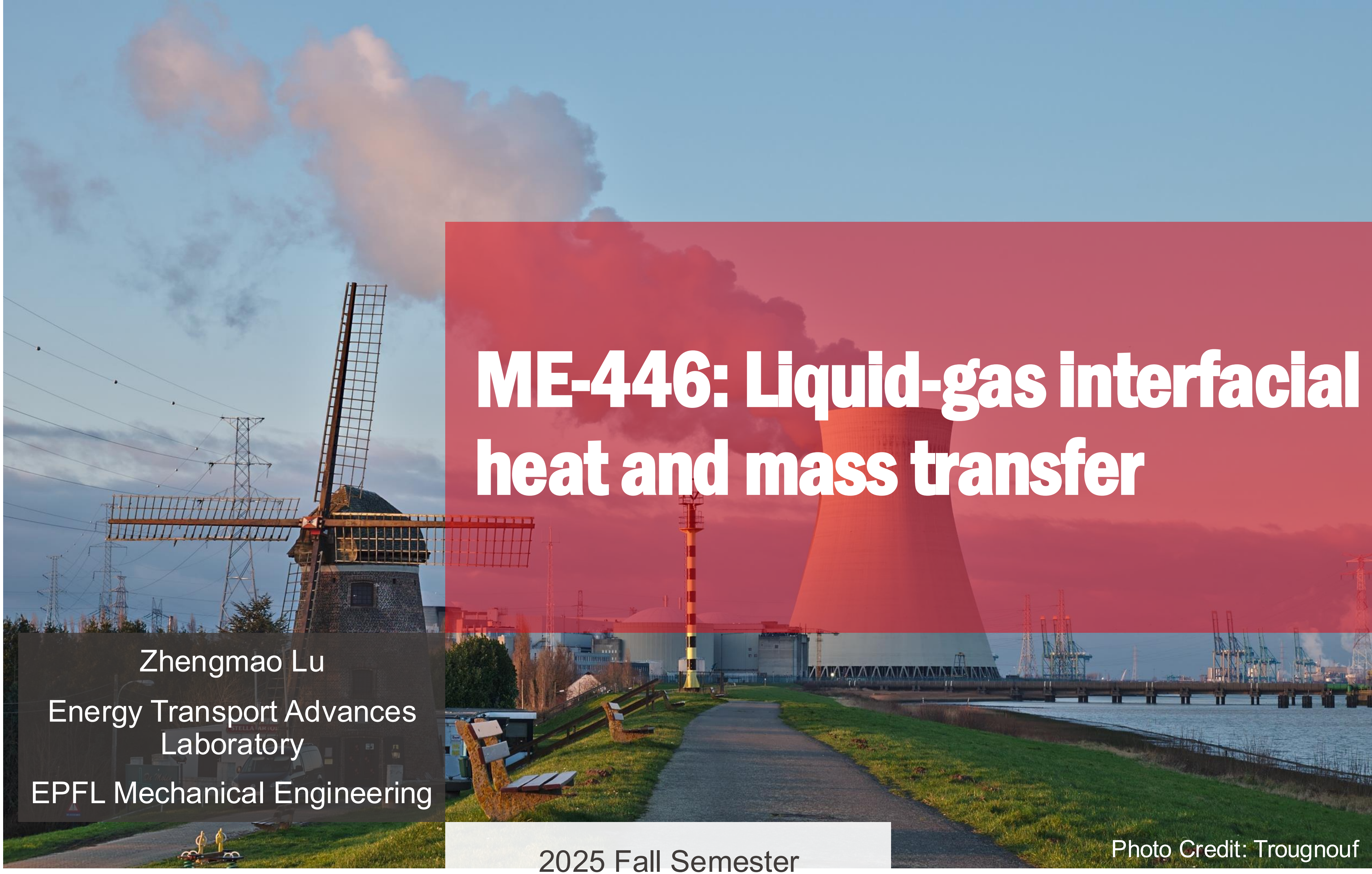


ME-446: Liquid-gas interfacial heat and mass transfer

Zhengmao Lu

Energy Transport Advances Laboratory

EPFL Mechanical Engineering

2025 Fall Semester

Photo Credit: Trougnouf

Instructors

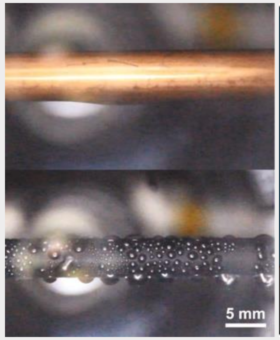
- I'm Zhengmao Lu (zhengmao.lu@epfl.ch)
  - Phase change heat transfer, interfacial phenomena, micro/nano, cooling
  - 22 years in China; 10 years in the US; Joined EPFL in February 2023
- Teaching Assistant: Gautier Rouaze (gautier.rouaze@epfl.ch)

Energy Transport Advances Laboratory

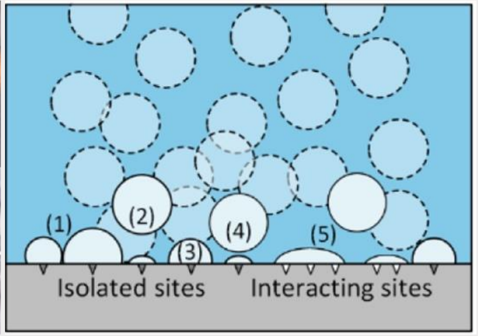
Zhengmao Lu EPFL > STI > IGM > ETA-Lab

Leverage **liquid-gas interfacial transport** to address the challenge of sustainability

