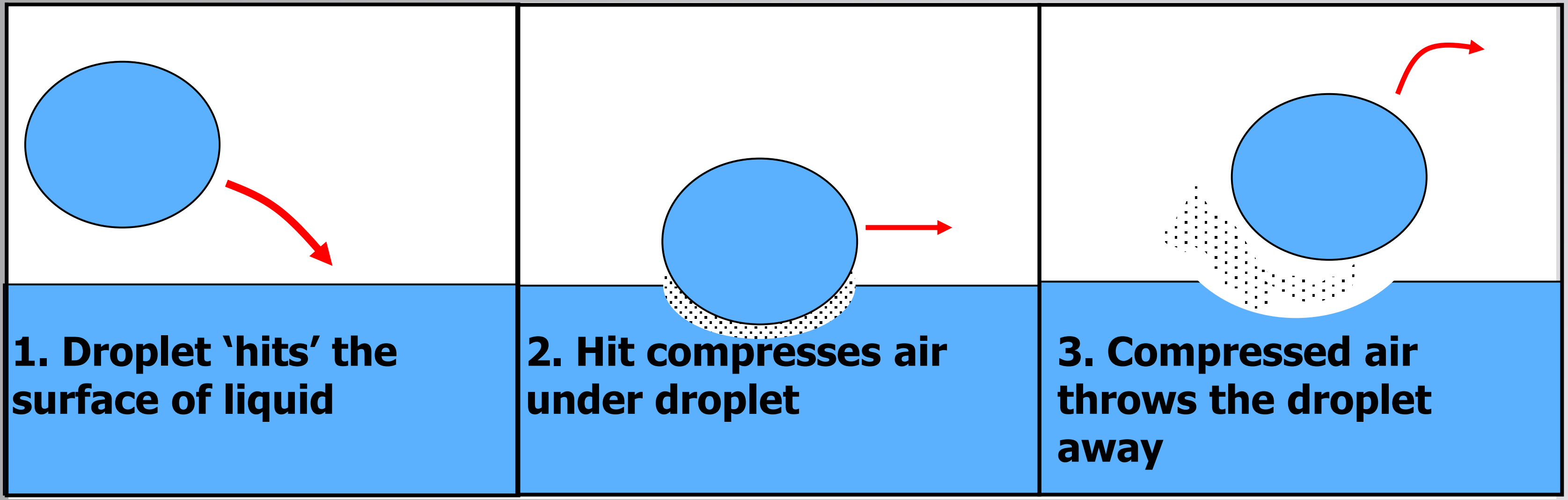
4. water with soap

BOUNCING DROPLETS

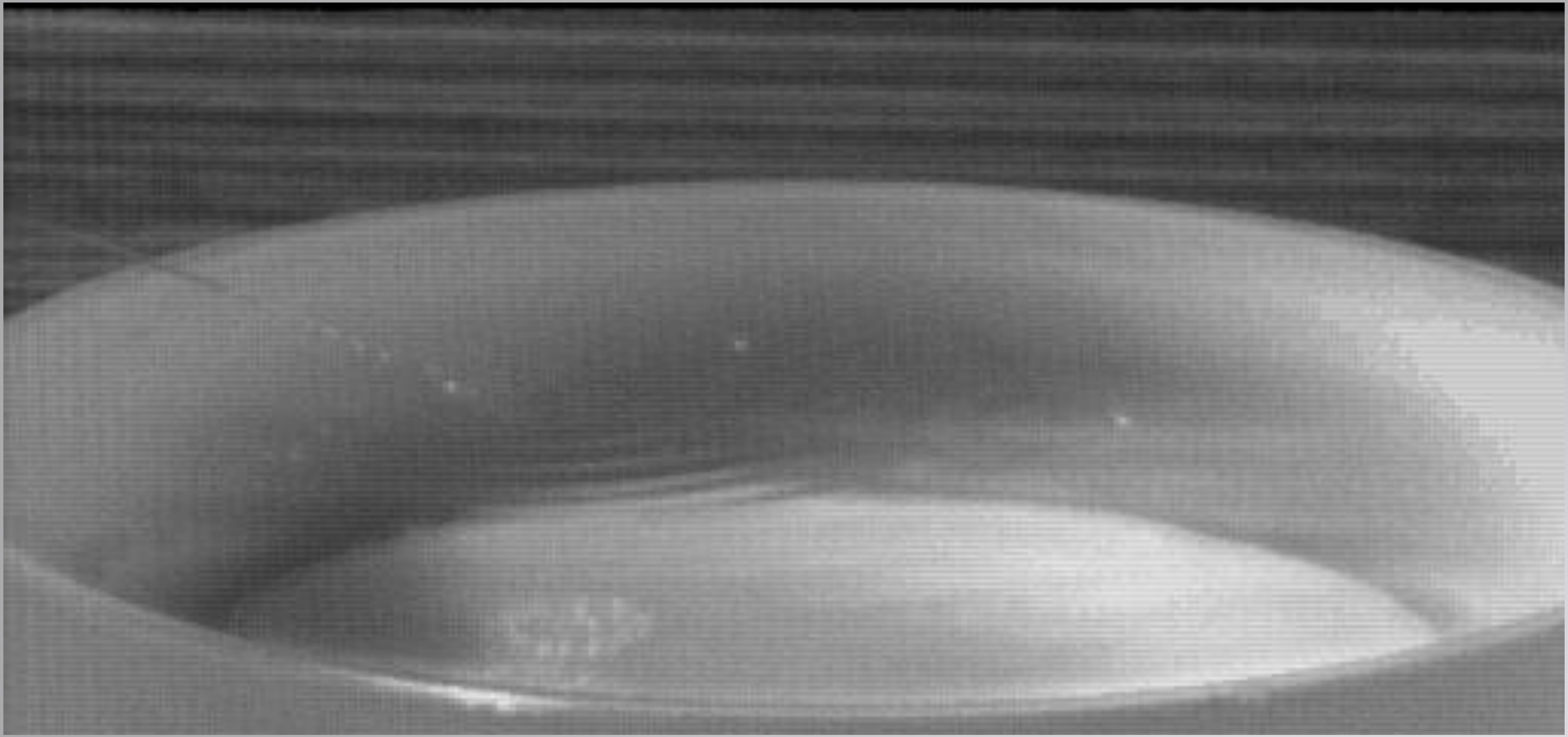
To obtain bounce, there must be big velocity and momentum of droplet (in perpendicular direction)

Compression of the air under droplet

Throwing the droplet away - bounce



FILM 500 FPS



THEORETICAL MODEL

Considering bounce as a totally ellastic collision:

$$\frac{m\left(\sqrt{V_x^2+V_y^2}\right)^2}{2}+\sigma_{air}S=\frac{m\left(\sqrt{\alpha V_x^2+\beta V_y^2}\right)^2}{2}+\sigma_{water}S_1+\sigma_{air}S_2$$

Energy conservation principle for droplet

Where:

m – mass of droplet

V_x, V_y – elements of droplet velocity

σ_{air} , σ_{water} – surface tensions

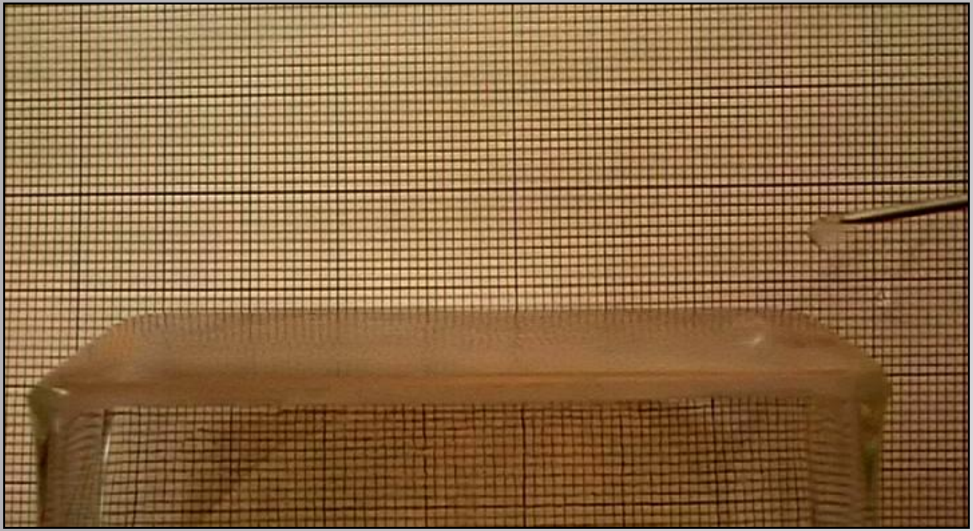
S – droplet area

$$\boxed{m\left[V_x^2(1-\alpha)+V_y^2(1-\beta)\right]=2(\sigma_{water}-\sigma_{air})S_1}$$

