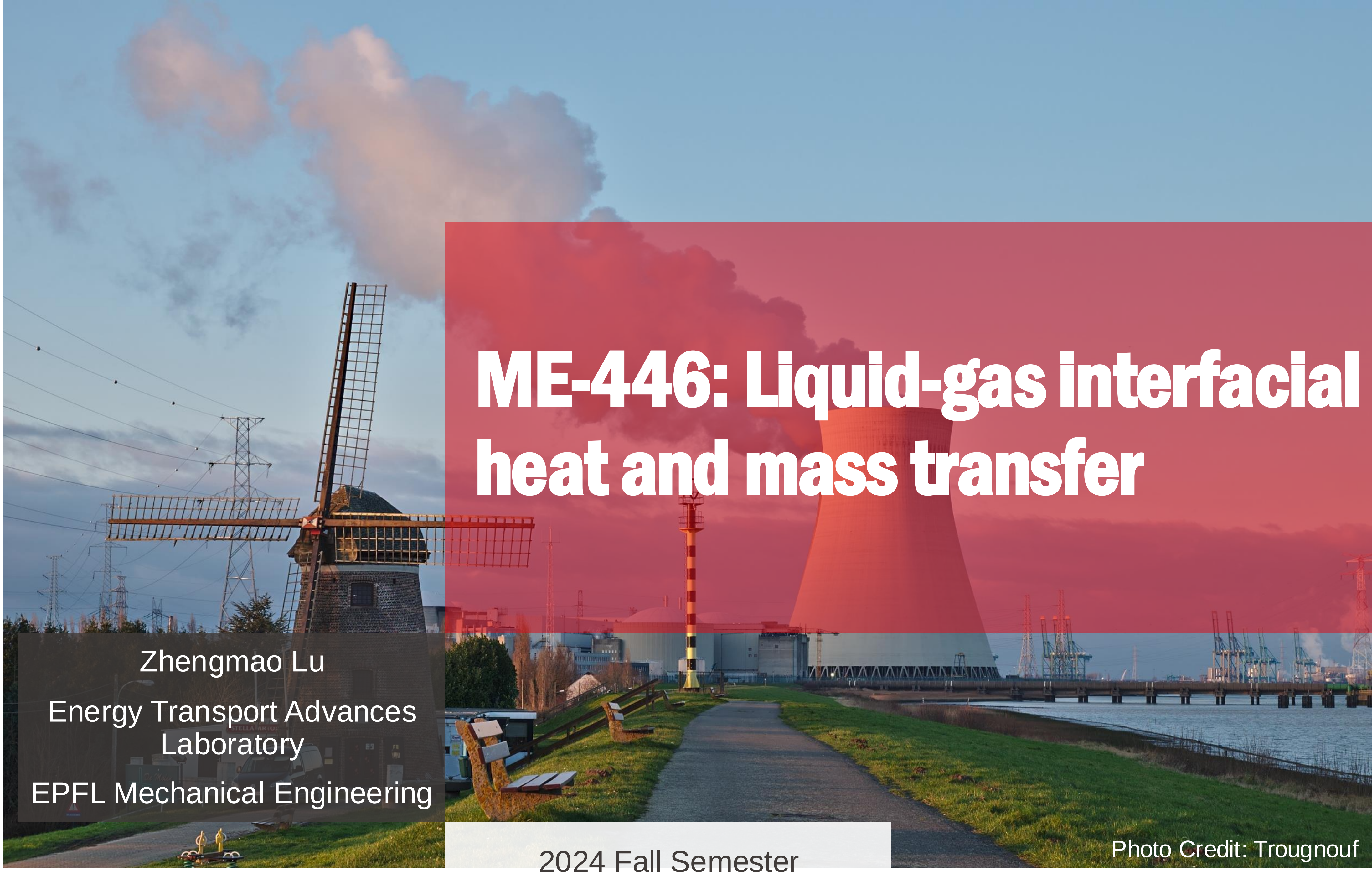
EPFL

ETA-Lab
Energy Transport Advances



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

Zhengmao Lu

Energy Transport Advances Laboratory

EPFL Mechanical Engineering

2024 Fall Semester

Photo Credit: Trougnouf

Instructors

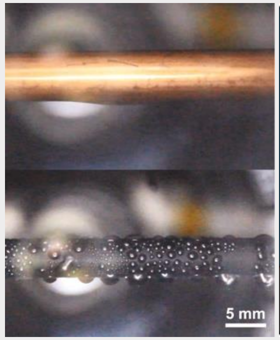
- I'm Zhengmao Lu (zhengmao.lu@epfl.ch)
  - Phase change heat transfer, interfacial phenomena, micro/nano, cooling
  - 22 years in China; 10 years in the US; Joined EPFL in February 2023
- Teaching Assistant: Gautier Rouaze (gautier.rouaze@epfl.ch)