Generation

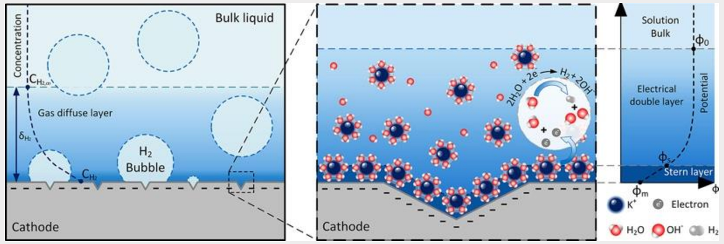


Condensation



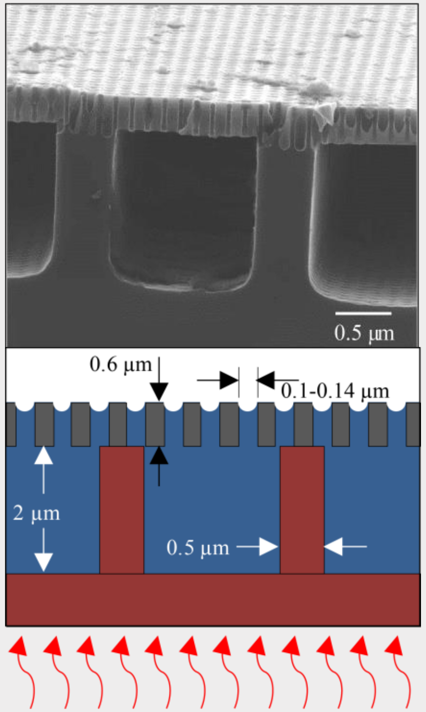
Boiling

Storage

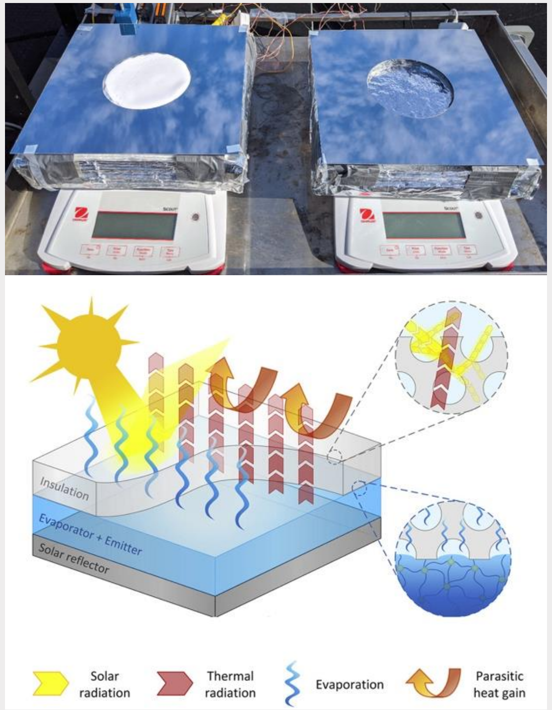


Alkaline water electrolysis

Usage

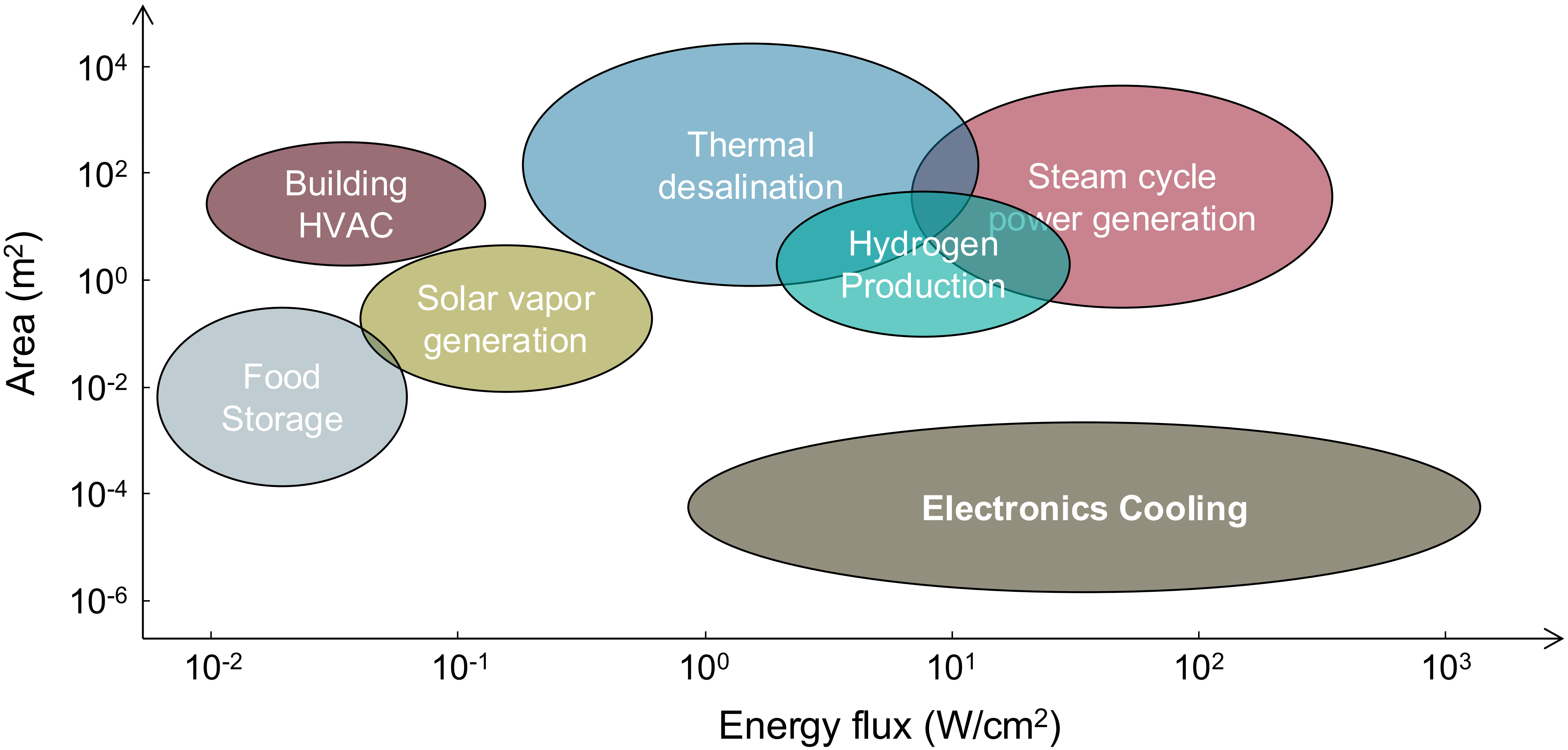


Electronics cooling



Passive building cooling

Broad Application of Liquid-Gas Interfacial Transport

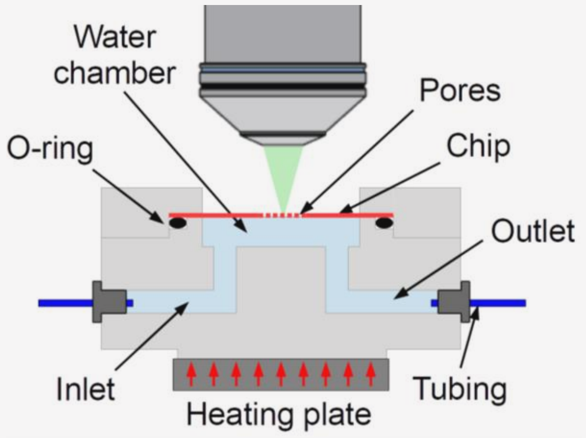


Current Research Activities

Length scale

nanometer | millimeter | meter

Interface contamination



Boiling bubble dynamics

Course Info

- Lectures
  - Thursday (08:15-10:00); we'll have a 15-minute break at 9h.
- Exercises
  - Thursday (10:15-11:00)
- Moodle
  - Important course info will be announced through Moodle
- Office hour
  - Thursday one hour after the exercise

Assessment

- Homework presentation 25%

  - In each week's exercise session, 3-4 of you will form a HW group, work together on a problem set, and present your solution to the class.
  - We will post a Google Sheet of the HW group with preassigned names on Moodle, but feel free to trade slots.
  - The rest of the class is also expected to work on the same problem set prior to the exercise session. Solution will be posted the week after for self-correction.
  - For the HW presentation, you get the full score if you show reasonable amount of effort regardless whether you get the correct answer.

Assessment

- Journal presentation 25%

  - We will post several recent papers in the area of liquid-gas interfacial phenomena. You can sign up for the one in which you are most interested.
  - People who choose the same paper form a JP group. Each group has a size limit based on the specific paper. The sign-up sheet and the papers will be posted later in the semester, first come first service.
  - In the two weeks before the last lecture week, each JP group will give an oral presentation (presentation period = group size x 5 min + 5 min Q&A)
  - I will evaluate your presentation based on whether you show reasonable amount of effort to understand and communicate your understanding to the audience.

Assessment

- Final Exam 50%
  - Will be closely related to exercise problems
  - There will be a review session in the last week of the semester.

Lab Tour

- We will organize a tour of the ETA-Lab in Week 10 (to be confirmed)

Reference Books

- **Carey**, V. P. (Van P.). Liquid-Vapor Phase-Change Phenomena: An Introduction to the Thermophysics of Vaporization and Condensation Processes in Heat Transfer Equipment. Third edition. Boca Raton: CRC Press, 2020.
- **Lienhard** IV, John H, and John H Lienhard V. A Heat Transfer Textbook. 5th ed. Mineola (N.Y.): Dover Publications, 2019.
- **Bird**, R. Byron, Warren E Stewart, and Edwin N Lightfoot. Transport Phenomena. Rev. 2nd ed. New York: Wiley, 2007.

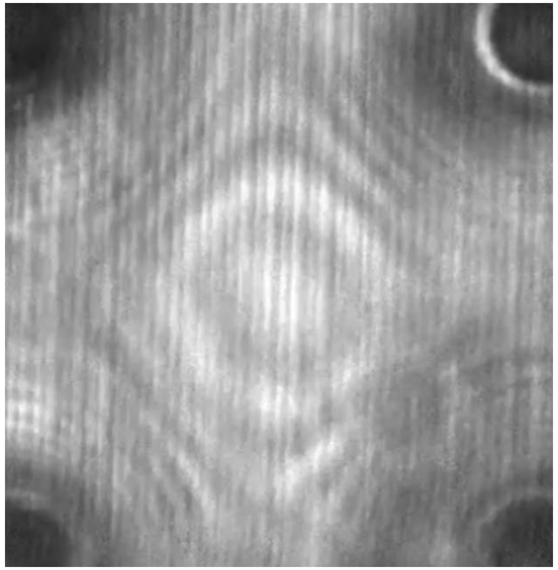
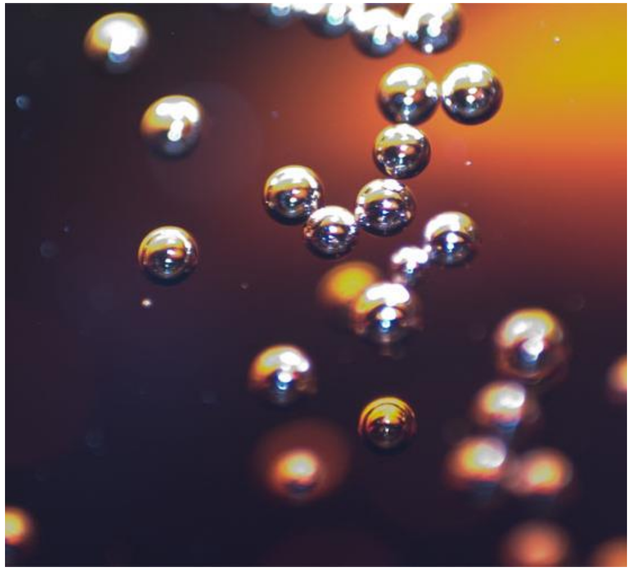
What We Study in ME-446