ENERGY DISSIPATION

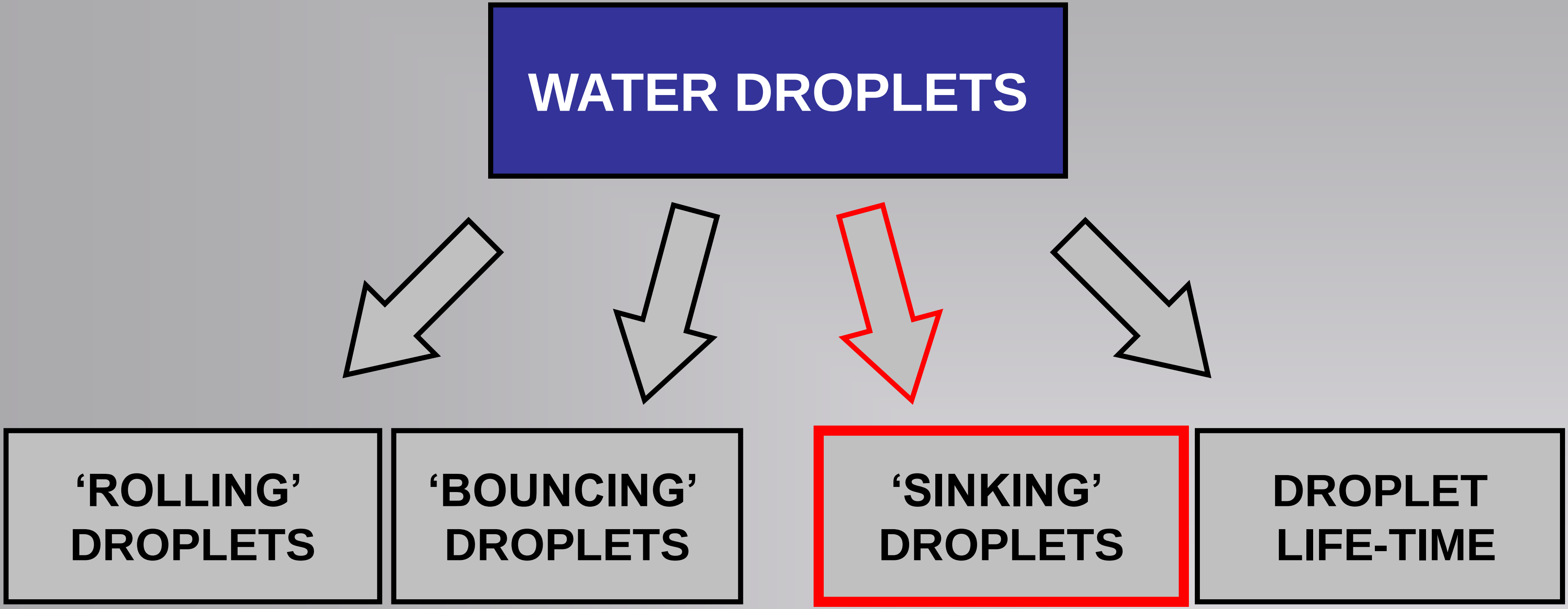
$$\boxed{m\left[V_x^2\left(1-\boxed{\alpha}\right)+V_y^2\left(1-\boxed{\beta}\right)\right]=2\left(\sigma_{water}-\sigma_{air}\right)S_1}$$