Energy Transport Advances Laboratory

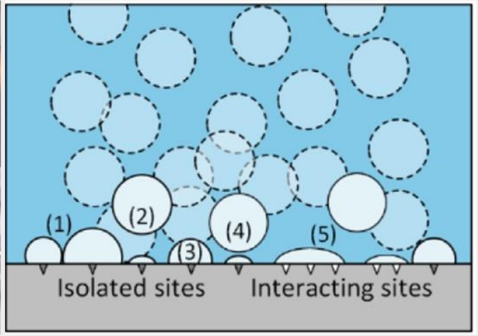
Zhengmao Lu EPFL > STI > IGM > ETA-Lab

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

Generation

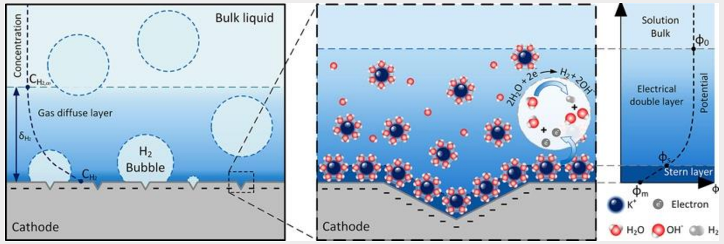


Condensation



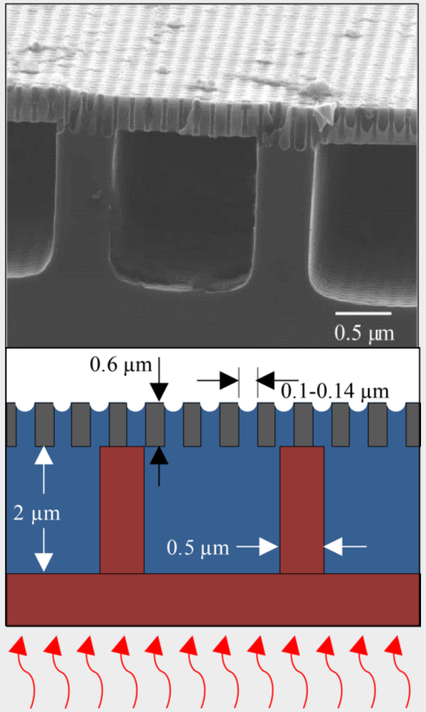
Boiling

Storage

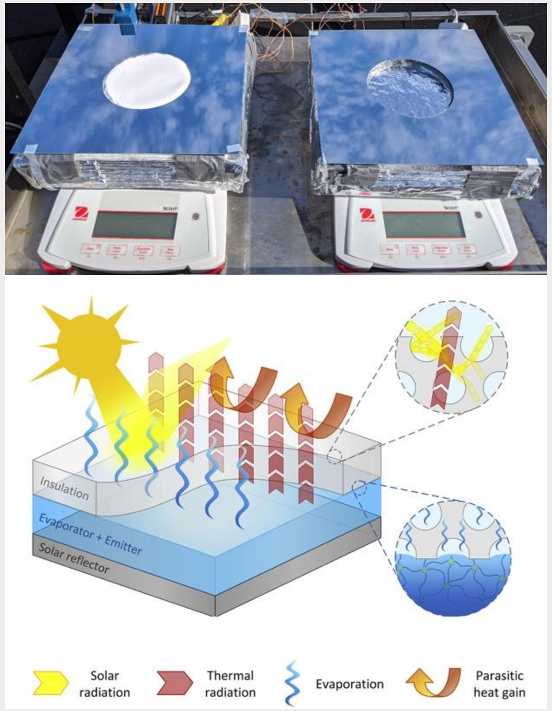


Alkaline water electrolysis

Usage

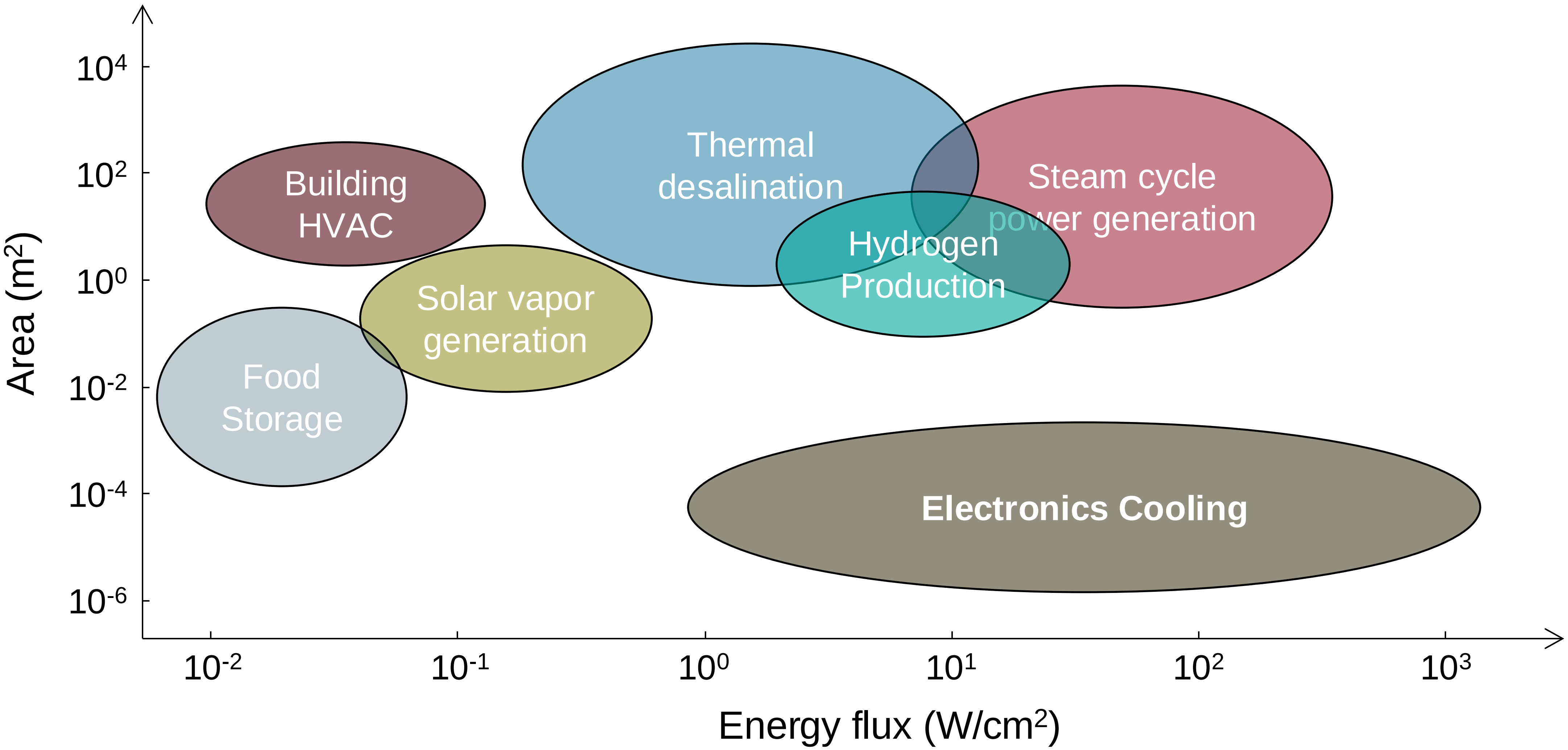


Electronics cooling



Passive subambient cooling

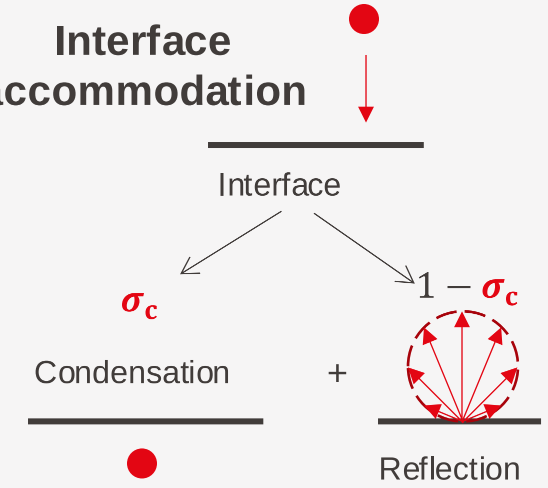
Broad Application of Liquid-Gas Interfacial Transport