Evaporation

Boiling

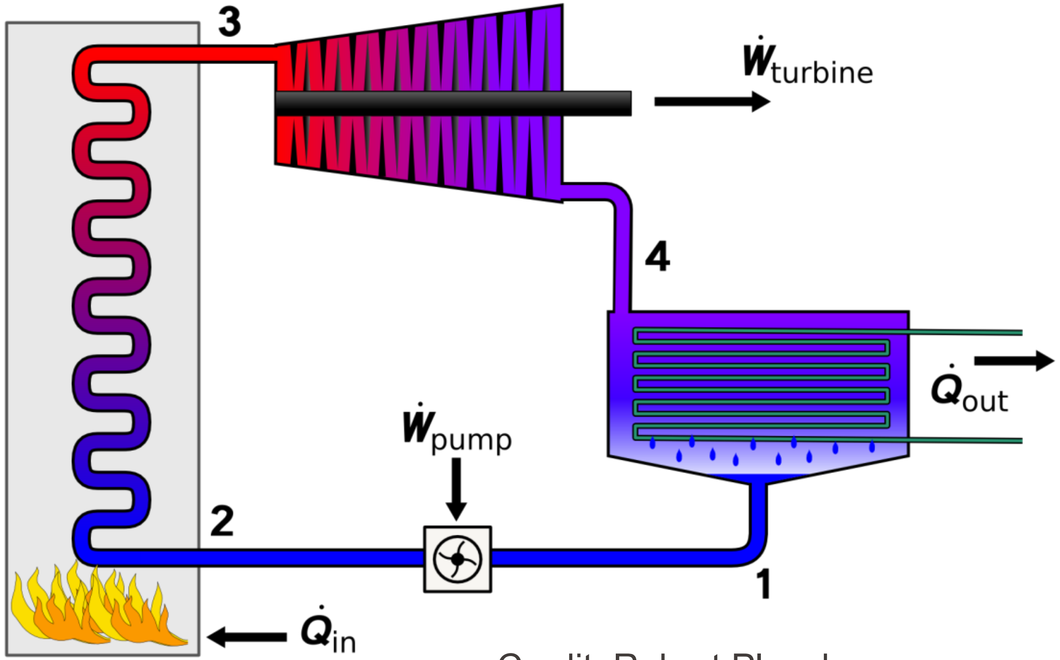
Condensation

What We Study in ME-446

Film	Bubble	Droplet
		
Langmuir 2016 32 (2), 519-526	Credit: Spiff	Credit: Jesse Marino

Heat and mass transfer across liquid-gas interfaces as phase change occurs

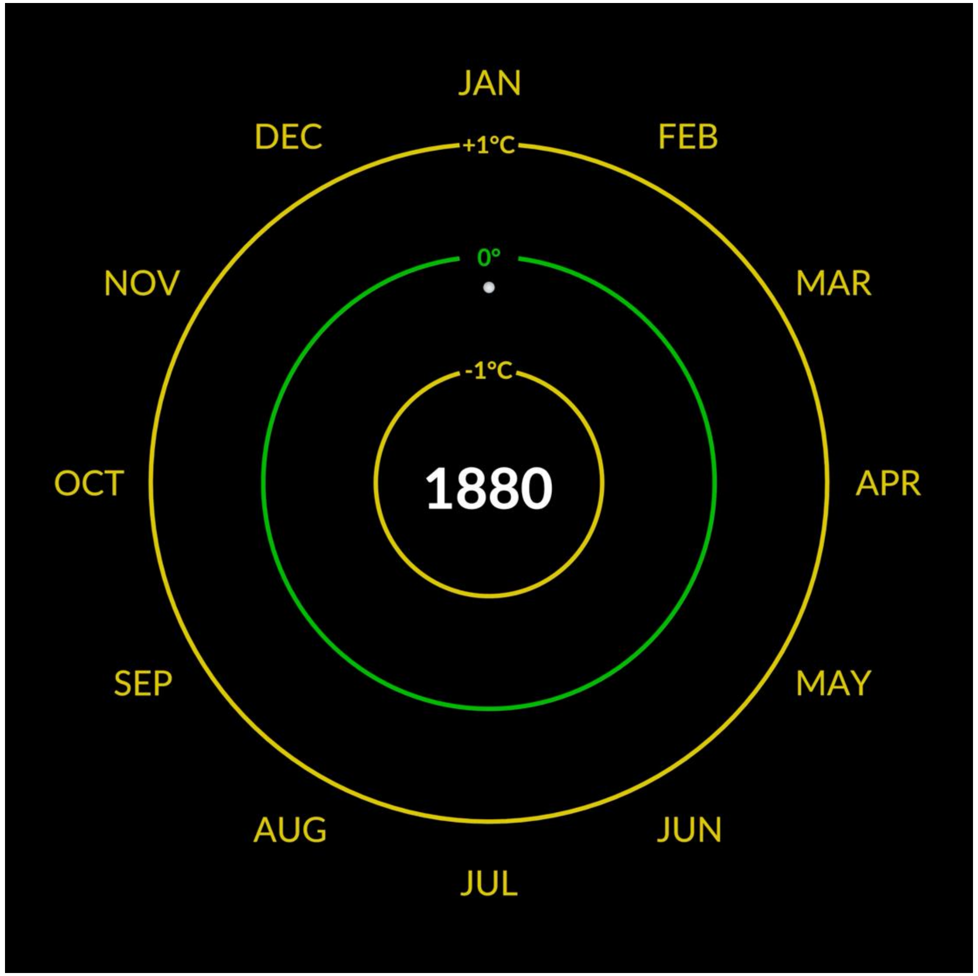
Why We Study ME-446



Credit: Robert Ploucha

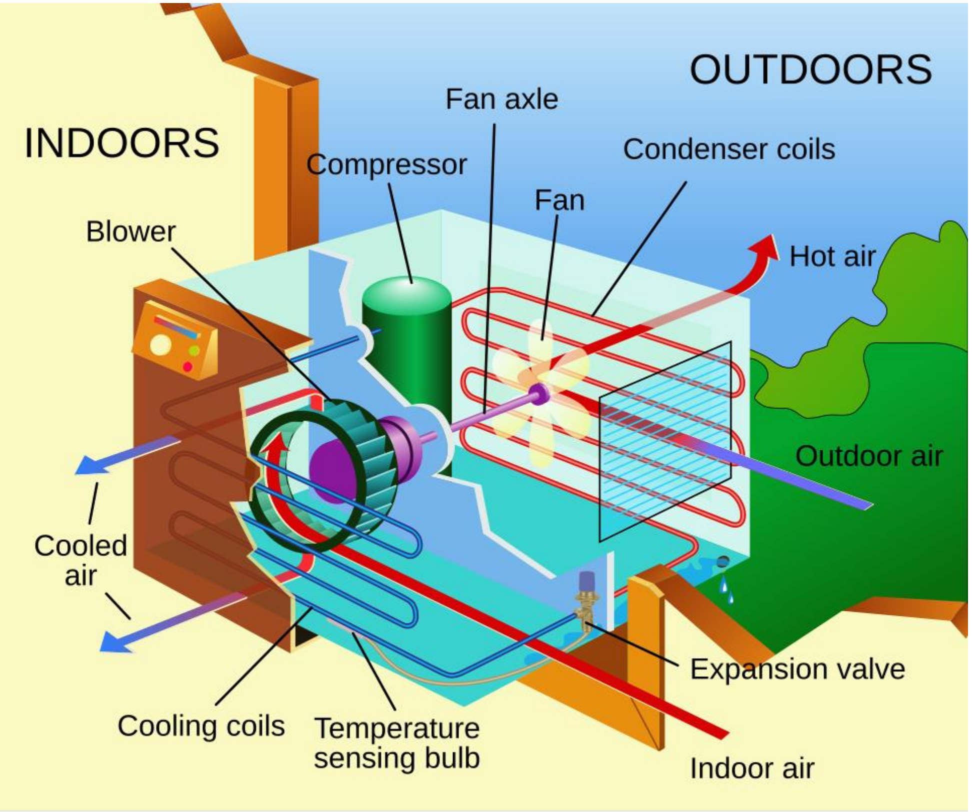
Boiling and condensation play critical roles in power generation

Why We Study ME-446



https://svs.gsfc.nasa.gov/5190/

Why We Study ME-446

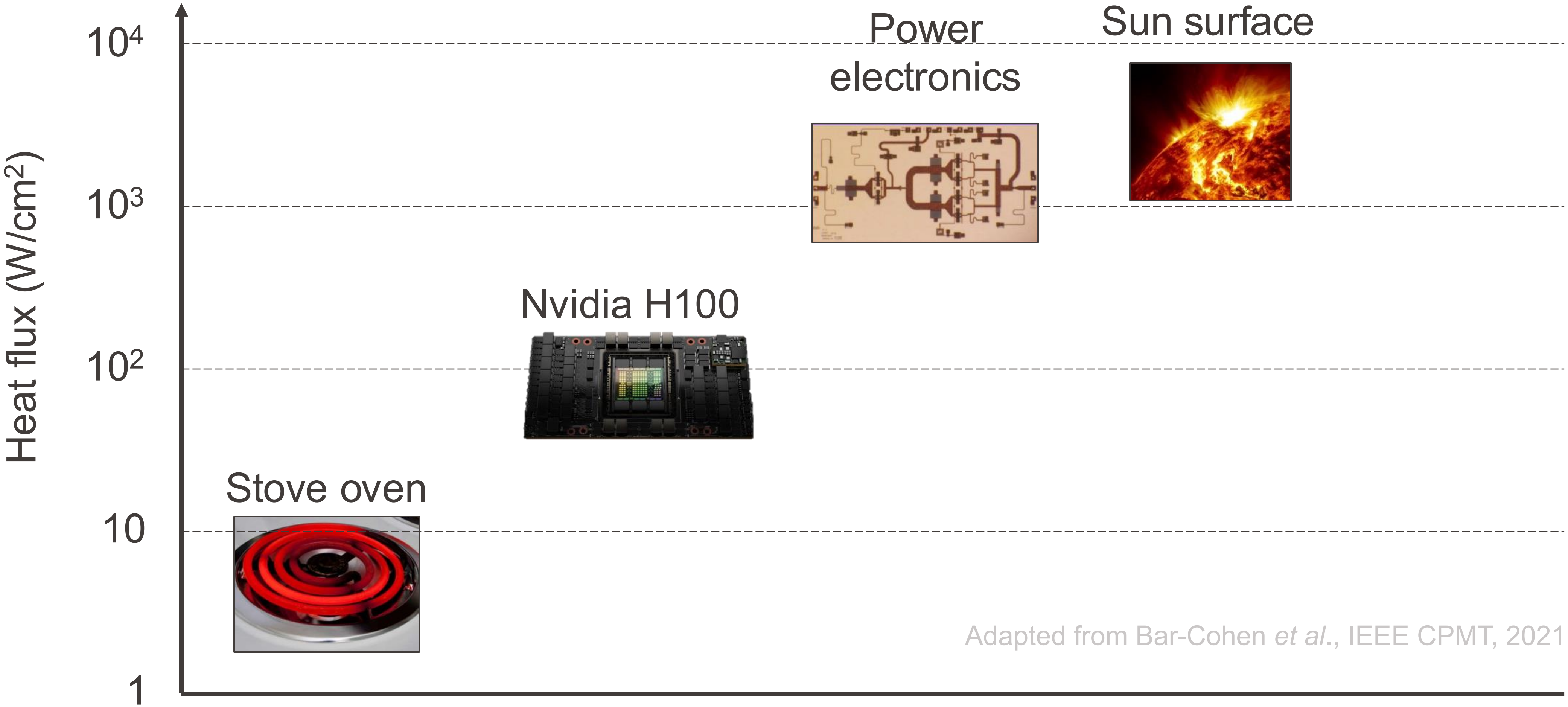


Source: The New Book of Knowledge 1997. p.102

Evaporators and condensers are key components of air conditioning and refrigeration systems

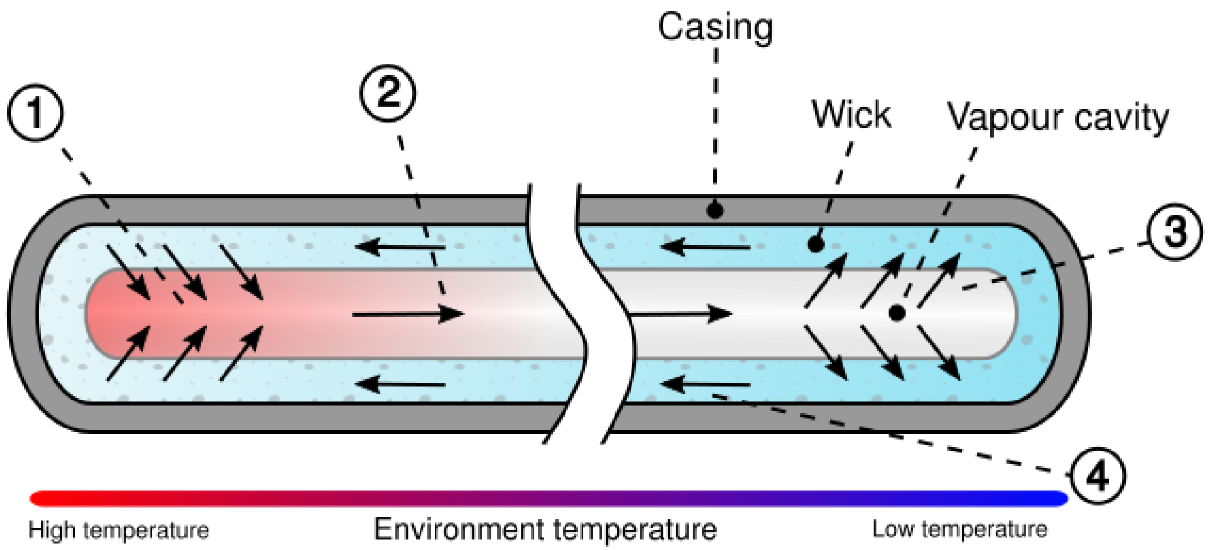
Why We Study ME-446

Electronics cooling critical for device performance and reliability



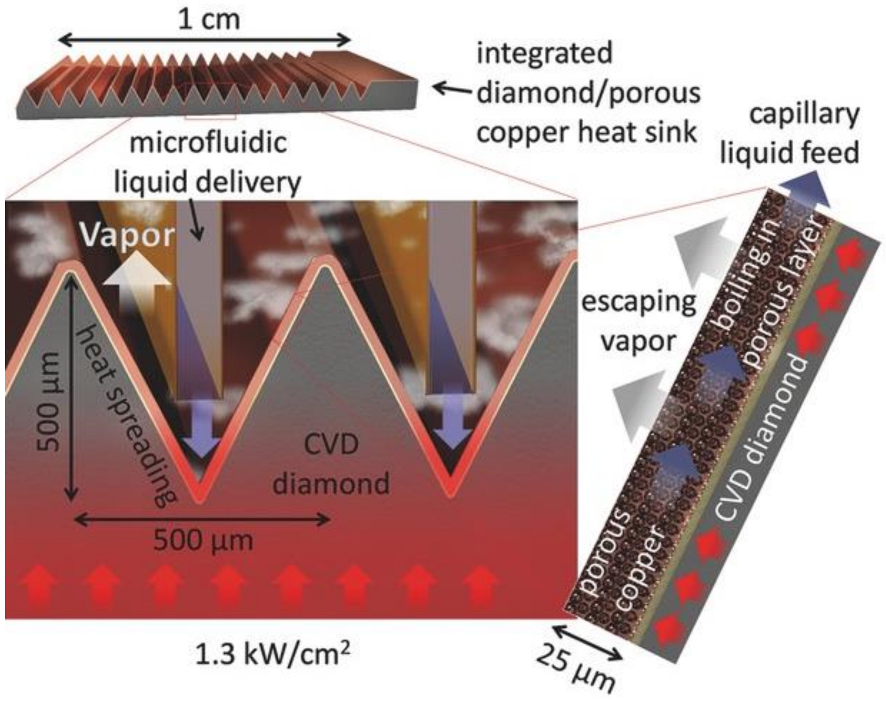
Adapted from Bar-Cohen *et al*., IEEE CPMT, 2021

Why We Study ME-446



Heat pipe thermal cycle
1) Working fluid evaporates to vapour absorbing thermal energy.
2) Vapour migrates along cavity to lower temperature end.
3) Vapour condenses back to fluid and is absorbed by the wick, releasing thermal energy.
4) Working fluid flows back to the higher temperature end.