We measured α and β using film 25 fps



$$\boxed{\alpha=0,60\pm0,05}\qquad\boxed{\beta=0,20\pm0,05}$$

PRSENTATION OUTLINE



WATER DROPLETS

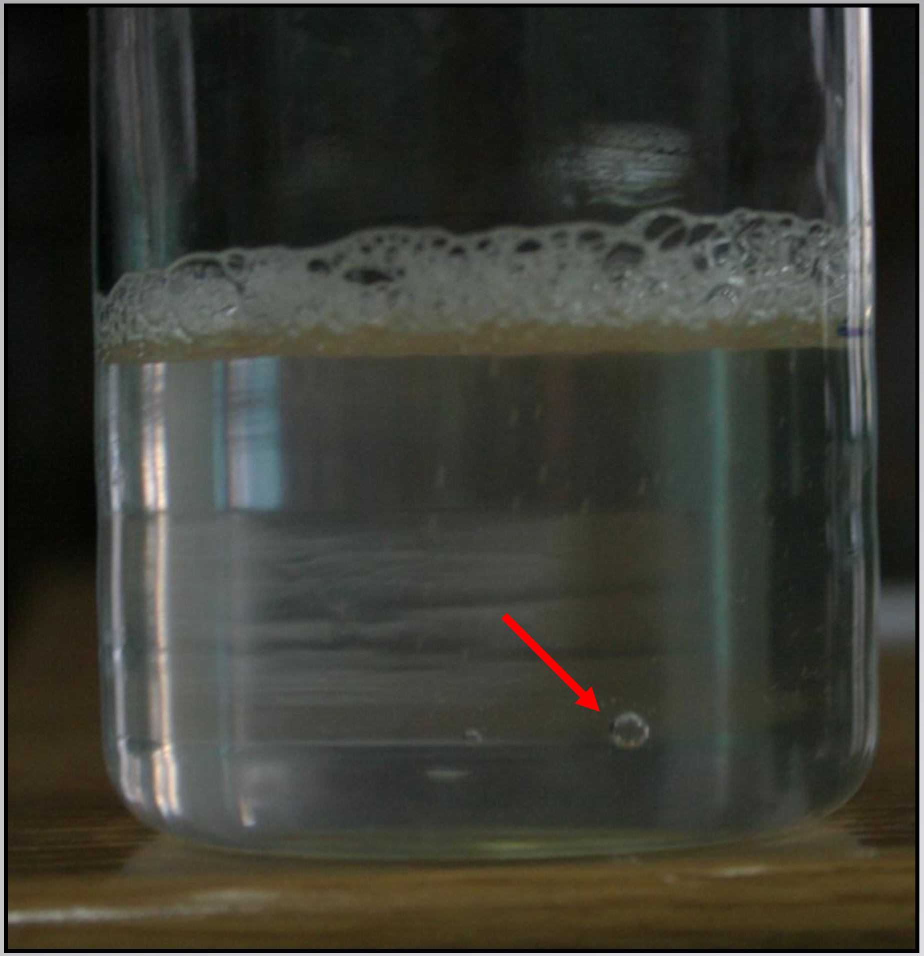
‘ROLLING’ DROPLETS

‘BOUNCING’ DROPLETS

‘SINKING’ DROPLETS

DROPLET LIFE-TIME

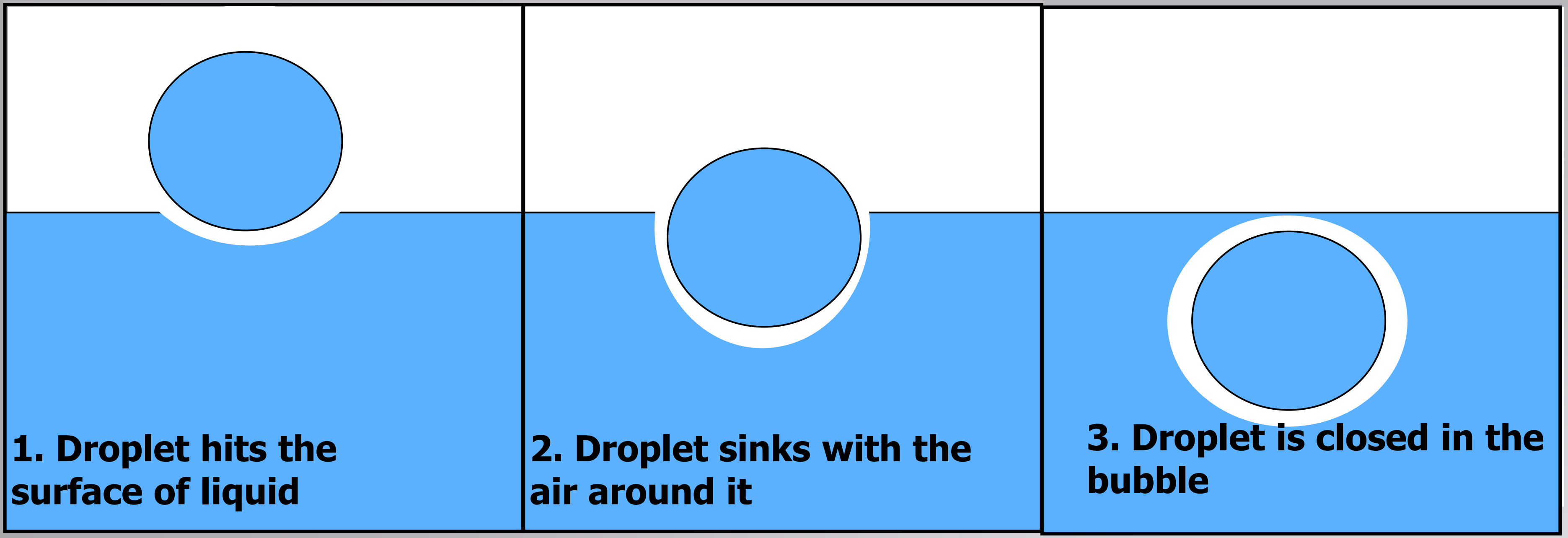
SINKING DROPLETS



SINKING DROPLETS

SINKING DROPLETS

1. Formation of the phenomenon



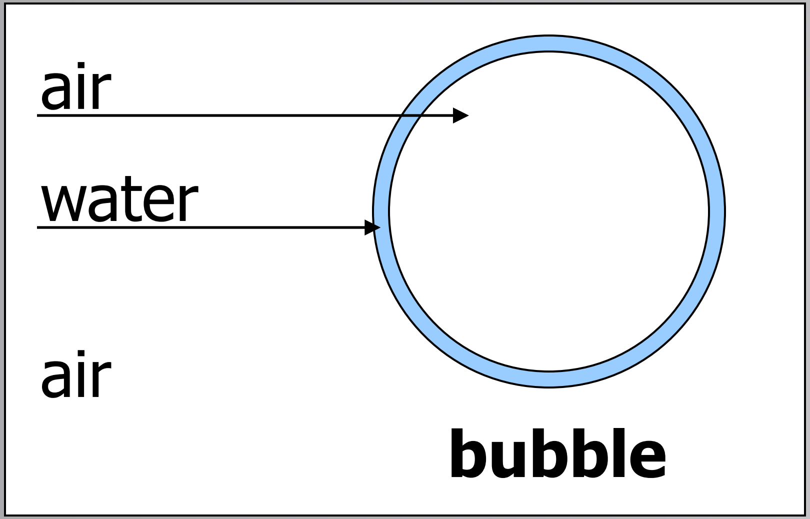
1. Droplet hits the surface of liquid

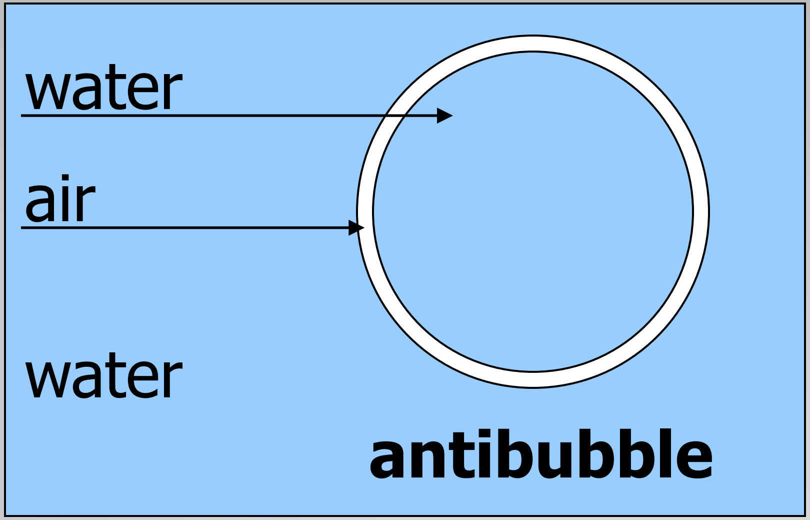
2. Droplet sinks with the air around it

3. Droplet is closed in the bubble

SINKING DROPLETS

2. Water droplet as ‘antibubble’



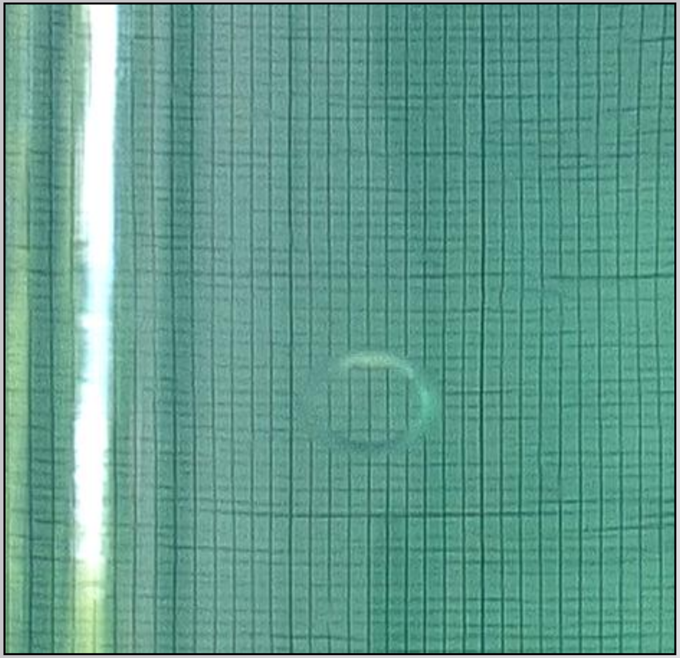


SINKING DROPLETS

3. How does the antibubble form?

Air bubble is formed from the air closed under the droplet during hitting surface of the water in the vessel

‘Antibubble’ is a droplet closed in air bubble

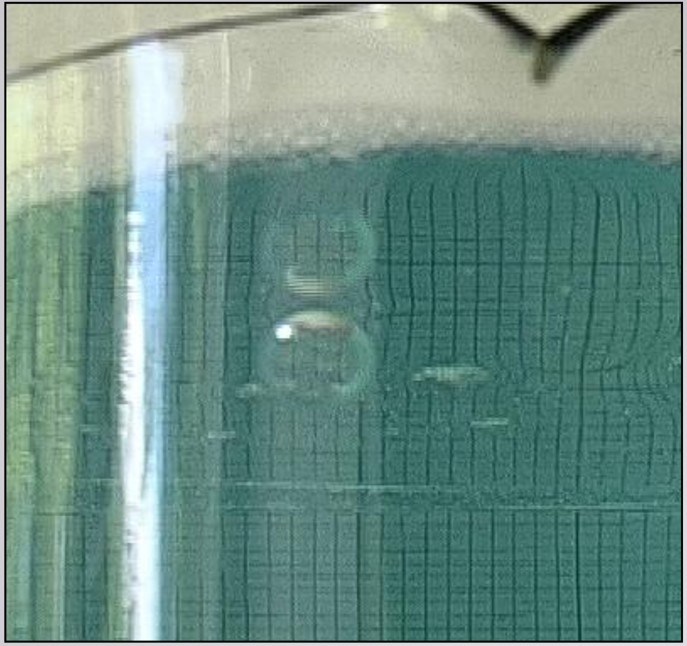


SINKING DROPLETS

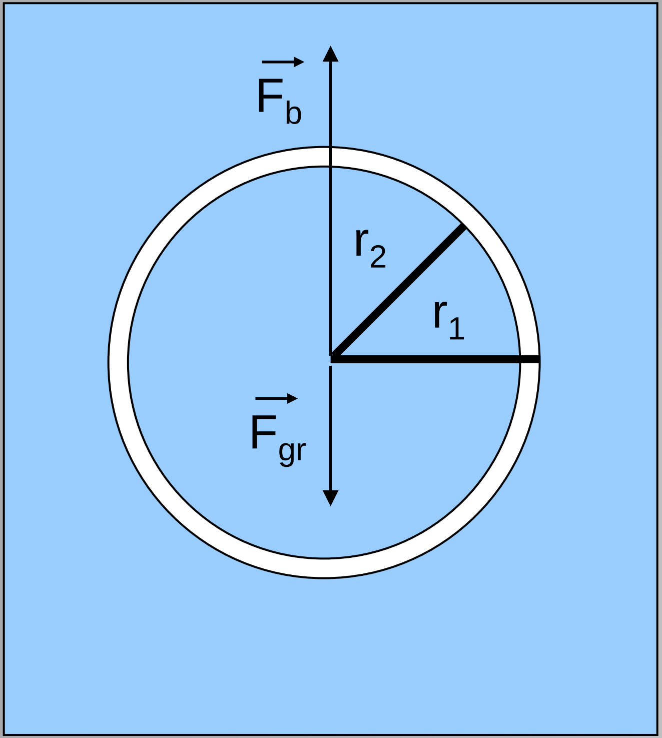
4. Under what conditions does the antibubble occur?

We obtained antibubbles only using water with soap. It is caused by the stucture of soap molecules, part of which is hydrophobic and another part is hydrophyllic

Structure created by soap molecules is the ‘structure’ for air bubble and make the phenomenon possible