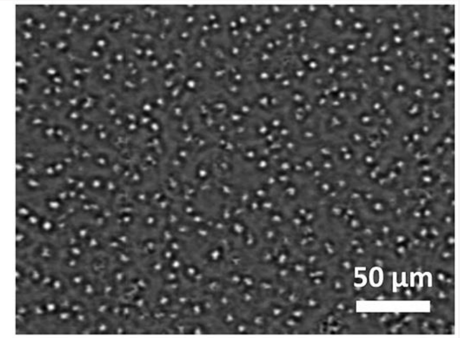
η-Lab's Current Directions

Interface

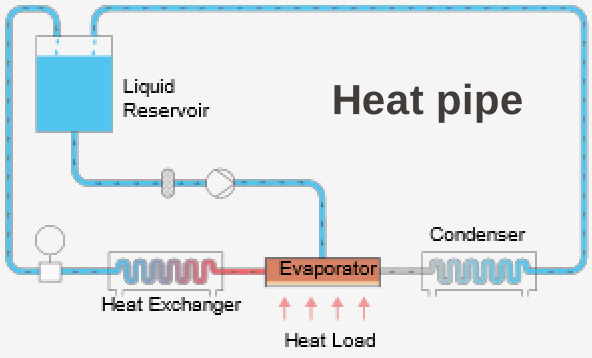
Interface accommodation



Nucleation process

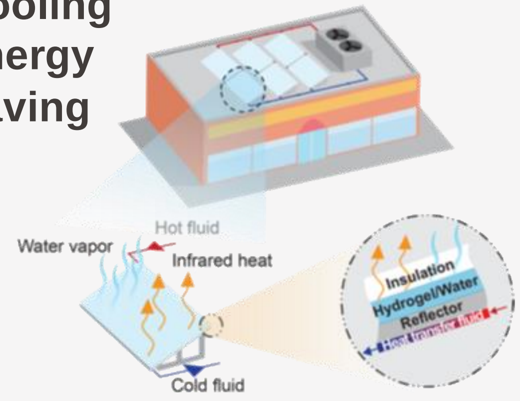


Device



System

Cooling energy saving



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. You do NOT need to submit anything.
  - 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 more recent papers in the area of liquid-gas interfacial phenomena. You can sign up for the one that 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, 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)