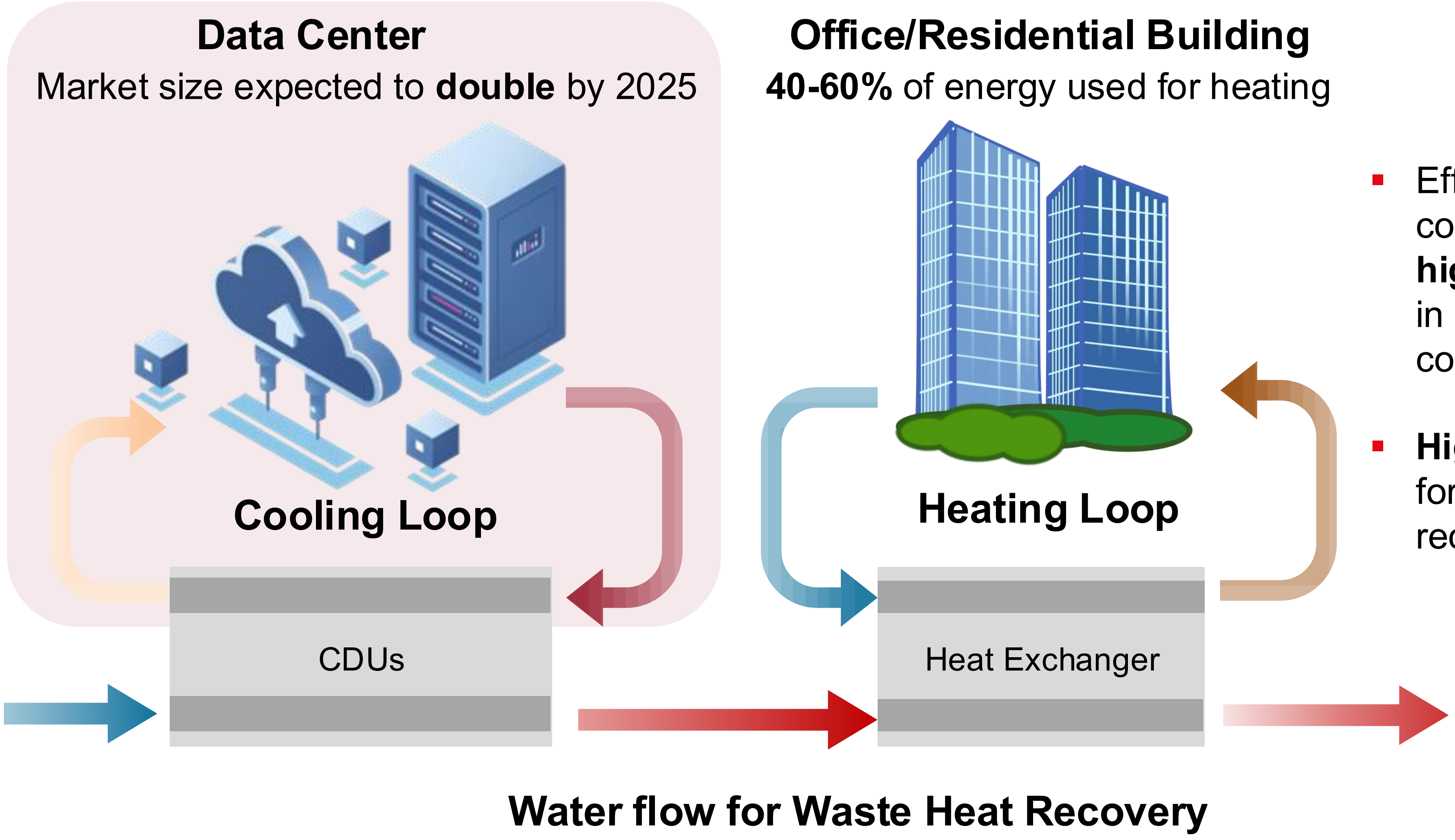
Credit: Zootalures and Offnfopt



Two-phase cooling from microporous copper

Palko, *et al.*, *Advanced Functional Materials*, 2017

Why We Study ME-446



- Efficient chip-level cooling enables **higher temperature** in data center cooling loop
- **Higher efficiency** for waste heat recovery

Why We Study ME-446

ETA-Lab
Energy Transport Advances

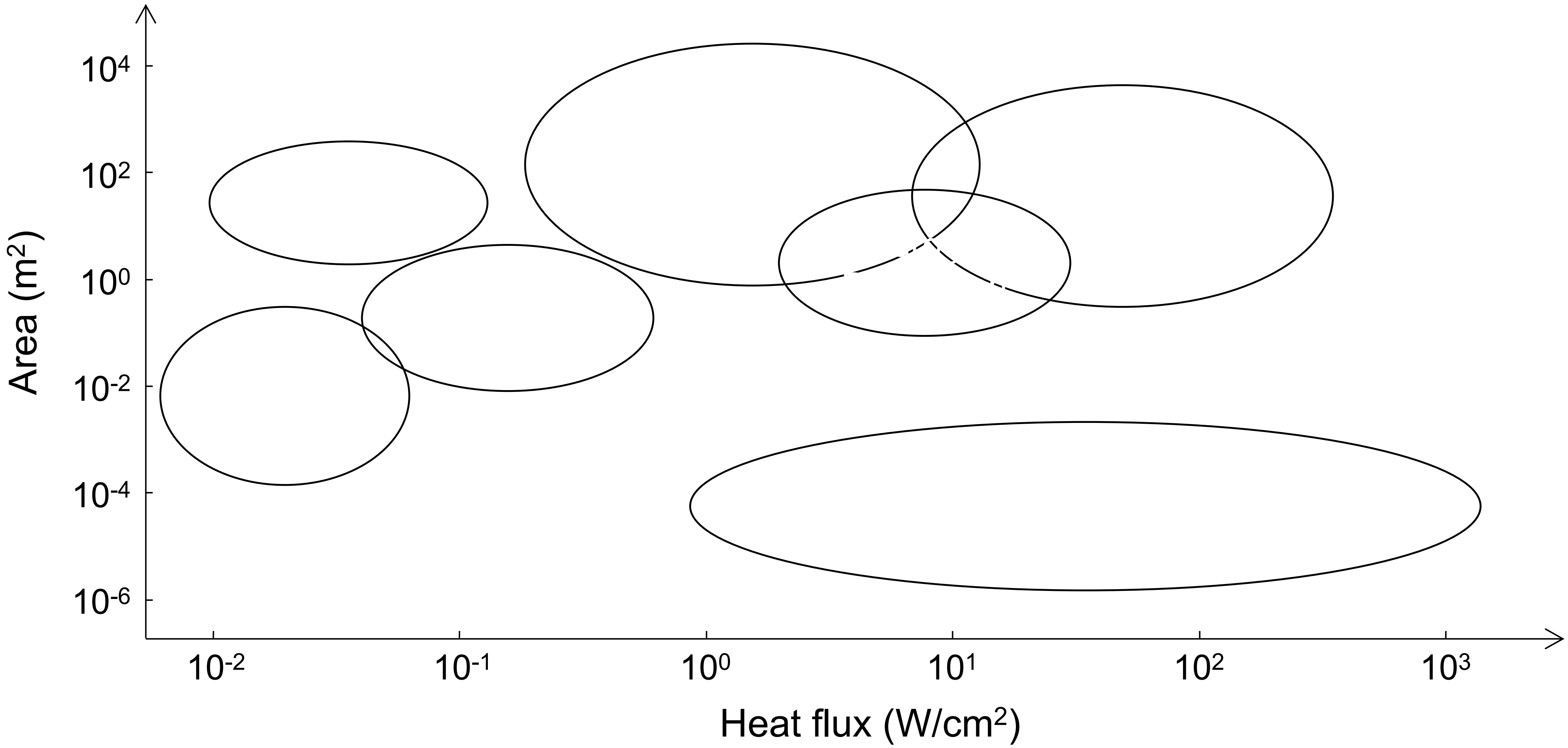
REDUCING THE CARBON FOOTPRINT OF DATA CENTERS

HEATING BITS

EPFL Sustainability Project

https://heatingbits.epfl.ch

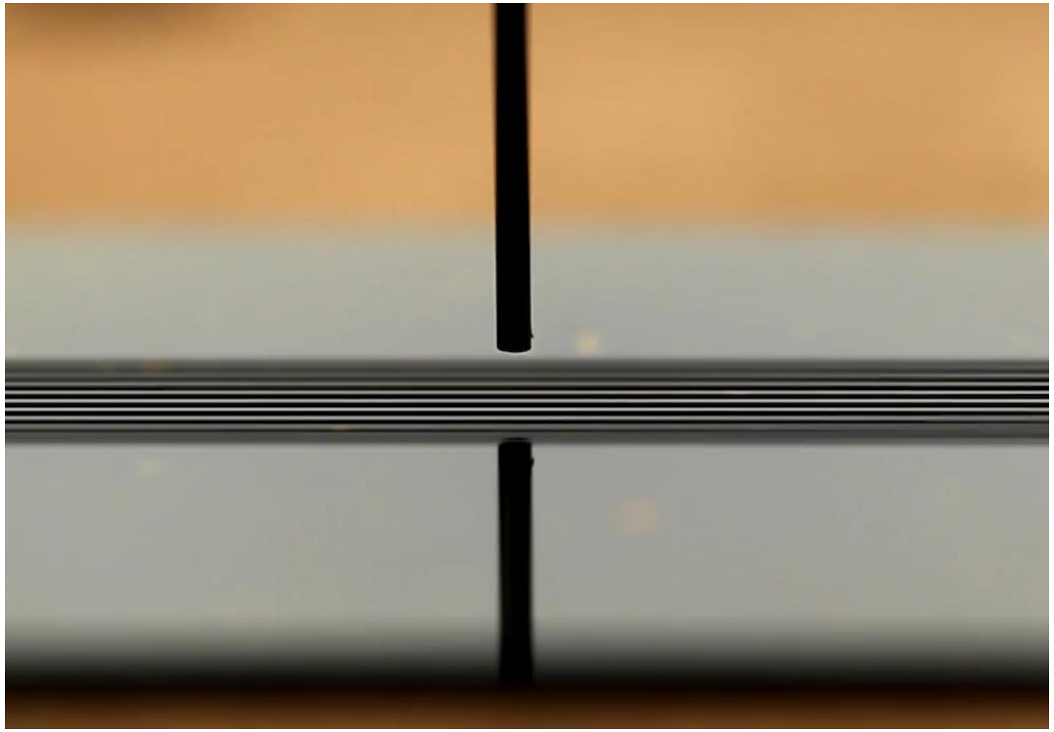
Broad Applications of Liquid-Vapor Phase Change



What We Study in ME-446

- 1. Capillarity and wetting
- 2. Evaporation physics
- 3. Pool boiling
- 4. Condensation
- 5. Flow boiling