AIR LAYER THICKNESS CALCULATIONS



$$(r_1 - r_2) \sim 10^{-3}\ \mathrm{mm}$$

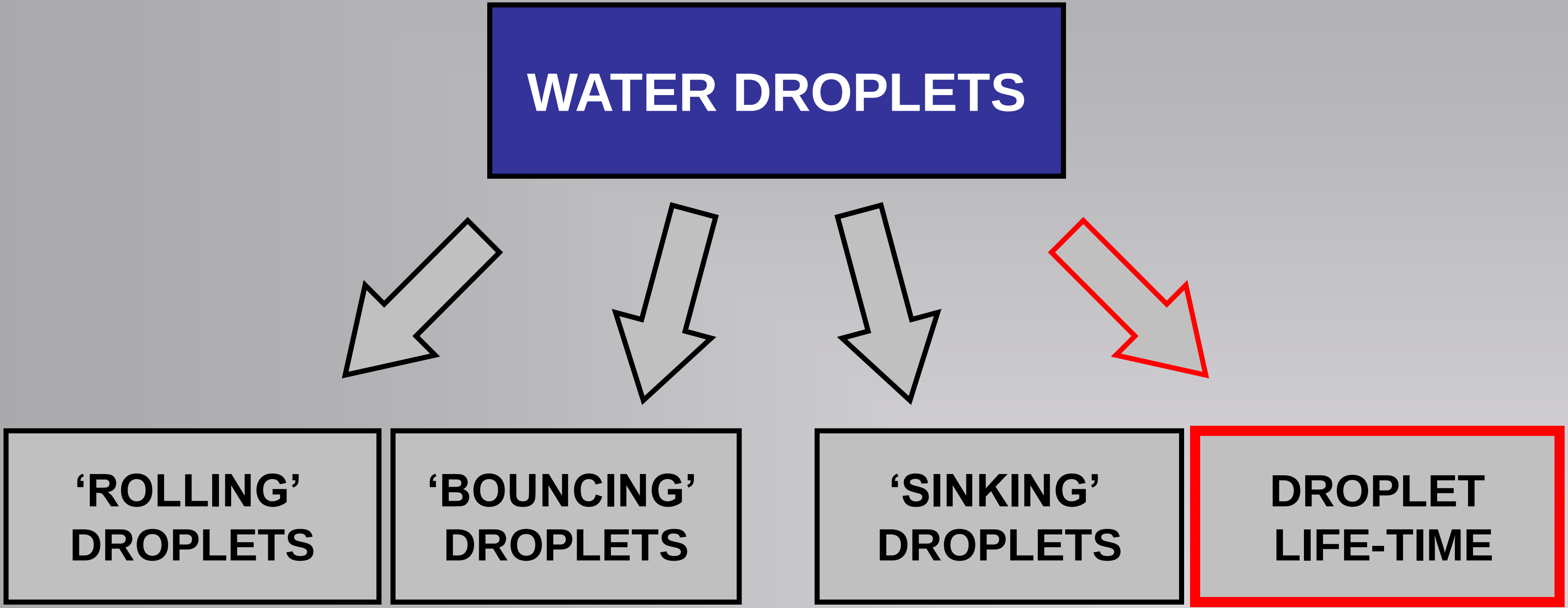
air layer

$F_b > F_{gr}$

Antibubble moves upwards

From this movement
we can calculate
thickness of the air layer

PRSENTATION OUTLINE



WATER DROPLETS

‘ROLLING’ DROPLETS

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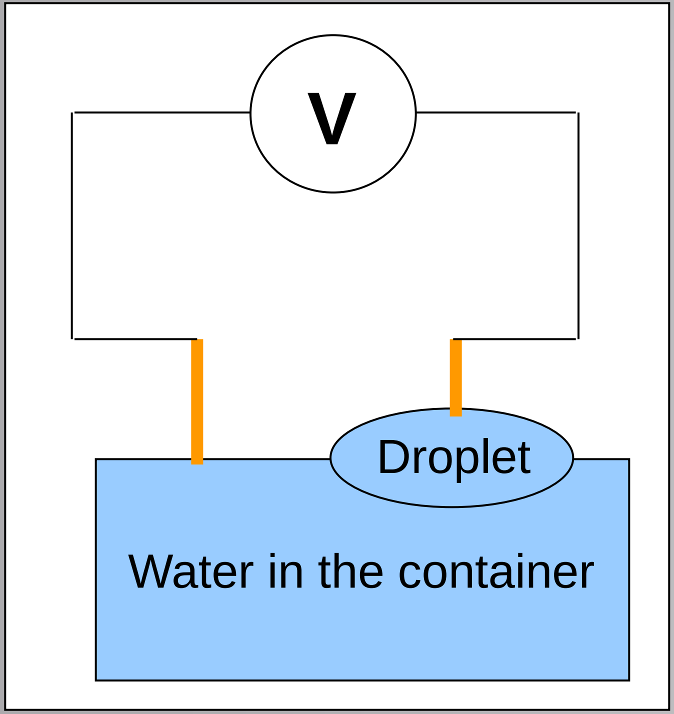
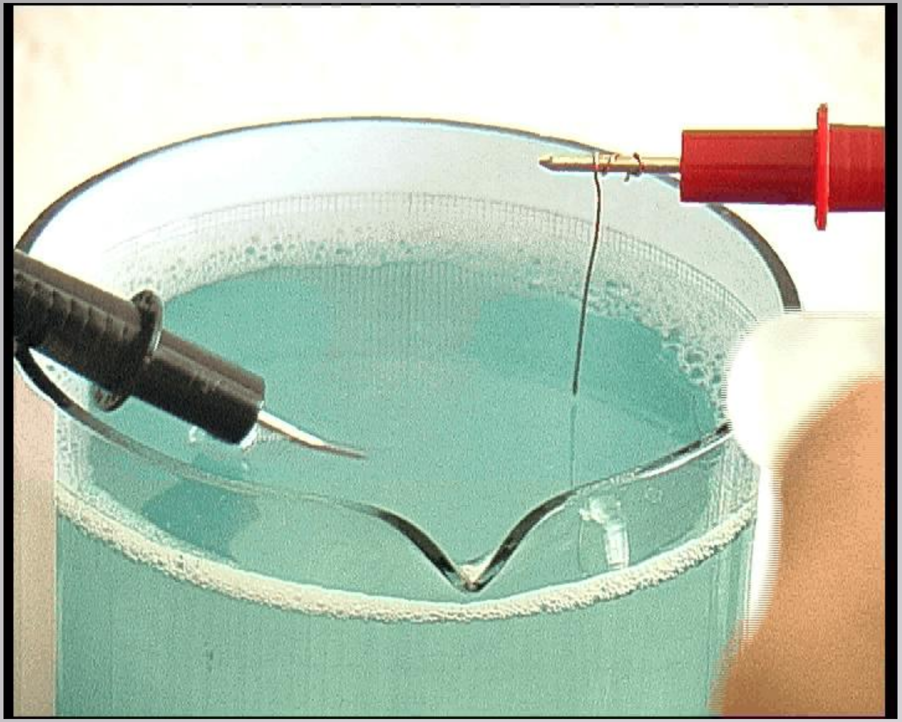
‘SINKING’ DROPLETS

DROPLET LIFE-TIME

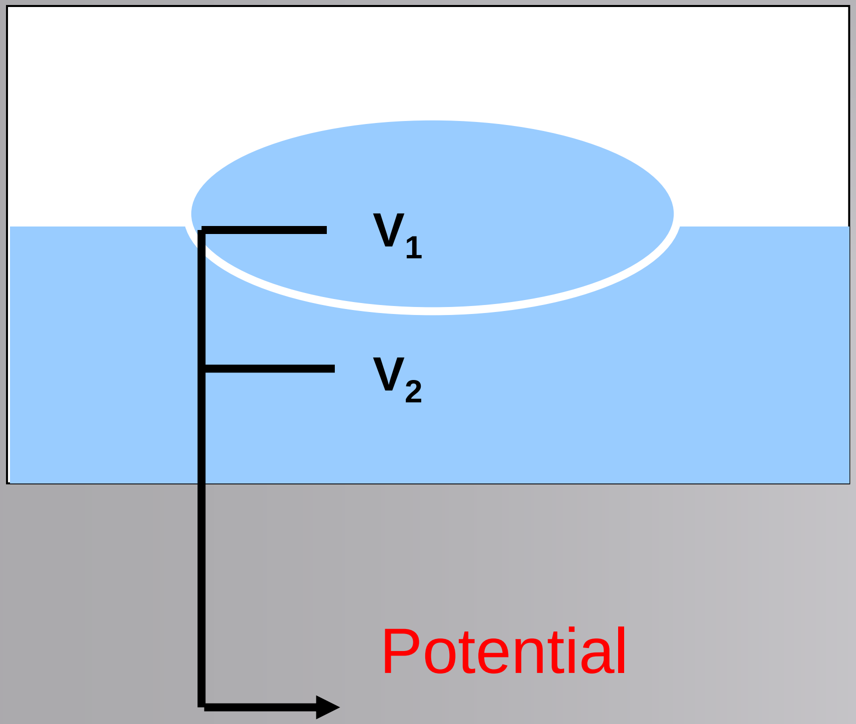
DROPLET LIFE – TIME





Potential between droplet and water: ca. 3mV

POTENTIAL DIFFERENCE INFLUENCE

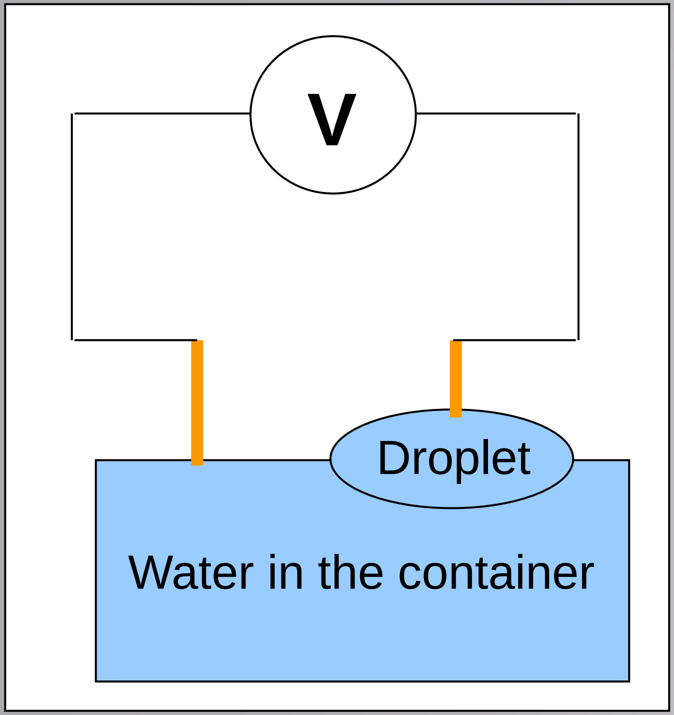


Potential difference

Potential difference between droplet and water in the container makes the phenomena hard to obtain, because it causes attraction of the water particles in droplet and container

Droplets merge in short time

POTENTIAL DIFFERENCE



No potential between droplet and water

CONCLUSIONS

- The reason for delining discussed phenomena is a thin air layer between droplet and air in the container

- The air layer is ca. 10^{-3} mm thick

- Presence of soap or other surface-active substances has a big influence on the phenomenon

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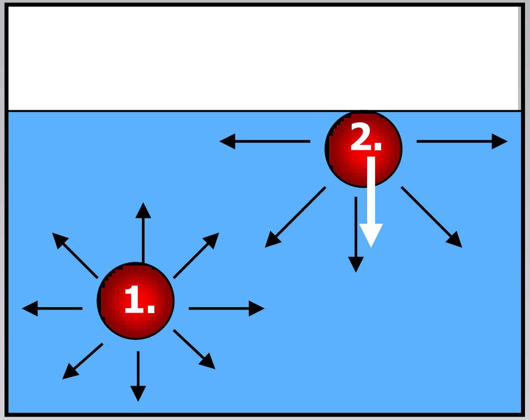
THEORETICAL ANALYSIS

SURFACE TENSION

In liquid there are strong intermolecular interactions:

- In case of molecule allocated inside liquid all the intermolecular forces acting on it undergo neutralization(1.)
- In case of molecule allocated near the surface of there are no intermolecular forces acting on it in upward direction. Hence, downward forces are not neutralized (2.)