Assessment

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

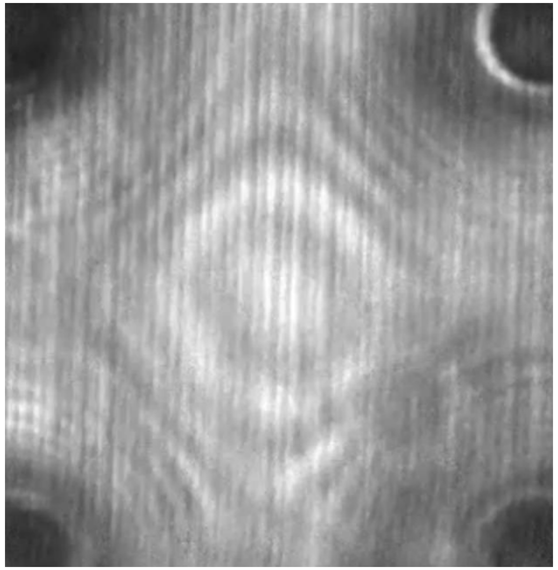
Reference Books

- **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

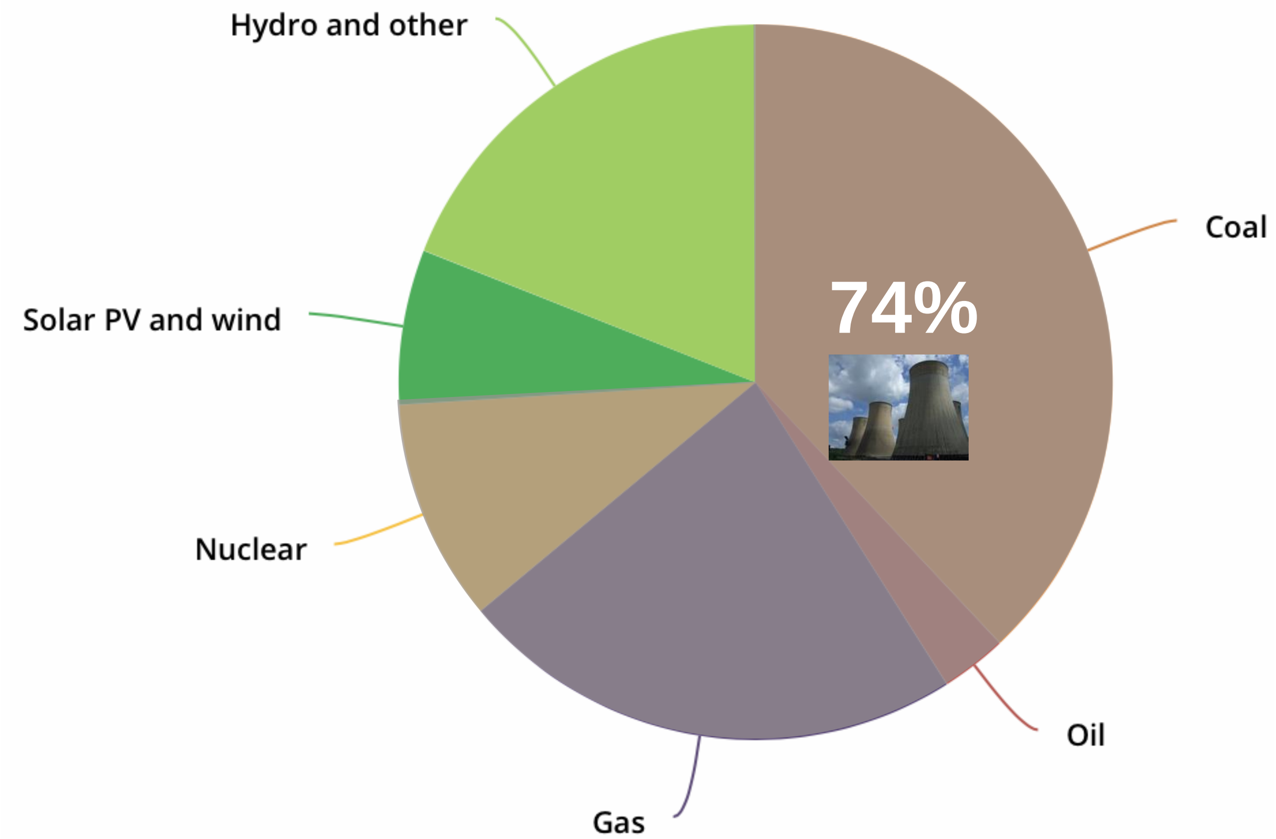
Evaporation	Boiling	Condensation
		

What We Study in This Course

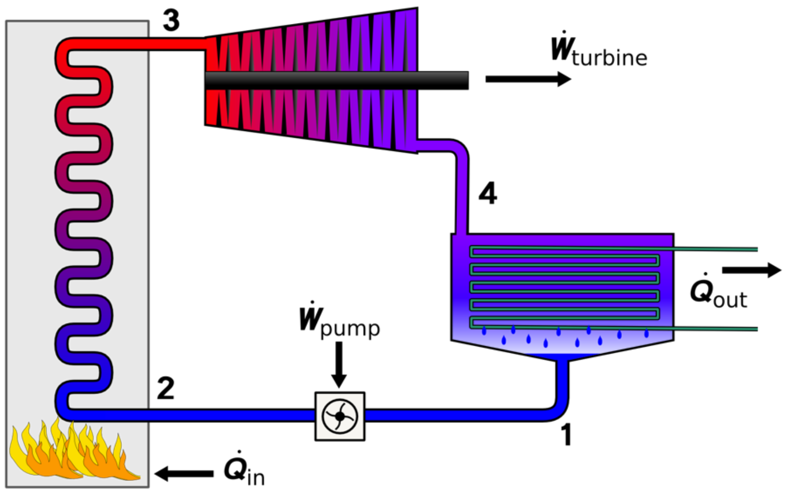
Film	Bubble	Droplet
		