Capillarity and Wetting



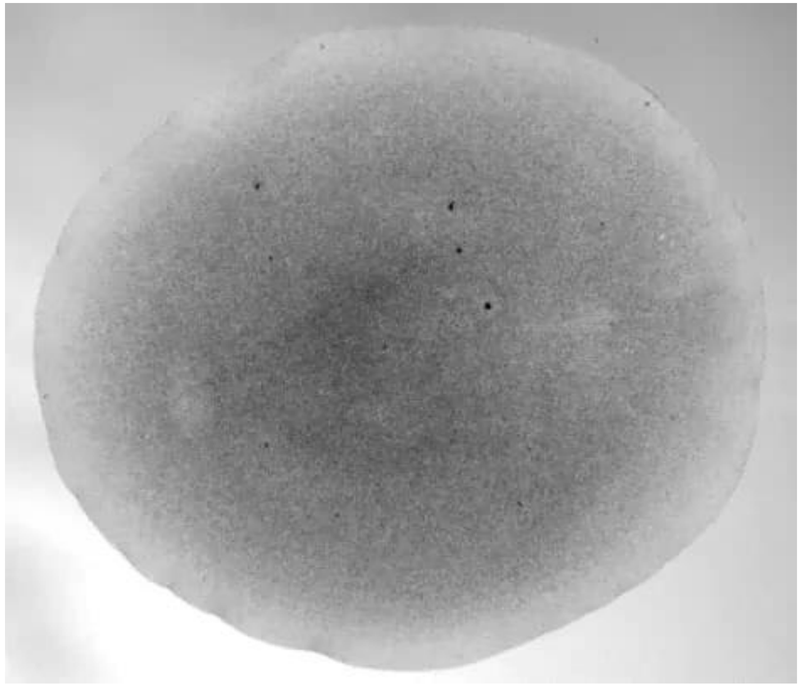
Capillary Wicking

Wilke *et al.*, *PNAS* 2021

Hydrophobicity

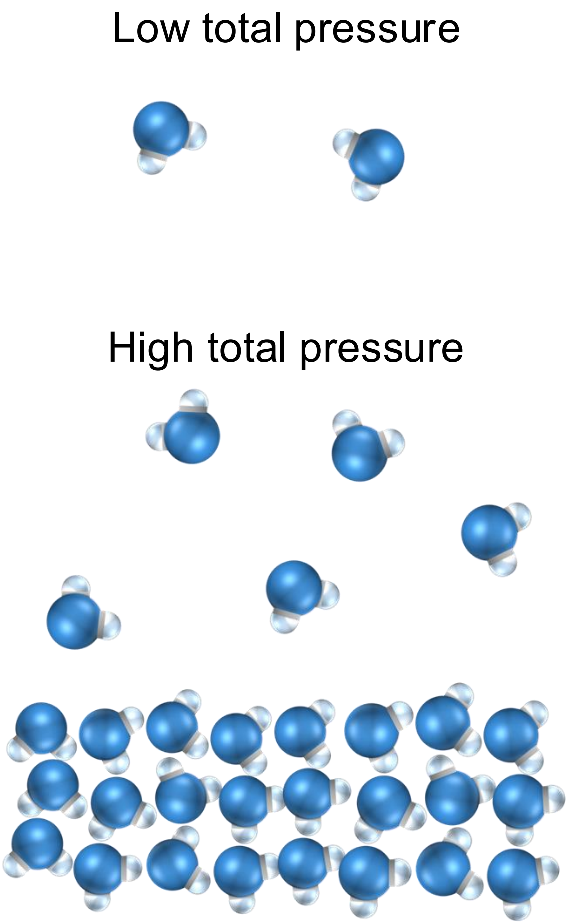
http://davewirth.blogspot.com/2011/11/final-lotus-of-year.html

Evaporation Physics



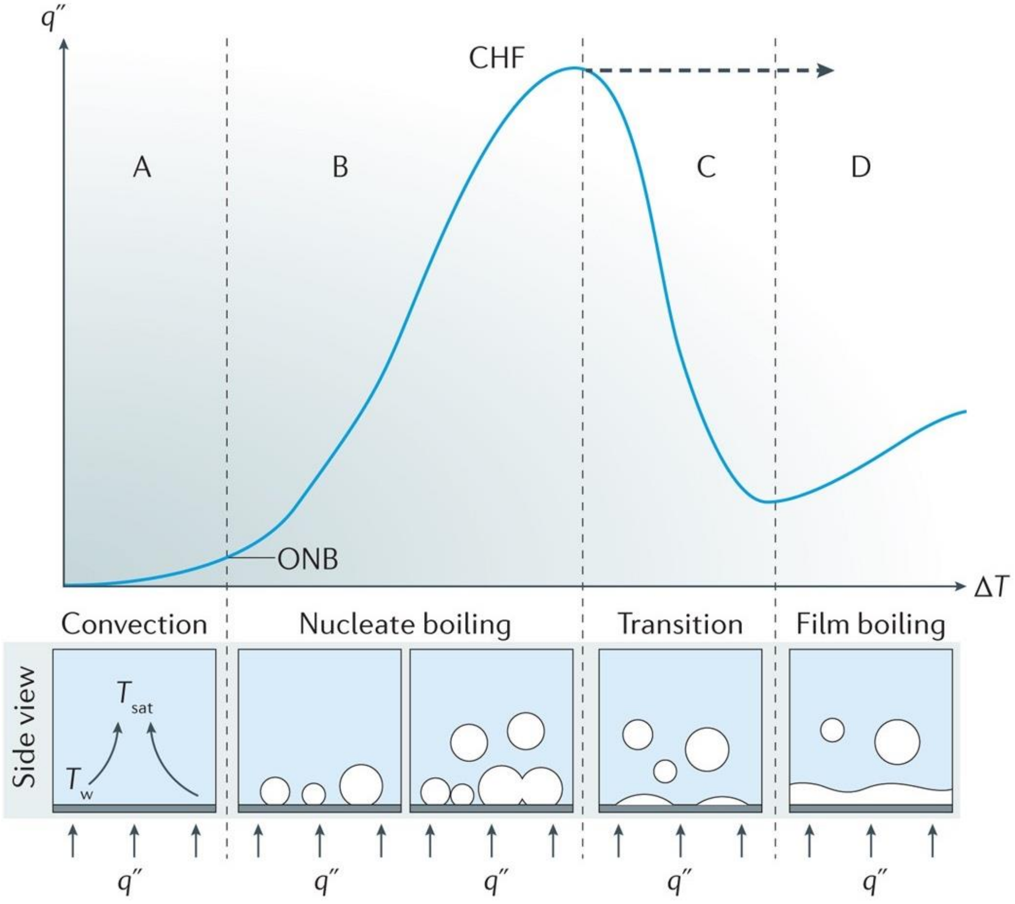
Yunker *et al.*, *Nature* (2011)

Molecular gas dynamics

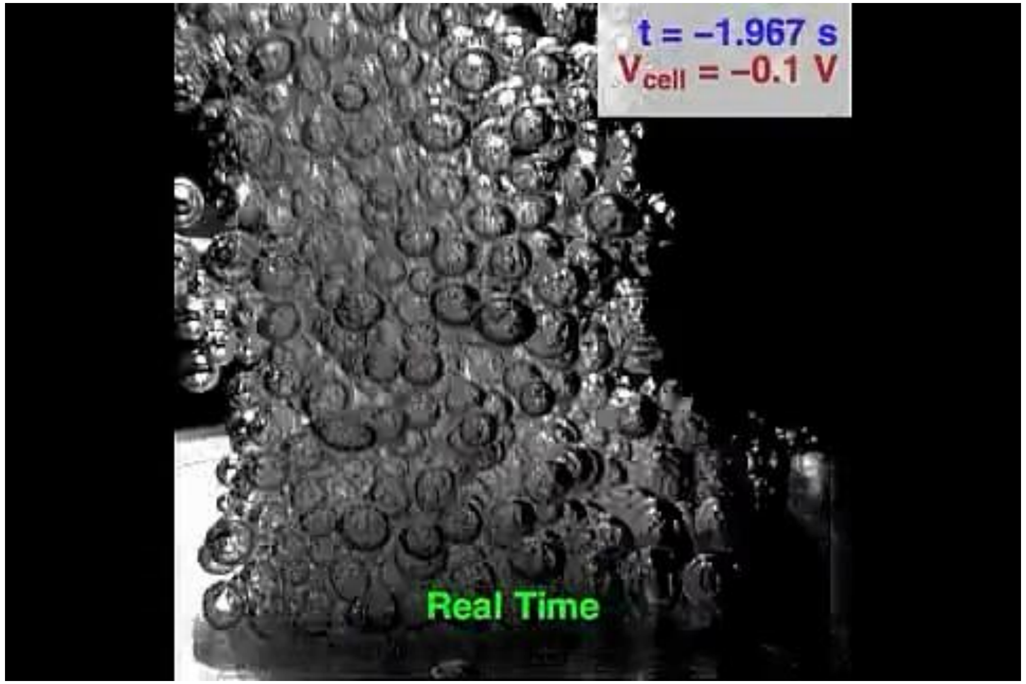


Lu *et al.*, *Nat. Comm.* 2019

Pool Boiling

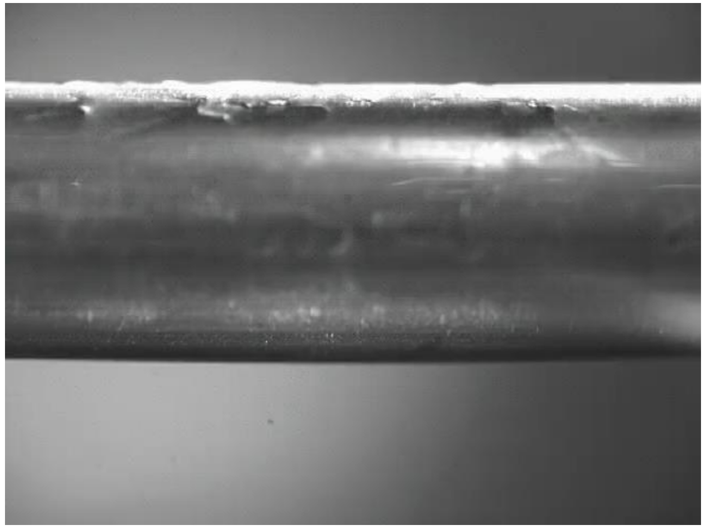


Cho *et al.*, *Nature Reviews Materials* 2016

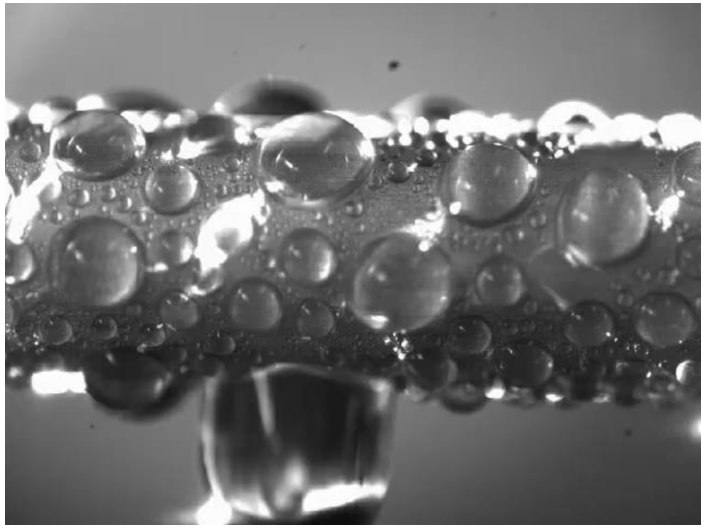


Cho *et al.*, *Nat. Comm* (2016)