SURFACE TENSION



SURFACE TENSION

Surface tension can be given by the equation:

$$\alpha = \frac{W}{S}\left[\frac{J}{m^2}\right]$$

where:
α – surface tension
W – work done
S – change of free surface

Each substance has different α coefficient:

Pure water: $\alpha_{\mathbf{w}} = 7{,}28 \cdot 10^{-2}\left[J/m^2\right]$

Water and soap: $\alpha_{\mathbf{s}} = 4{,}5 \cdot 10^{-2}\left[J/m^2\right]$

Vegetable oil: $\alpha_{\mathbf{o}} = 3{,}2 \cdot 10^{-2}\left[J/m^2\right]$

Ethyl alcohol: $\alpha_{\mathbf{a}} = 2{,}23 \cdot 10^{-2}\left[J/m^2\right]$

THEORETICAL ANALYSIS

Analysis of droplet's shape

We consider balance state for spherical surface with surface tnesion α and radius r:

$$2\pi r\alpha = \left(p_w - p_z\right)\pi r^2$$

r – radius of the sphere

p_w – pressure inside sphere

p_z – pressure outside sphere

After dividing by πr^2:

$$\boxed{\left(p_w - p_z\right) = \frac{2\alpha}{r}}$$

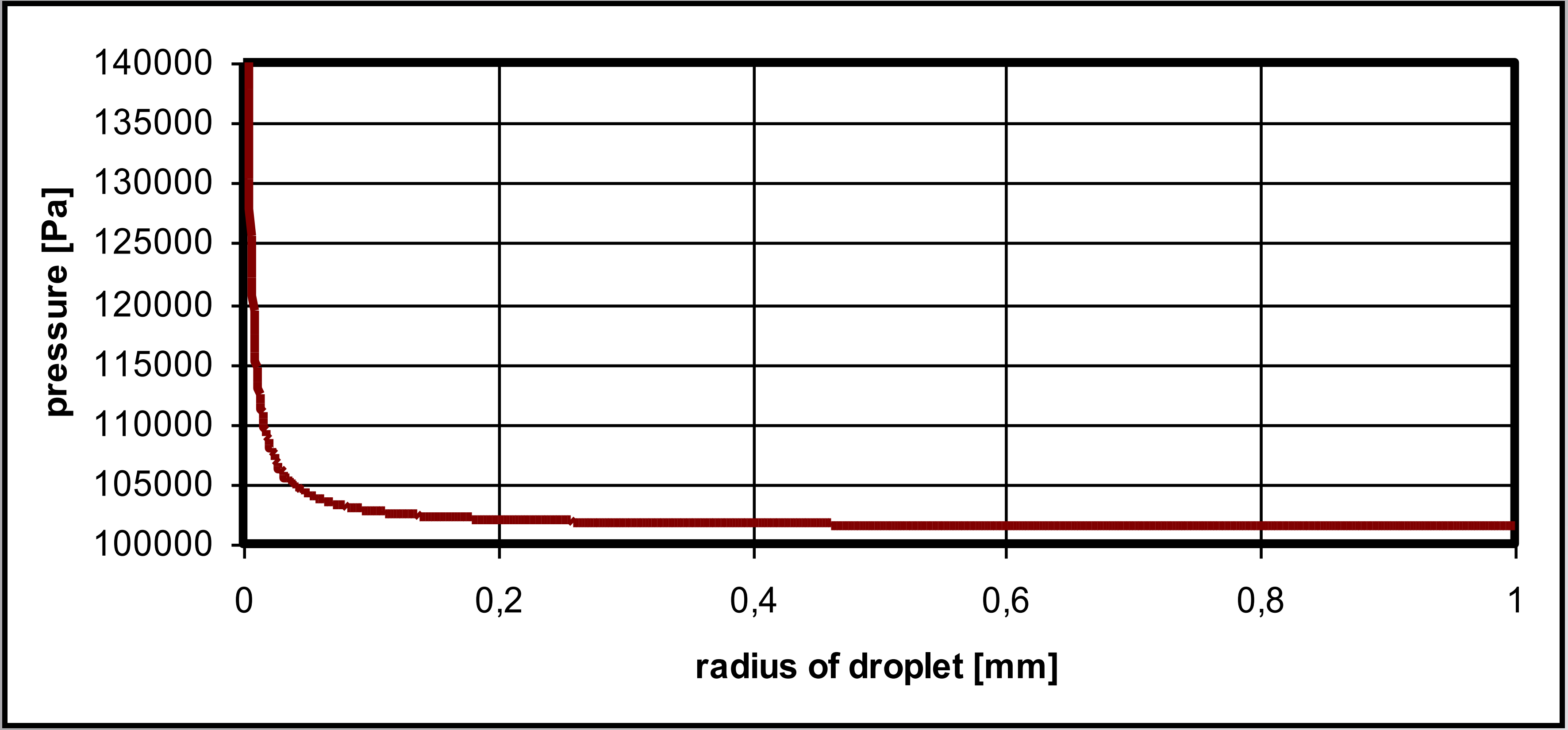
Laplace law for spherical surface

↓

The smaller radius of the sphere, the bigger pressure inside it.

THEORETICAL ANALYSIS

Pressure inside droplet versus radius of droplet



MODEL

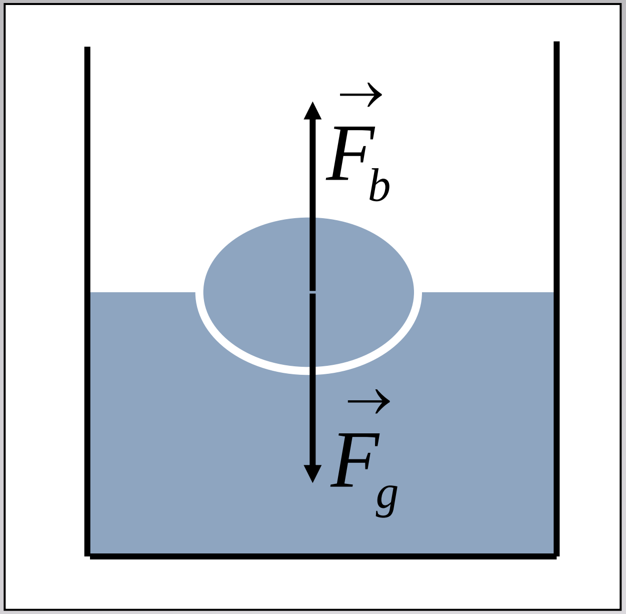
Two liquids have different values of surface tension coefficient and density

- All forces acting on a bubble are due to surface energy change and different densities of the liquids

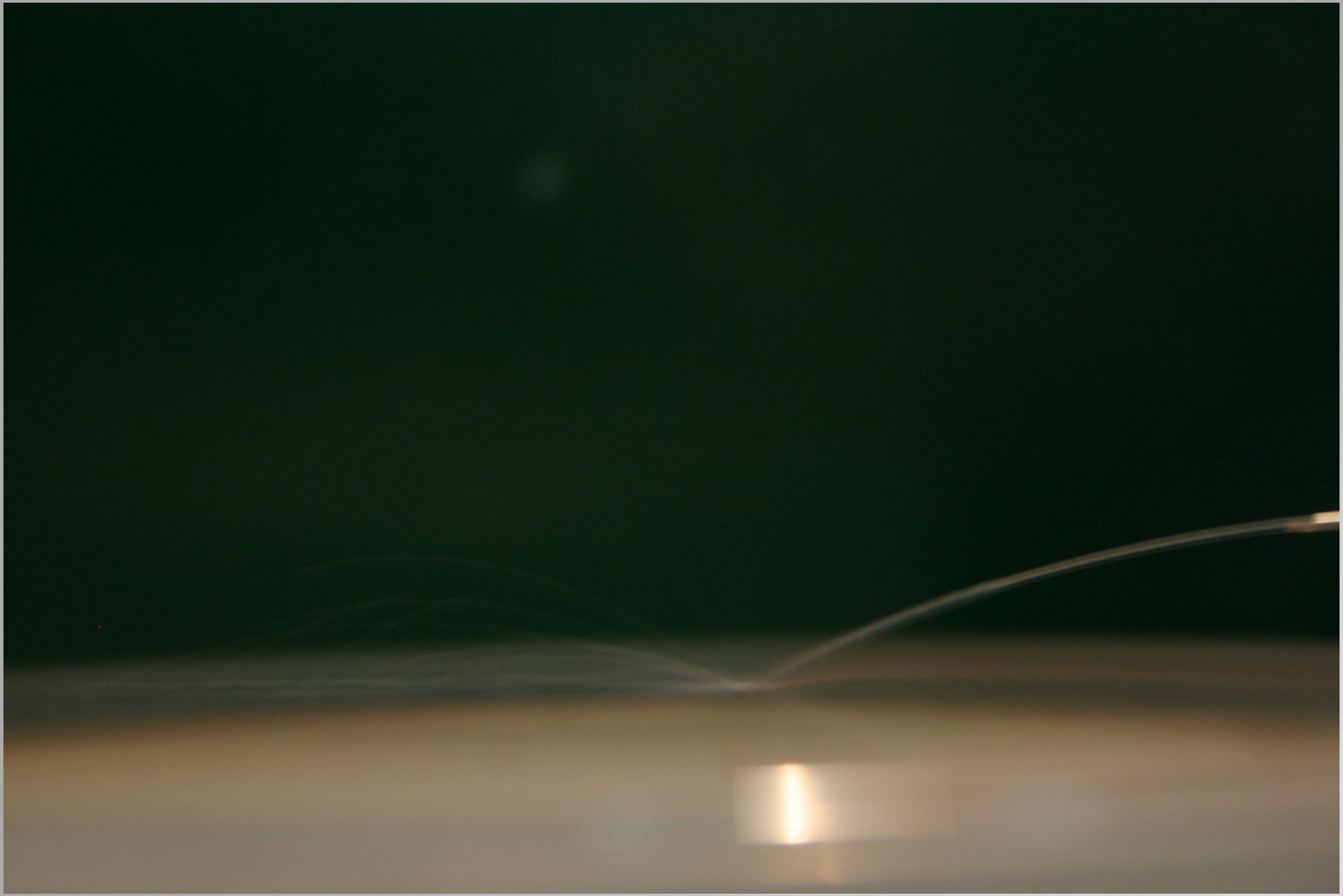
-We consider movement of the bubble’s center of mass - all forces acting on the bubble are applied to the centre of mass