Heat and mass transfer across liquid-gas interfaces

Why We Study Thermodynamics

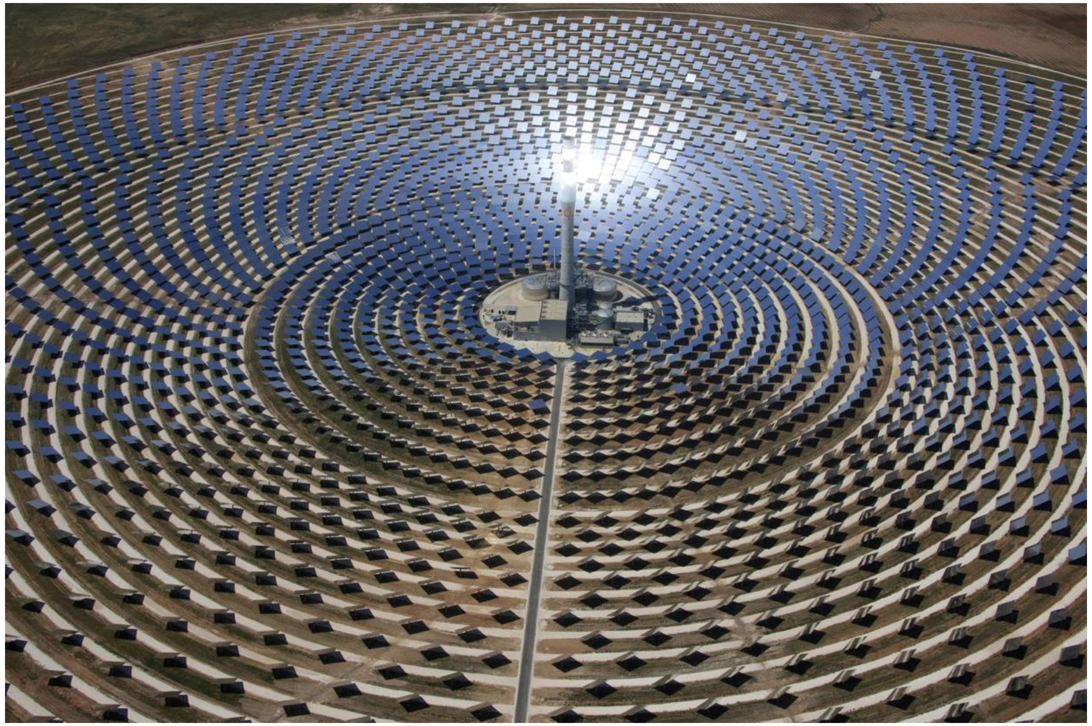


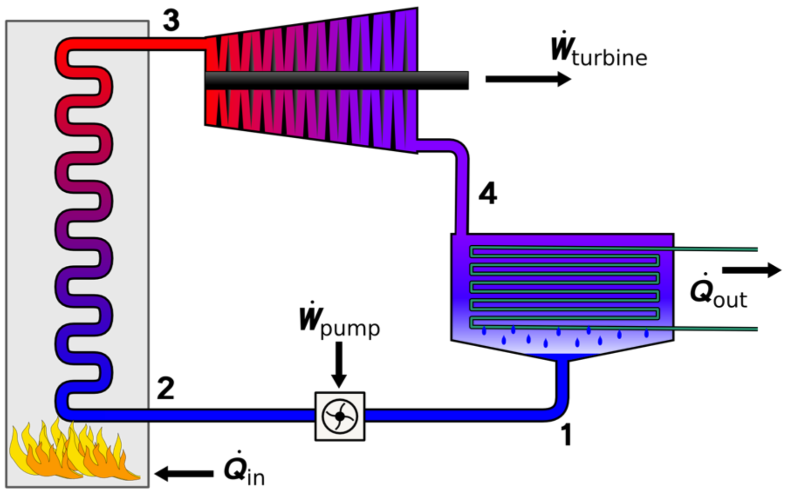
International Energy Agency, 2019



Credit: Andrew Ainsworth

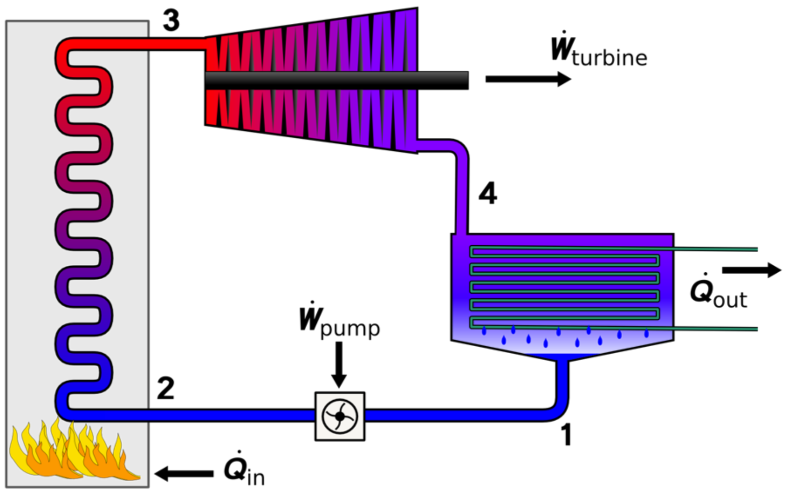
Why We Study ME-446





Concentrated solar power plant in Seville, Spain

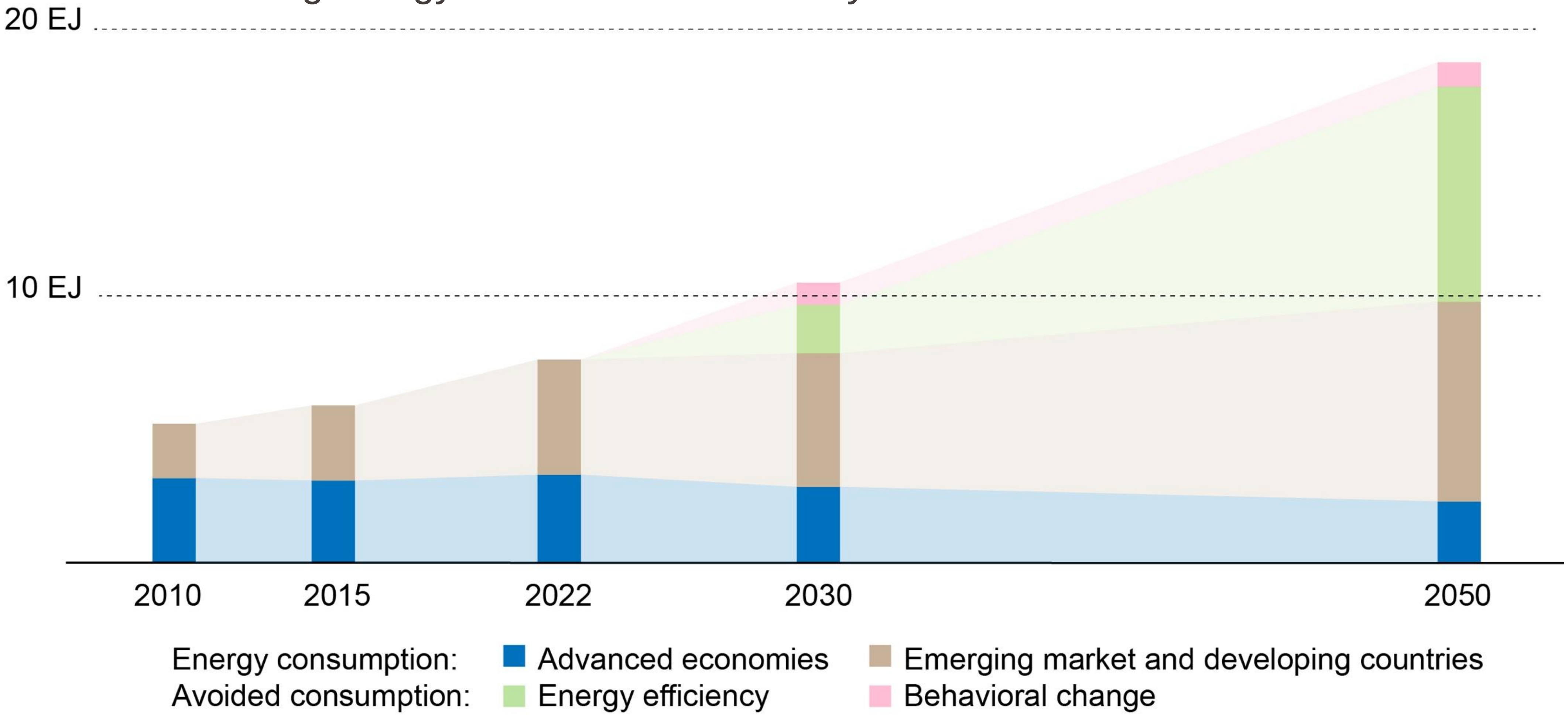
Why We Study ME-446



Power cycle is relevant even for nuclear fusion

Why We Study ME-446

Cooling energy demand will **double** by 2050 with no action taken



Why We Study ME-446

SCI AM Scientific American

The Summer of 2023 Was the Hottest in 2,000 Years

Ancient tree rings show that the summer of 2023 was the hottest in the past 2000 years because of human-caused climate change.