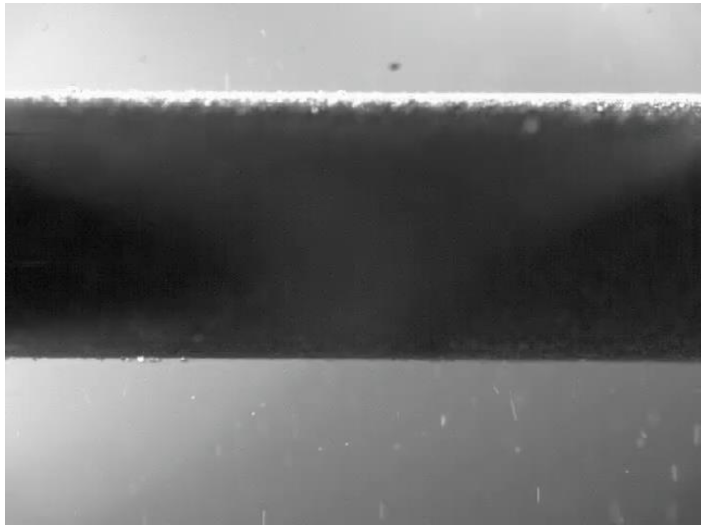
Condensation



Filmwise condensation



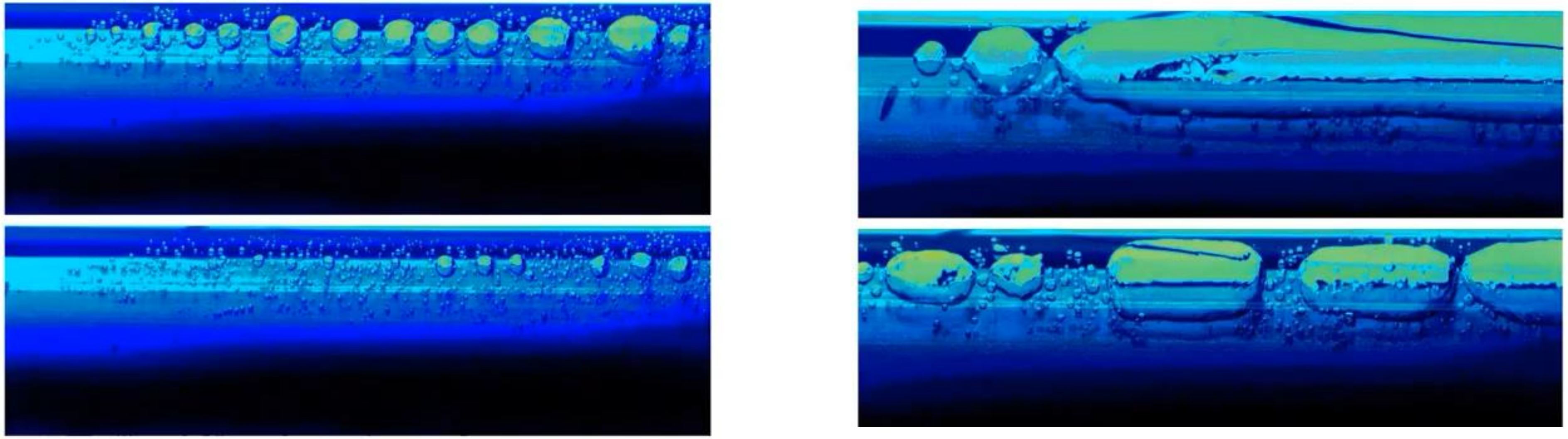
Dropwise condensation



Jumping-droplet condensation

Miljkovic *et al.*, *Nano Lett.* (2013)

Flow Boiling



Different regimes in flow boiling (slowed down 50 times)

https://www.youtube.com/shorts/HNcp7zDtwx8?feature=share

At the End of the Semester, You Should Be Able to

- Explain **capillarity-driven phenomena** in the context of fluid films, bubbles, and droplets
- Analyze and quantify **heat and mass transfer** across liquid-gas interfaces
- Model phase change systems for **energy and water applications**

Capillarity and Wetting

- Intended Learning Objectives
  - Explain the concept of **surface tension/surface energy**
  - Explain the concept of **Laplace pressure**
  - Apply **Young-Laplace equation** to liquid-gas interfaces

Reading materials: Carey Chapter 1.2, Chapter 2

Liquid-Vapor Interface (Molecular Perspective)

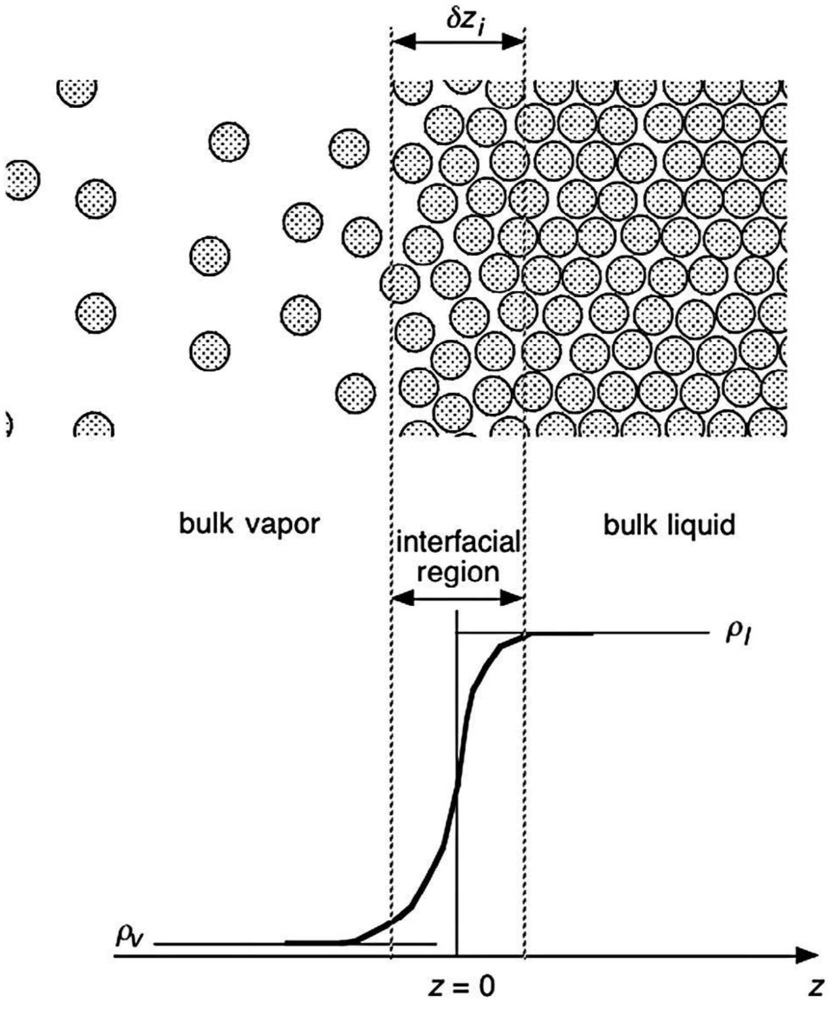
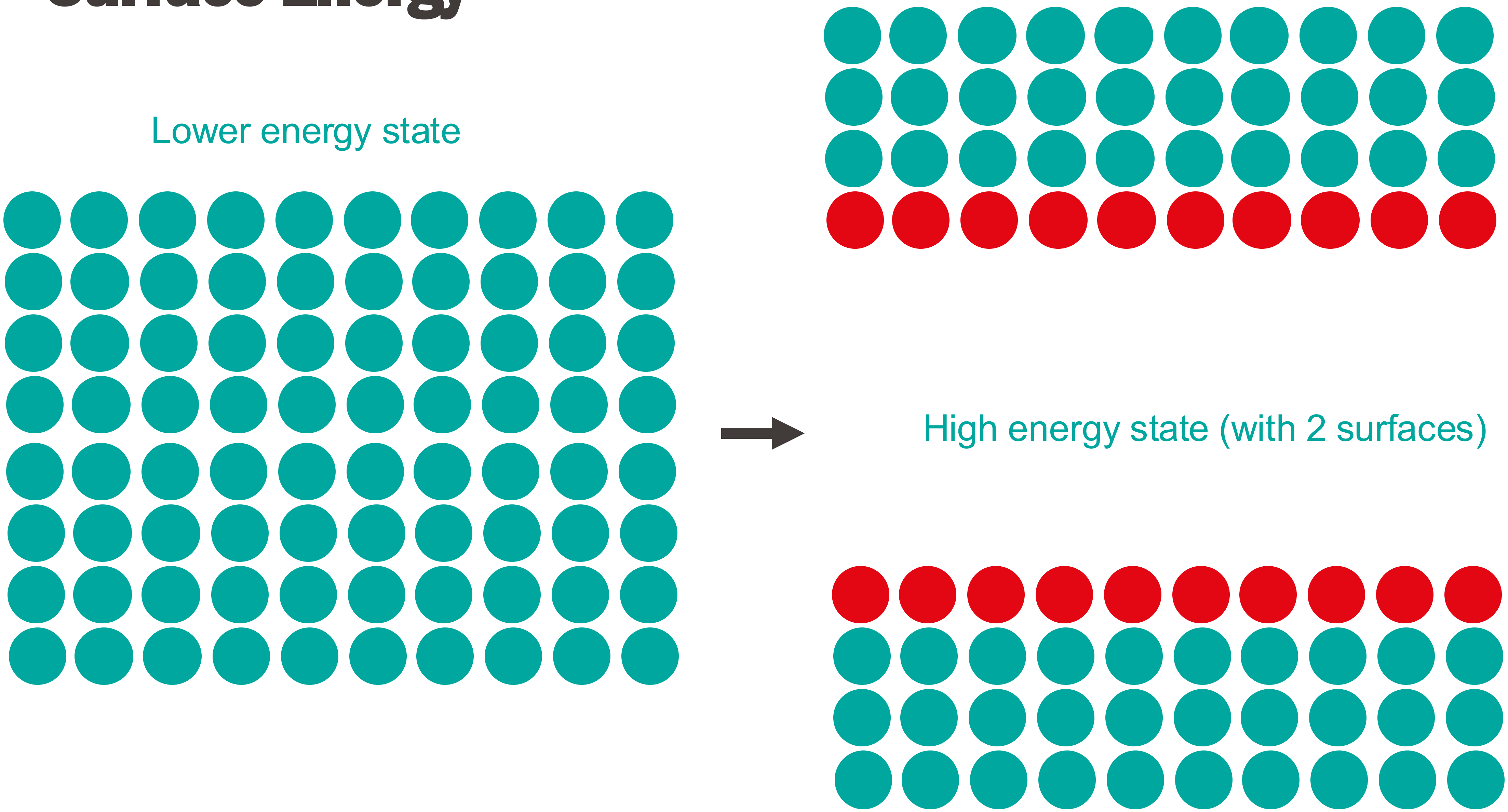


Figure 1.3 in Carey

Energy must be supplied to move molecules apart

Density distribution near an interface with molecules **attracting** one another

Surface Energy



Surface Energy

- Surface energy can be seen as the work that needs to be done to create a surface per unit area **(J/m^2)**
- Surface energy depends on the intermolecular interaction