-We neglect

$$F_b = F_g$$



DESCRIBED PHENOMENA



http://www.lsbu.ac.uk/water/

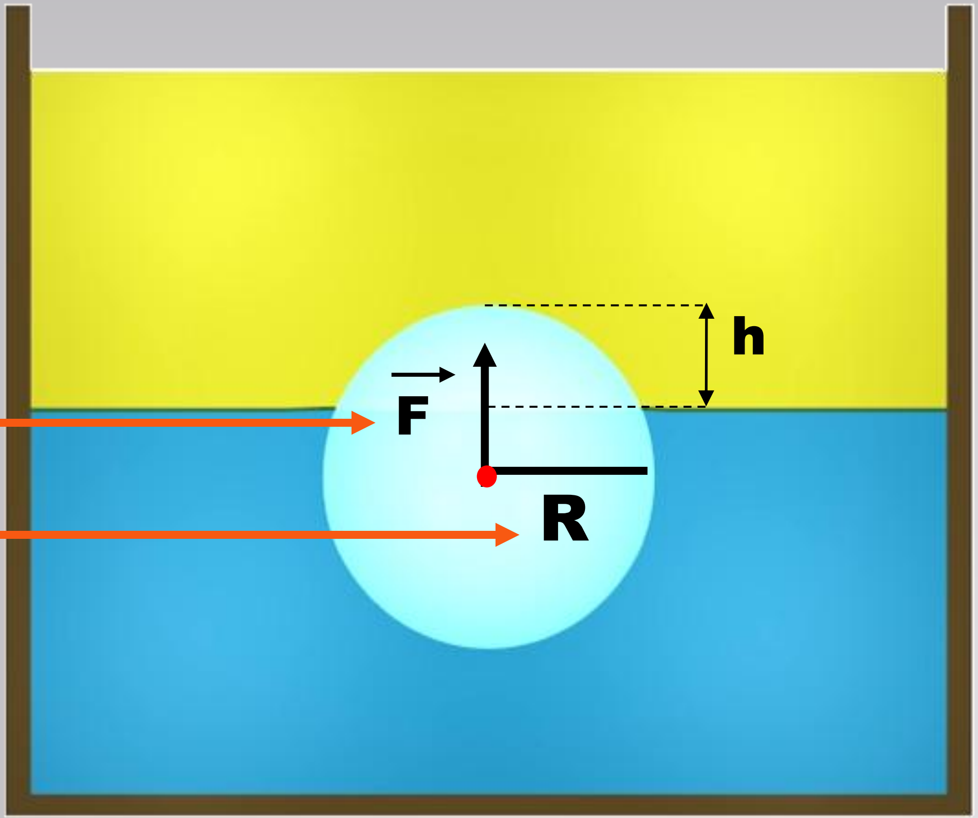
Bubble crosses a flat cracking interface without its deformation

Forces acting on a bubble:

-Buoyant force $F_B(h)$ – changes because of the $\Delta\rho$🕒0

-Surface tension forces $F_\sigma(h)$ – due to change of surface energy

$$\vec{F}(h) = \vec{F}_B(h) + \vec{F}_\sigma(h)$$



Resultant force

Bubble’s radius

Archimedes’ buoyant force

Buouant force is a sum of two terms due to upper part and lower part of the bubble:
$$\vec{F}_B = \vec{F}_u + \vec{F}_l = -\vec{g}(V_u \rho_u + V_l \rho_l)$$

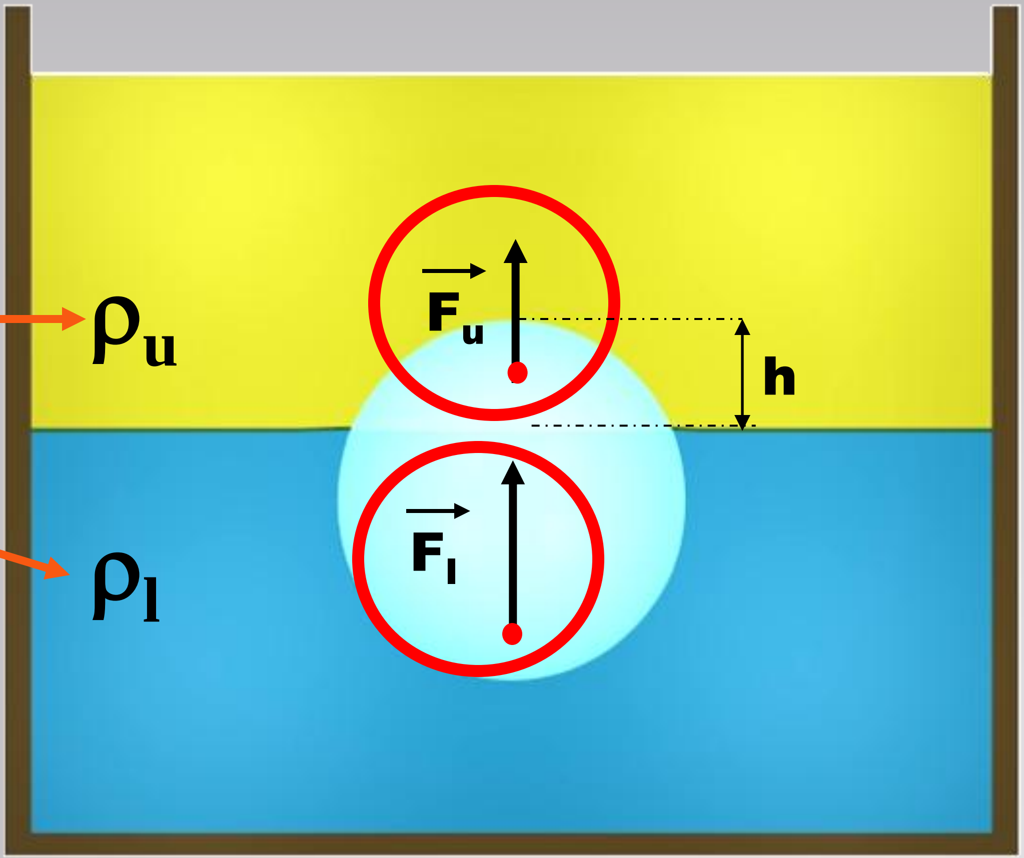
hence:
$$F_B = \pi g(4\rho_l R^3 + h^2 \Delta\rho(h - 3R))/3$$

Density:

the upper liquid

the bottom liquid

$\rho_l - \rho_u = \Delta\rho \geq 0$



Surface tension forces

Potential energy of the bubble and part of the interface involved equals:

$$E_c = E_u + E_l + E_{in} = \sigma_u S_u + \sigma_l S_l + \sigma_{in} S_{in}$$

By applying geometry to calculate surfaces S_u, S_l, S_{in} we obtain:

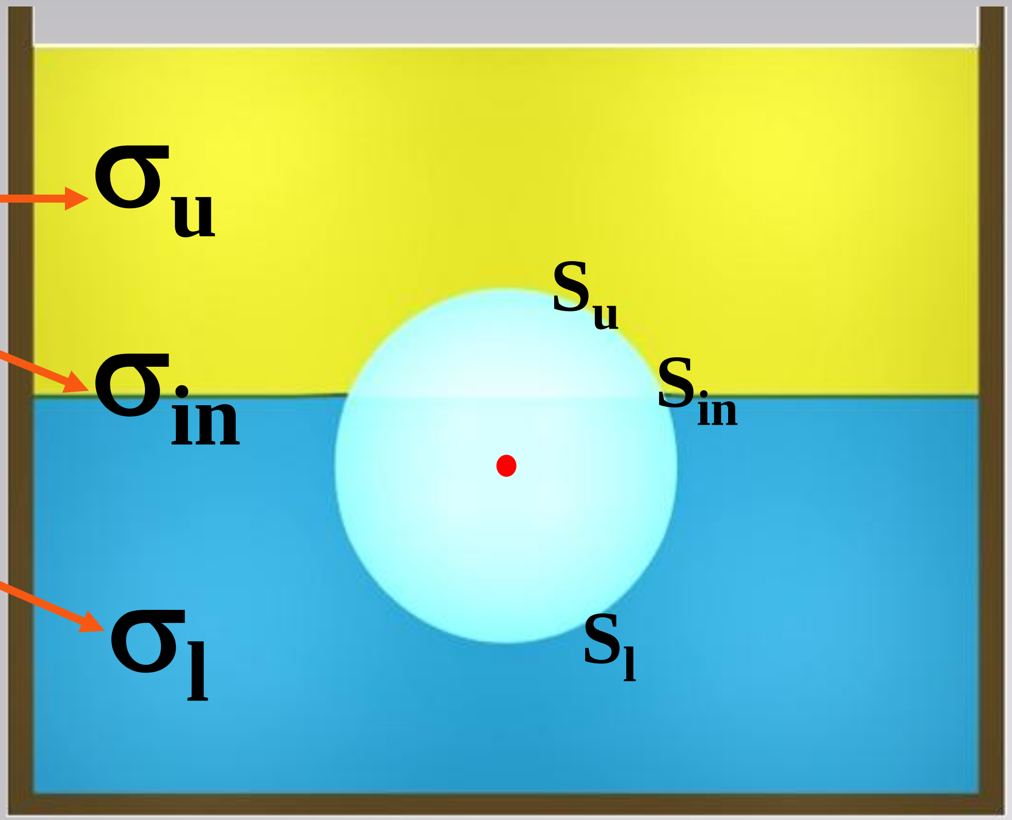
$$E_c = \pi(R^2 + h(h-2R))\sigma_{in} + 2\pi R(h(\sigma_u - \sigma_l) + 2\sigma_l R)$$