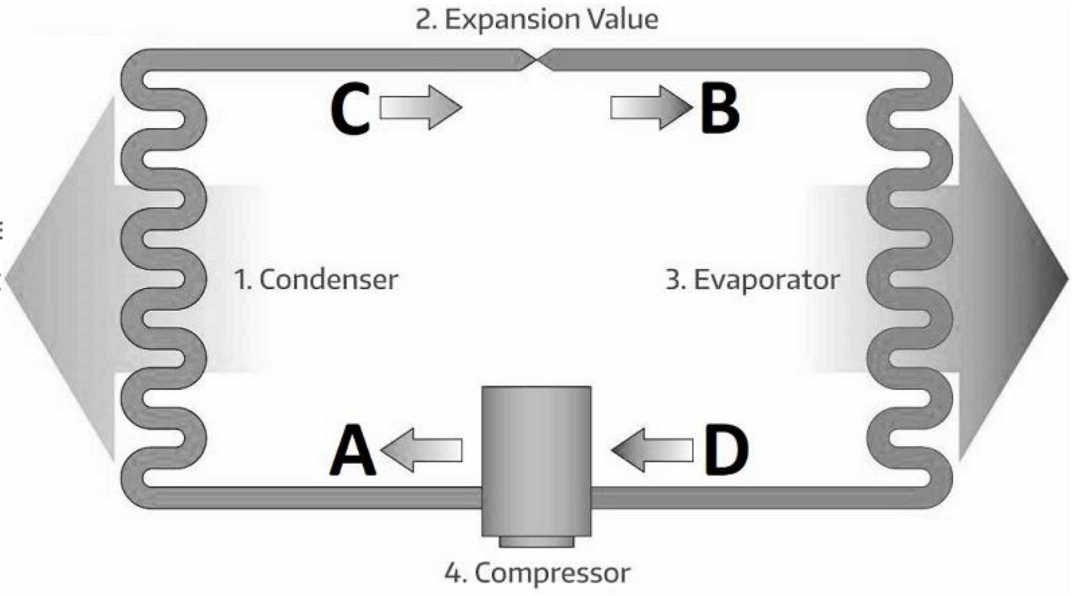
14 May 2024

BBC

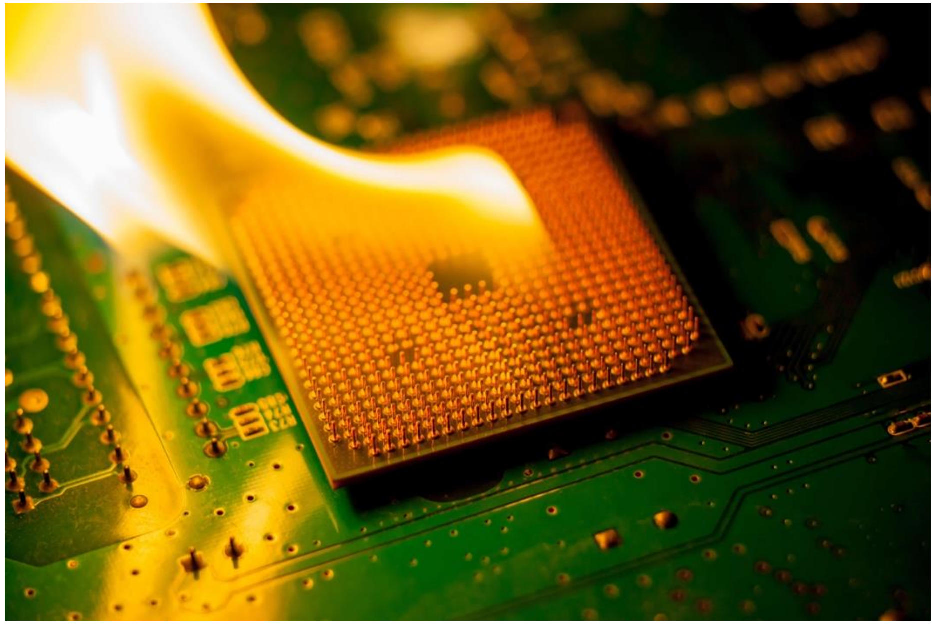
Summer 2024 was world's hottest on record

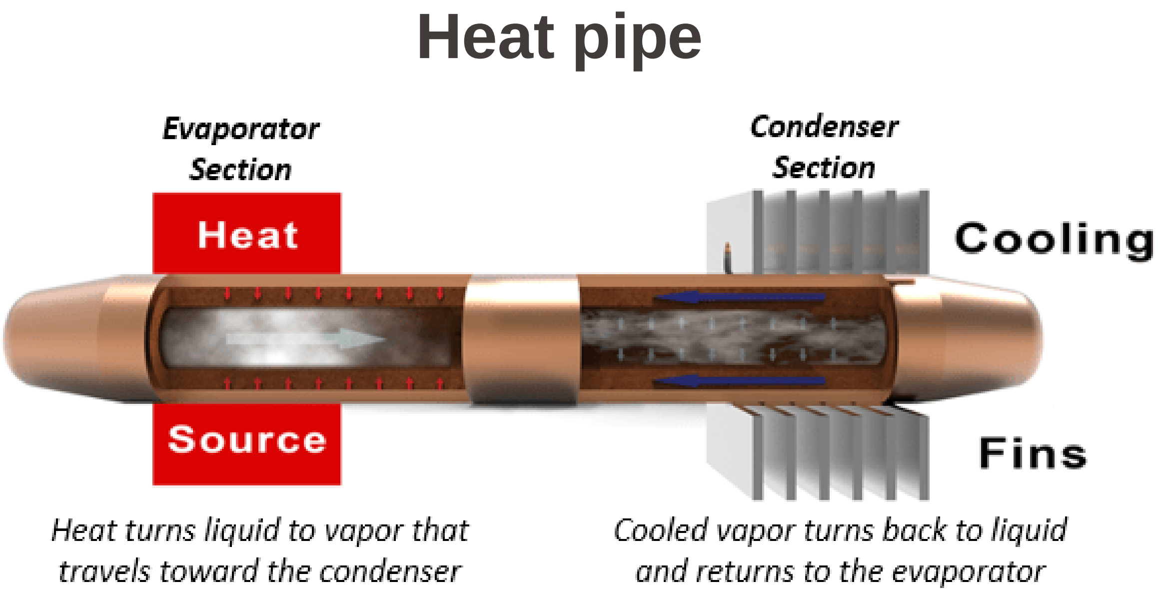
Summer 2024 was the Earth's warmest on record, according to the Climate Change Service. It was also the warmest across Europe at