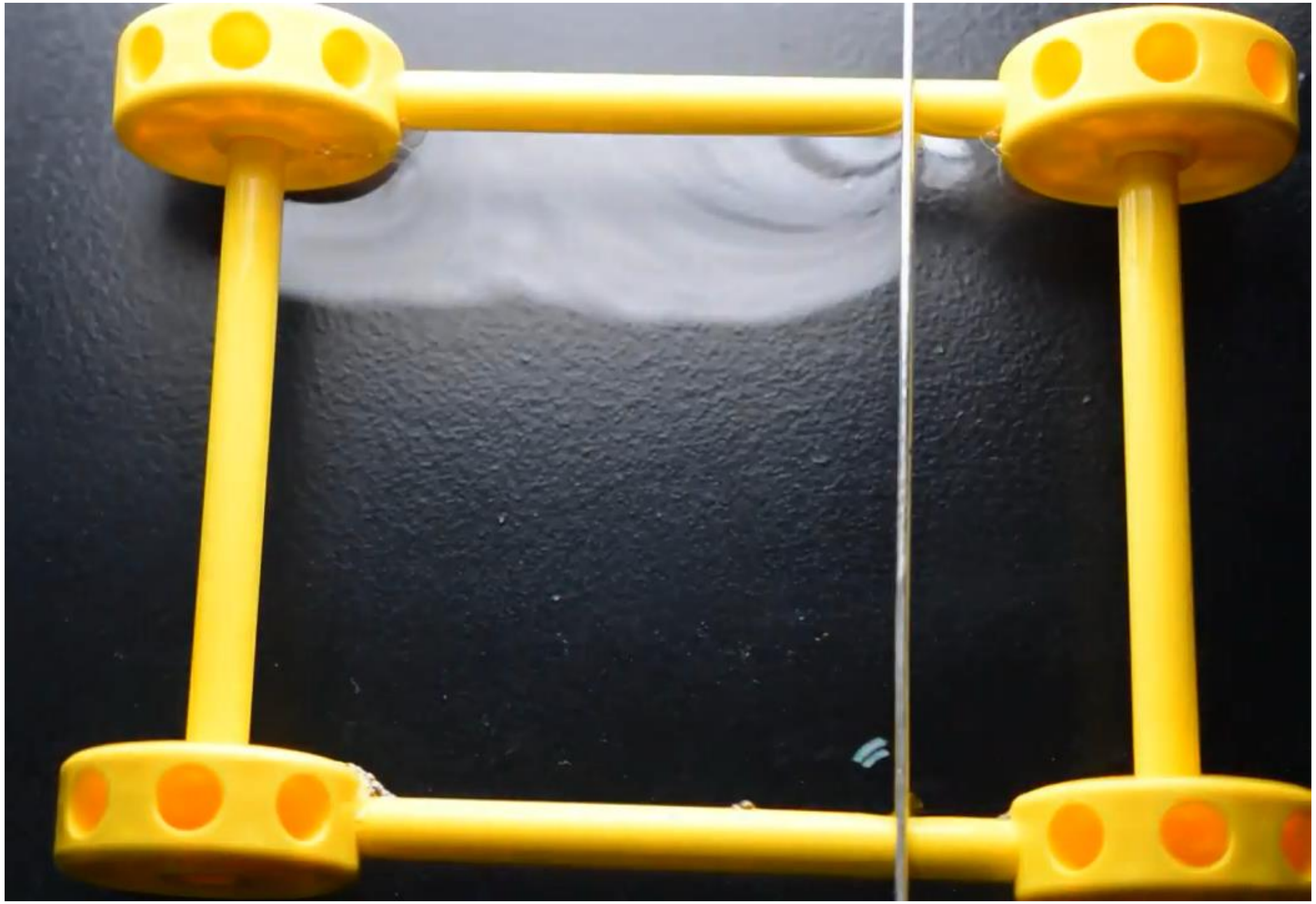
Force per length or energy per area?

Values of Surface Tension for Various Liquids in Contact with Air or its Own Vapor at Saturation

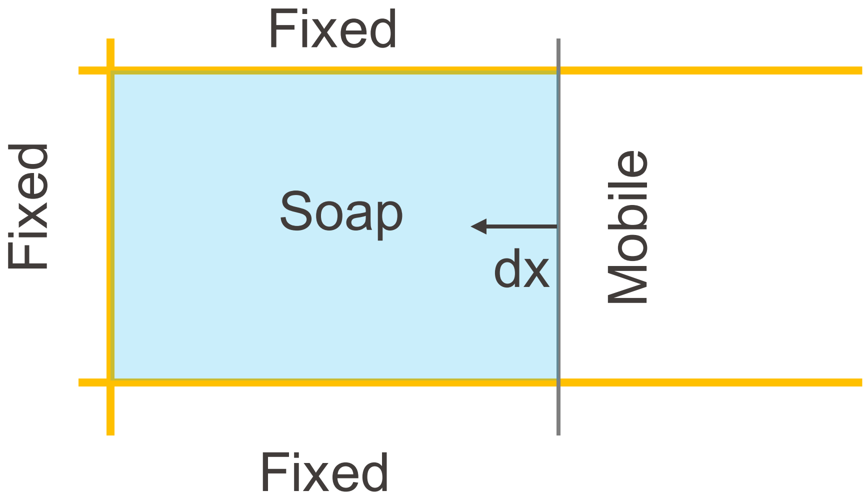
Liquid	Temperature (°C)	Surface Tension (mN/m)
Silver (Ag)	1100	878
Mercury (Hg)	20	484
Hydrazine (N_2H_4)	25	91.5
Water (H_2O)	20	72.8
Ethylene glycol ($C_2H_6O_2$)	20	48.4
Ammonia (NH_4)	–40	35.4
Carbon tetrachloride ($CC1_4$)	20	27.0
n-Butanol ($C_4H_{10}O$)	20	24.6
Acetone (CH_3COCH_3)	20	24.0
Ethanol (C_2H_6O)	20	22.8
Methanol (CH_4O)	20	22.6
R-113 ($CC1_2FCC1F_2$)	26.7	19.0
R-11 ($CC1_3F$)	26.7	18.0
R-12 ($CC1_2F_2$)	17	9.4
R-134a (CF_3CH_2F)	18	9.0
Helium II (He_{II})	–271	0.32
Helium III (He_{III})	–271	0.069

Carey, Table 2.1

Surface Tension: Force per Length

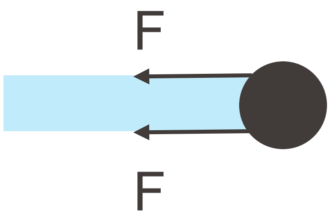


Surface Tension: Force per Length



- The mobile rod moves in the direction of the arrow spontaneously because the system wants to minimize surface energy

- The surface exerts line forces on the rod:



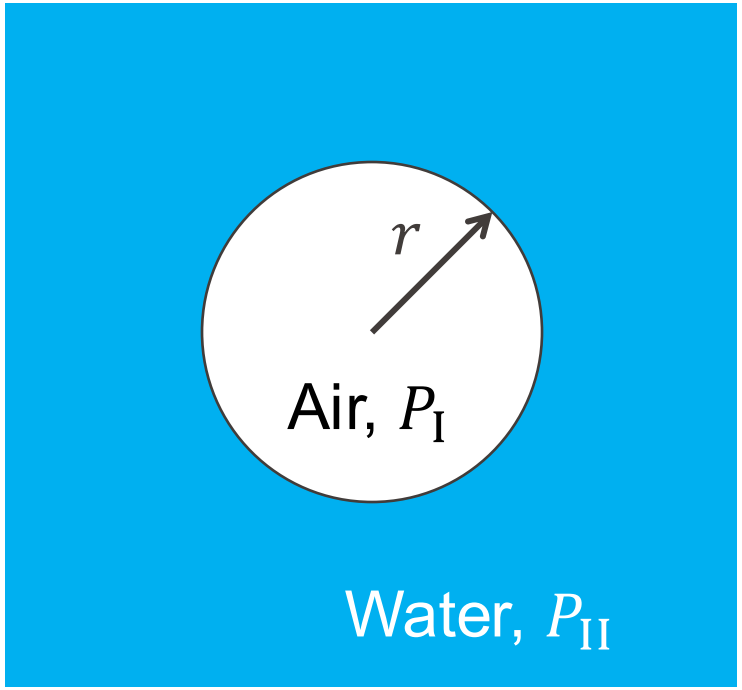
$$2Fdx = 2\sigma L dx$$

$$\sigma = \frac{F}{L}$$

Force per unit length, tensile, in-plane, normal to the contact line

Laplace Pressure

Air bubble in water



Derivation with the virtual work method

Imagine the spherical bubble expands from r to r+dr

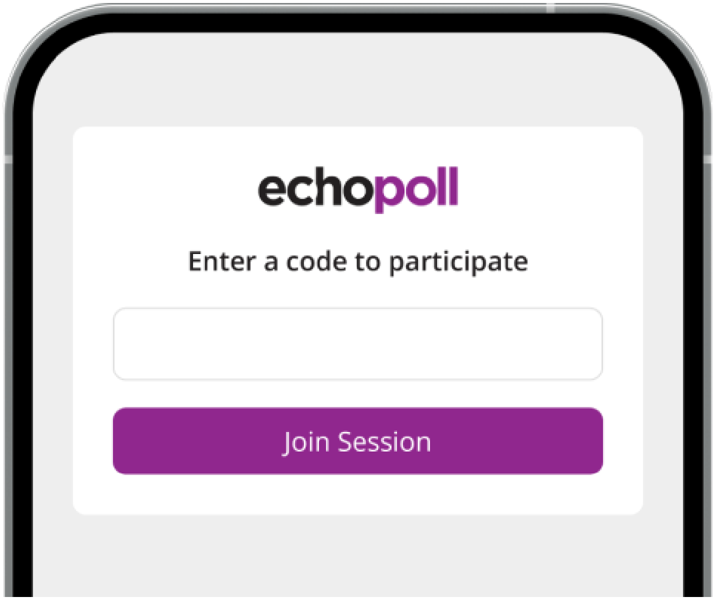
Net energy change should go to zero if system is in equil.

$$-P_{\mathrm{I}} \cdot 4\pi r^2 dr + P_{\mathrm{II}} \cdot 4\pi r^2 dr + \sigma \cdot d(4\pi r^2) = 0$$

$$\Rightarrow P_{\mathrm{I}} - P_{\mathrm{II}} = \frac{2\sigma}{r}$$

To join the session

Go to
echo360poll.eu

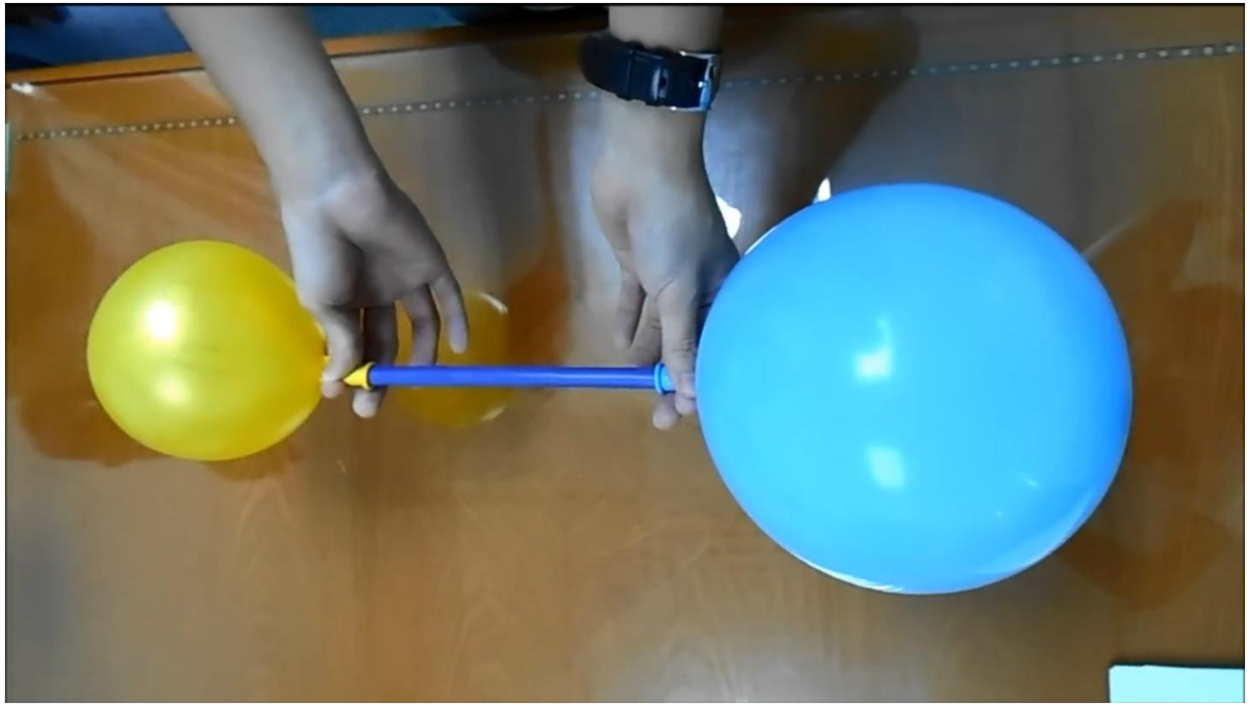


Enter Code

luepfl

Scan the QR code with your device

Laplace Pressure



What will happen here?