Surface tension of:

the **top liquid**

the **interface** between liquids

the **bottom liquid**

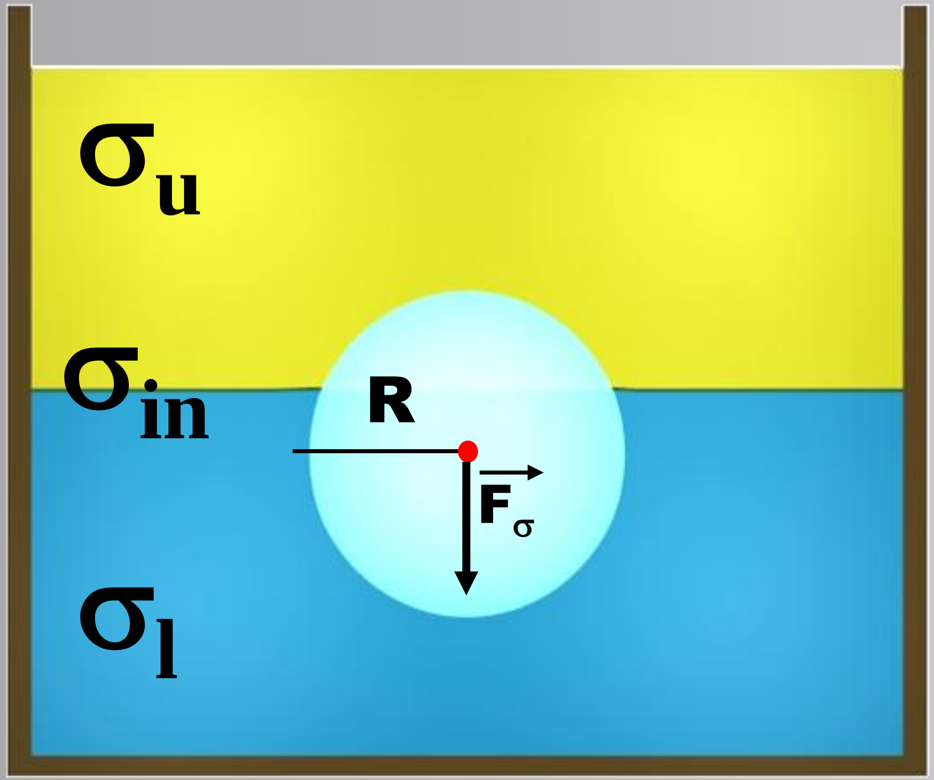


Surface tension force

In order to find **forces** acting on the bubble due to **surface tension** we can find a **gradient** of expression for surface potential energy:

$$E_c = \pi(R^2 + h(h-2R))\sigma_{in} + 2\pi R(h(\sigma_u - \sigma_l) + 2\sigma_l R)$$

hence: $$F_\sigma = -dE_c / dh = 2\pi(R(\sigma_l - \sigma_u + \sigma_{in}) - \sigma_{in} h)$$



If h < R:
- Fs acts downwards

If h > R:
- Fs acts upwards

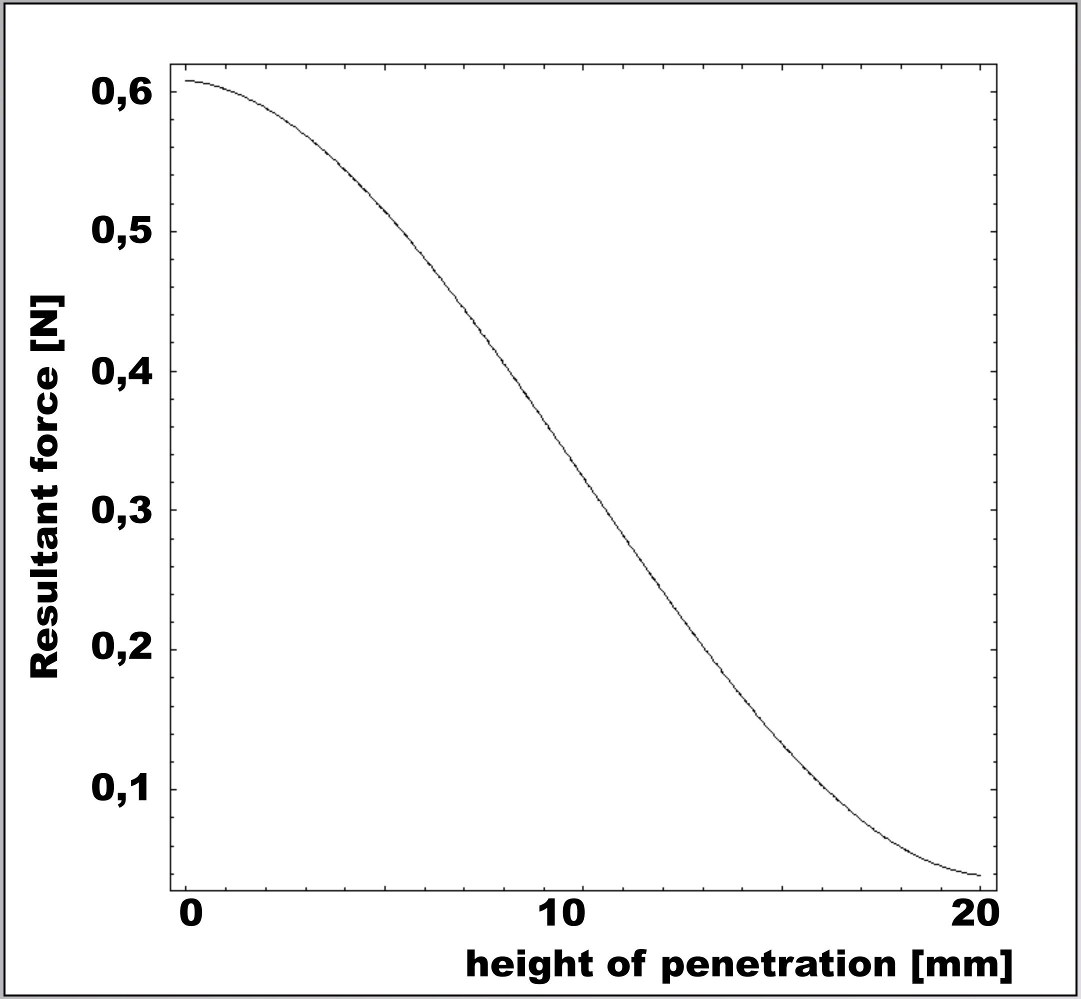
Resultant force

Resultant force is a sum of buoyant and surface tension forces:

$$F_c = 2\pi(R(\sigma_l - \sigma_u + \sigma_{in}) - \sigma_{in} h) + \pi g(4\rho_l R^3 + h^2 \Delta\rho(h - 3R))/3$$

R = 1 cm

mercury - water

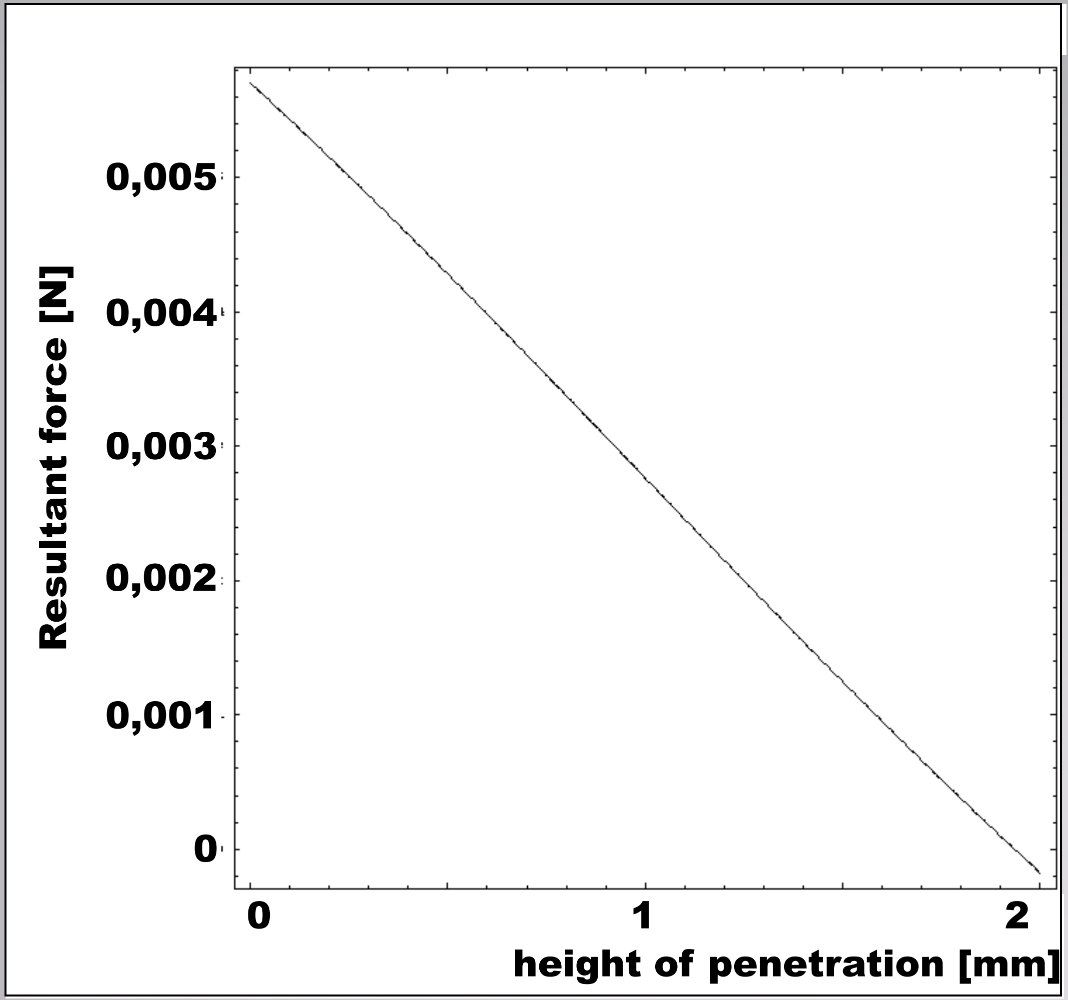


Resultant force

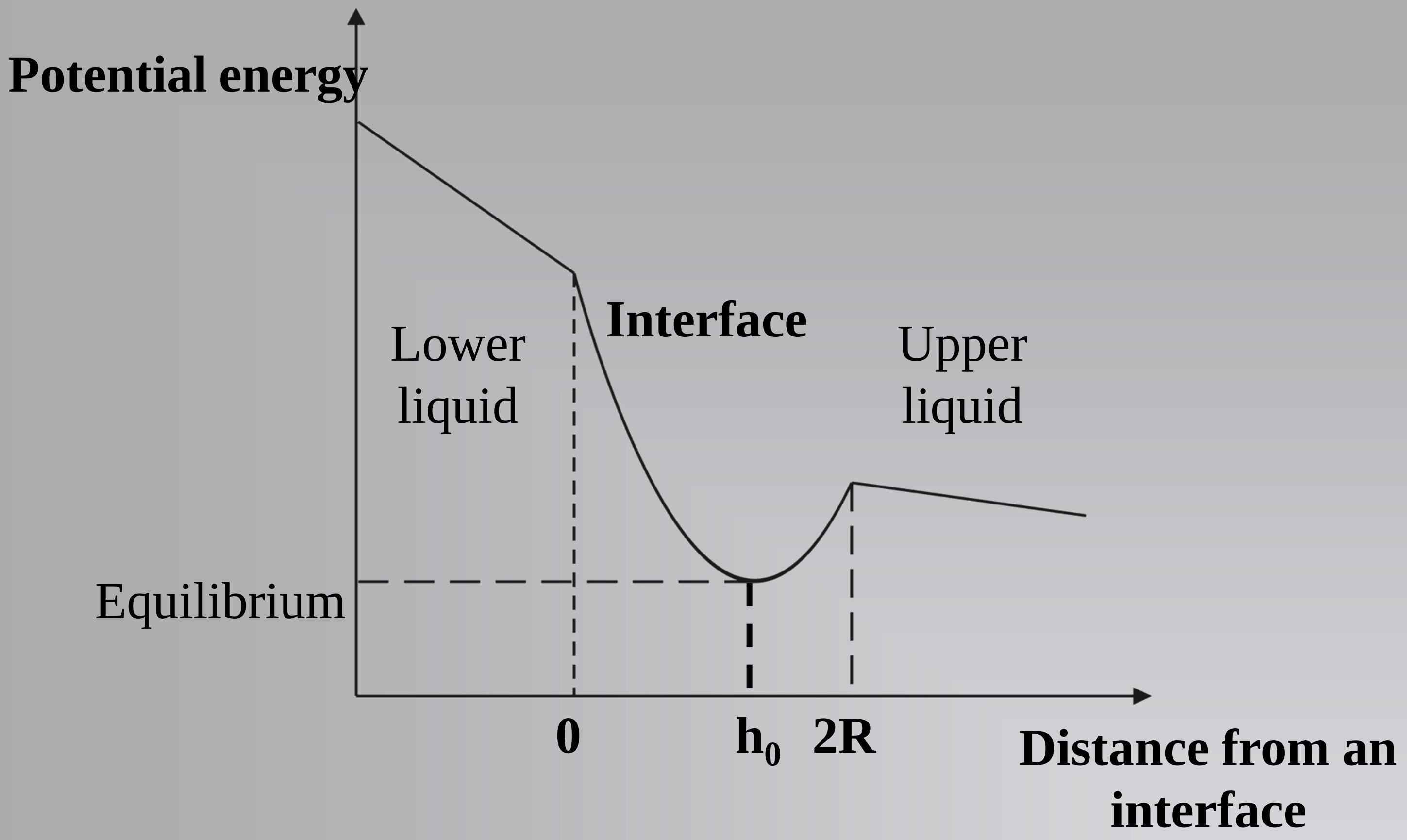
$$F_c = 2\pi(R(\sigma_l - \sigma_u + \sigma_{in}) - \sigma_{in}h) + \pi g(4\rho_l R^3 + h^2\Delta\rho(h-3R))/3$$

R = 1 mm

mercury - water



Potential energy



A magnitude of potential energy’s minimum is greater when the bubble is smaller because:

-Surface tension phenomenon has greater impact on bubble’s motion

-Buoyant force is far smaller than surface tension force

-Kinetic energy is smaller than surface free energy

Bubbles at an interface

A bubble will stop flowing out , if bouyant force equalls zero (special case $\rho_u=\rho_l$): $\mathbf{F_w = 0}$:

$$h_0 = 2\rho g R^3/3 + R(\sigma_{in} + \sigma_l - \sigma_u)/\sigma_{in}$$

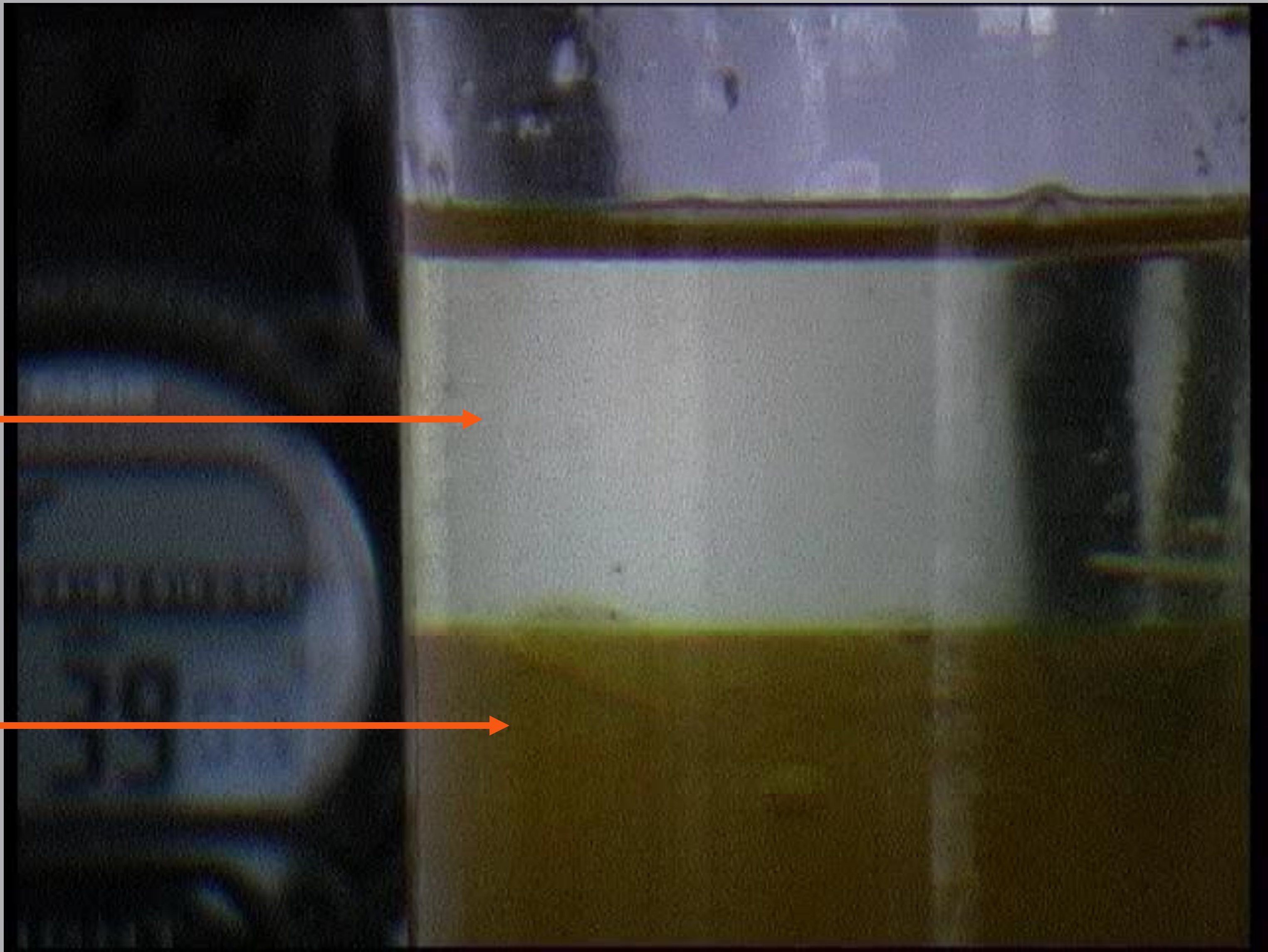
If : **0<h<2R** is satisfied, the bubble will stop flowing out. The radius of such bubble is equal (for any given ρ_g and ρ_d):

h=2R $$R_{\mathrm{min}} = \sqrt{3(\sigma_{\mathrm{in}} + \sigma_{\mathrm{u}} - \sigma_{\mathrm{l}})/2\rho_{\mathrm{u}} g}$$

If $(\sigma_{in} + \sigma_u - \sigma_l) <= 0$ any bubble will cross the interface

The bubble stops at the interface

R = 1,5 mm



Water

Liquid honey