A. Two balloon becomes equal in size

B. The yellow balloon becomes even smaller, and the blue balloon becomes even larger

C. Both balloons become larger

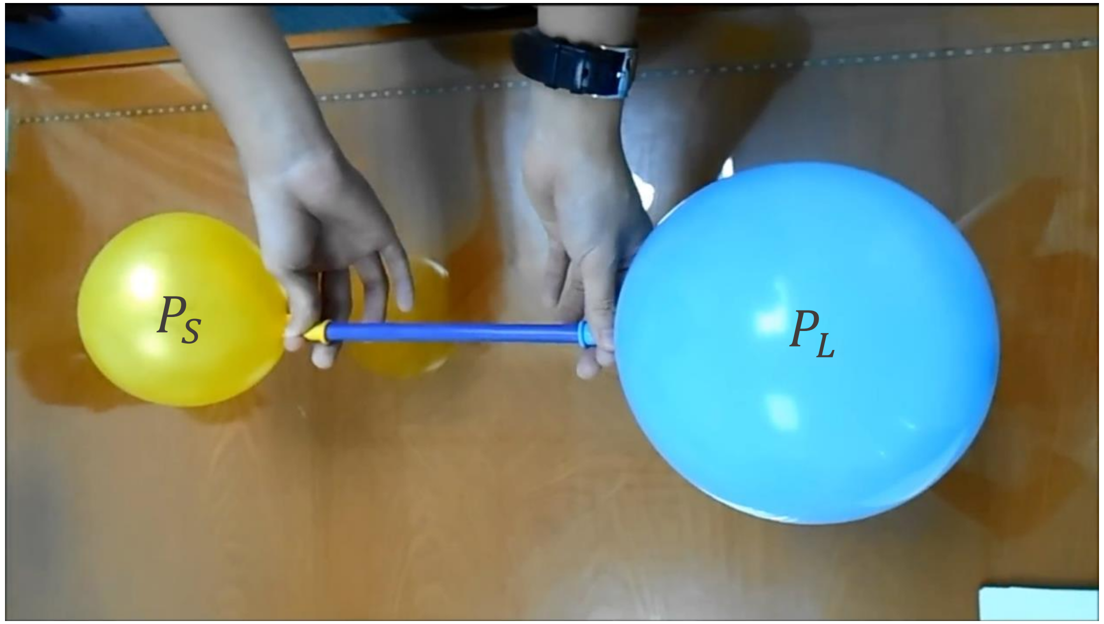
D. Both balloons become smaller

https://www.youtube.com/watch?v=_btWTwDVRj8&t=100s

Assuming balloon surfaces have the same surface tension

Laplace Pressure

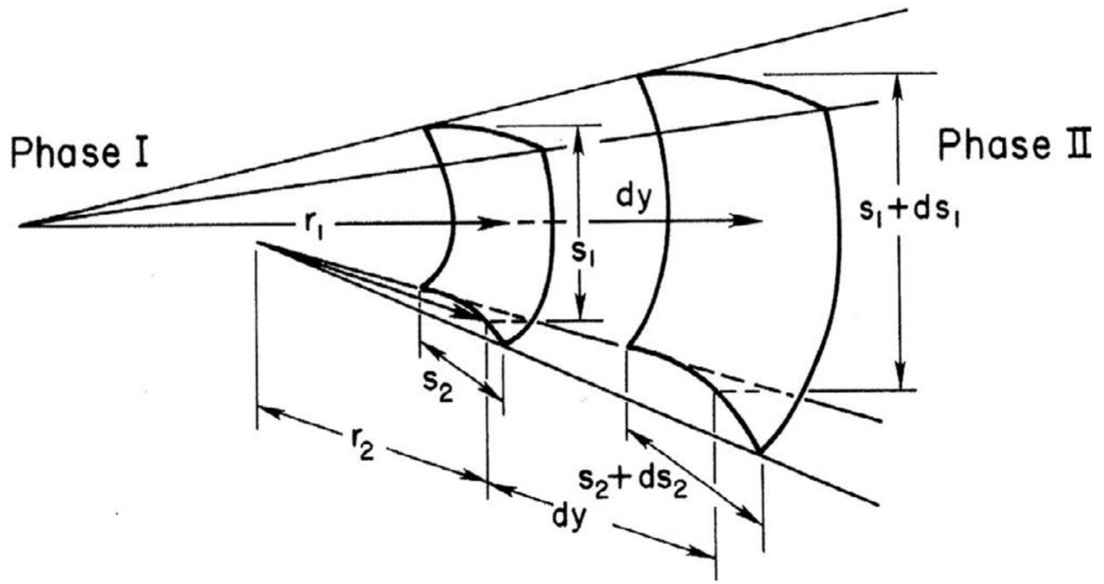
Small balloon empty itself into larger balloon



$$P_S - P_{atm} = \frac{2\sigma}{r_S}$$

$$P_L - P_{atm} = \frac{2\sigma}{r_L}$$

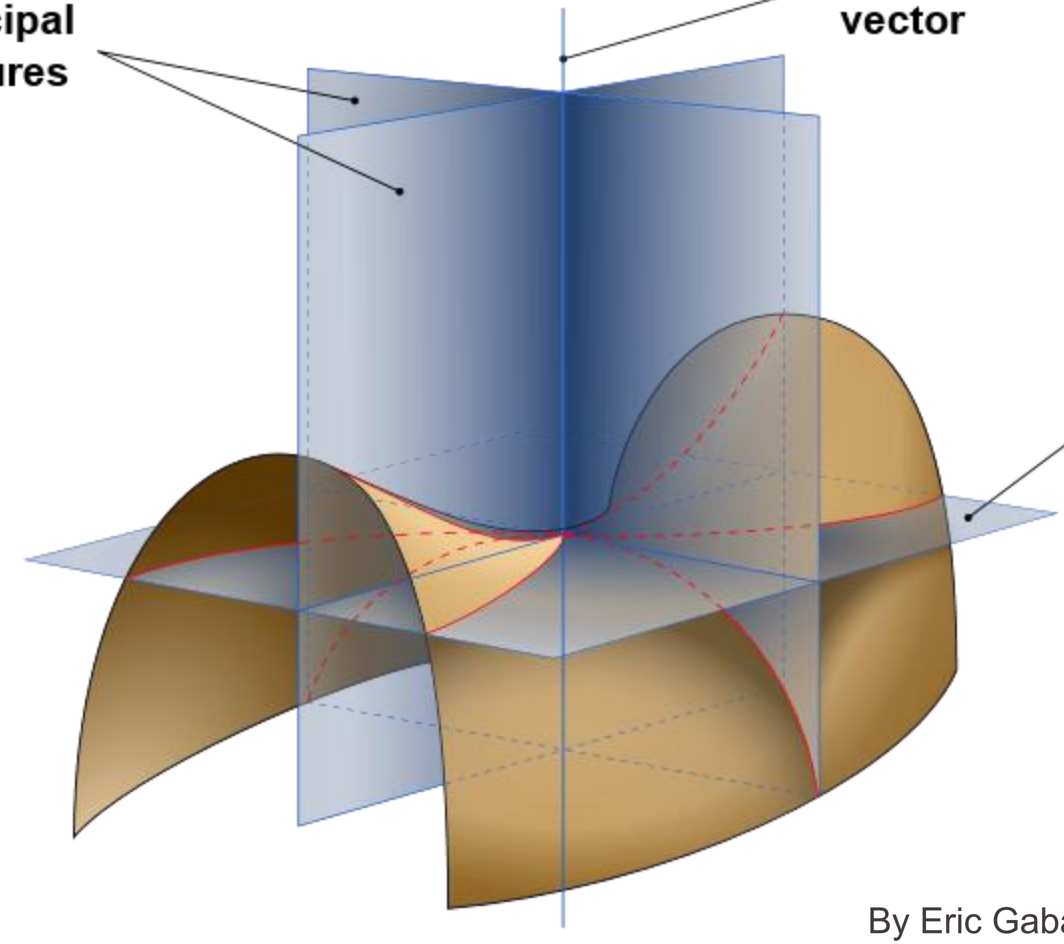
Non-Spherical Interface Shape



$$P_{\mathrm{I}} - P_{\mathrm{II}} = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

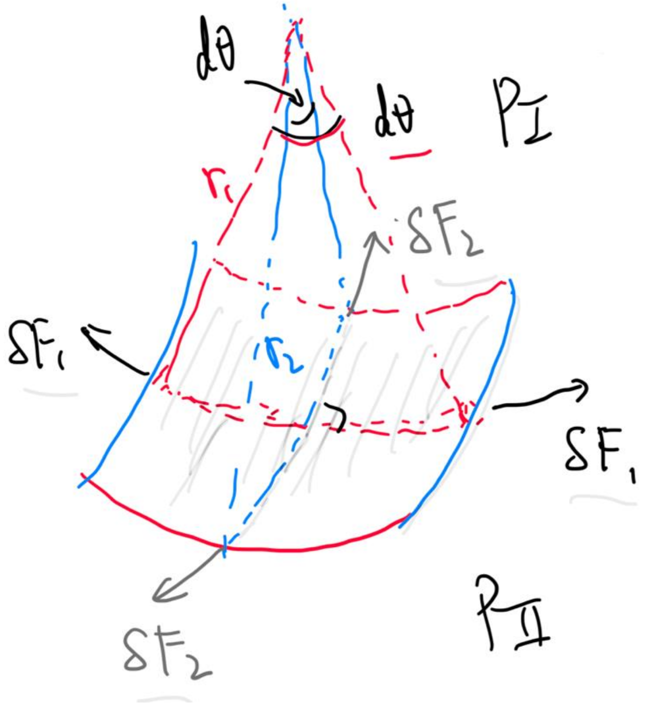
Young-Laplace Equation

Non-Spherical Interface Shape



By Eric Gaba (Sting)

Derivation of Y-L Equation



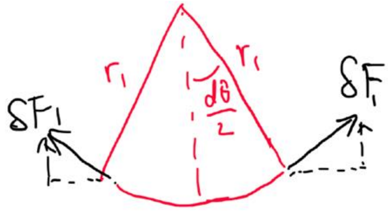
Area of differential surface

$$dS = r_1 d\theta_1 \cdot r_2 d\theta_2 = r_1 r_2 d\theta_1 d\theta_2$$

Surface tension force in Plane 1 $\delta F_1 = \sigma \cdot r_2 d\theta_2$

The force component perpendicular to the surface is

$$\delta F_1 \cdot \frac{d\theta_1}{2} \cdot 2 = \sigma r_2 d\theta_1 d\theta_2$$



Similarly, in Plane 2, the perpendicular force component is $\sigma r_1 d\theta_1 d\theta_2$

Force balance requires $(P_I - P_{II}) \cdot dS = \sigma r_2 d\theta_1 d\theta_2 + \sigma r_1 d\theta_1 d\theta_2$ $\Rightarrow P_I - P_{II} = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$

Summary

- **Surface energy/surface tension**: the work that needs to be done to create a surface per unit area
- **Laplace pressure**: a result of surface tension and surface curvature
- **Young-Laplace equation**: quantify Laplace pressure as a function of surface tension and two principal radii