5 days ago

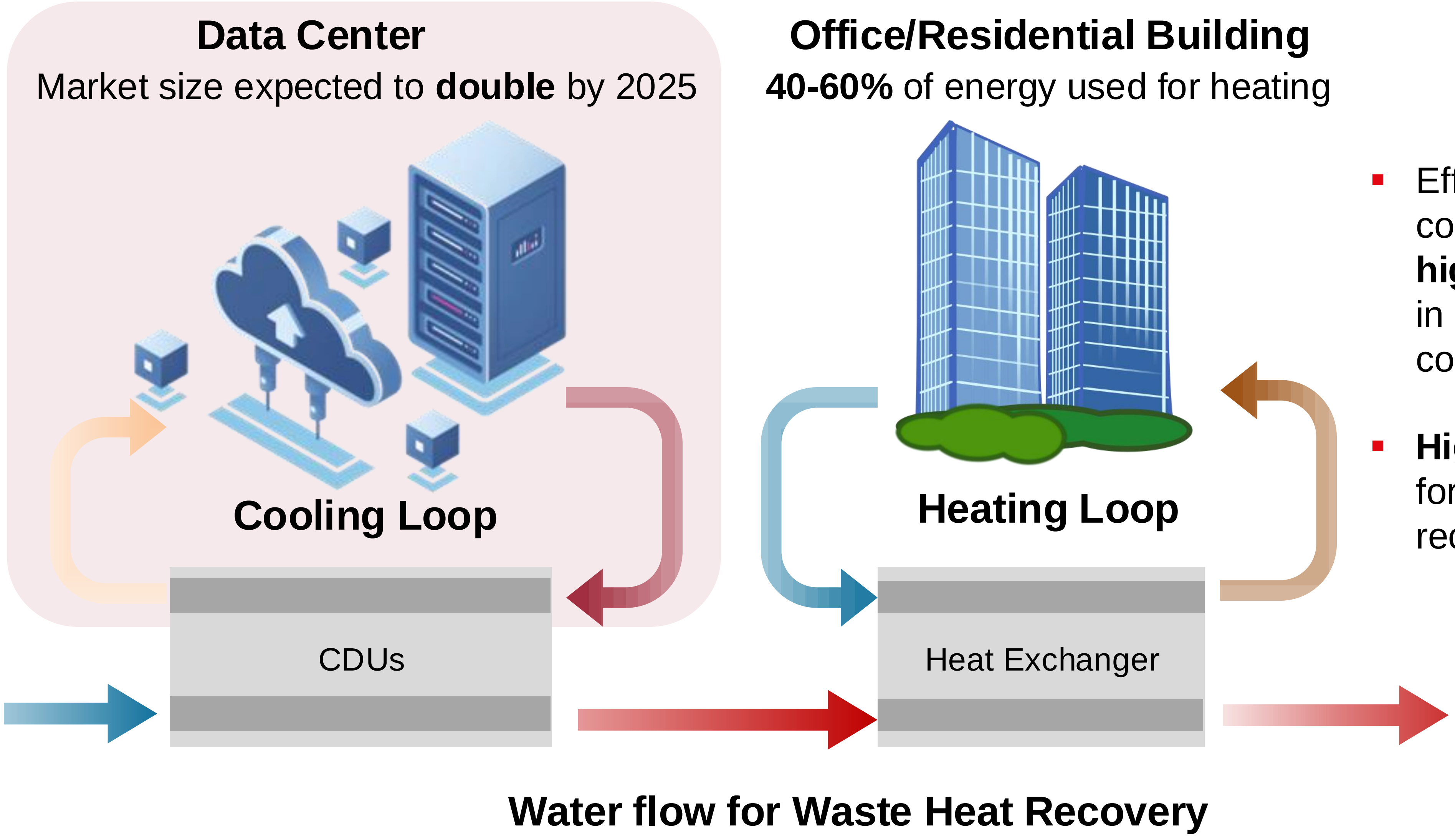


Why We Study This





Why We Study This



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

Why We Study This

REDUCING THE CARBON FOOTPRINT OF DATA CENTERS

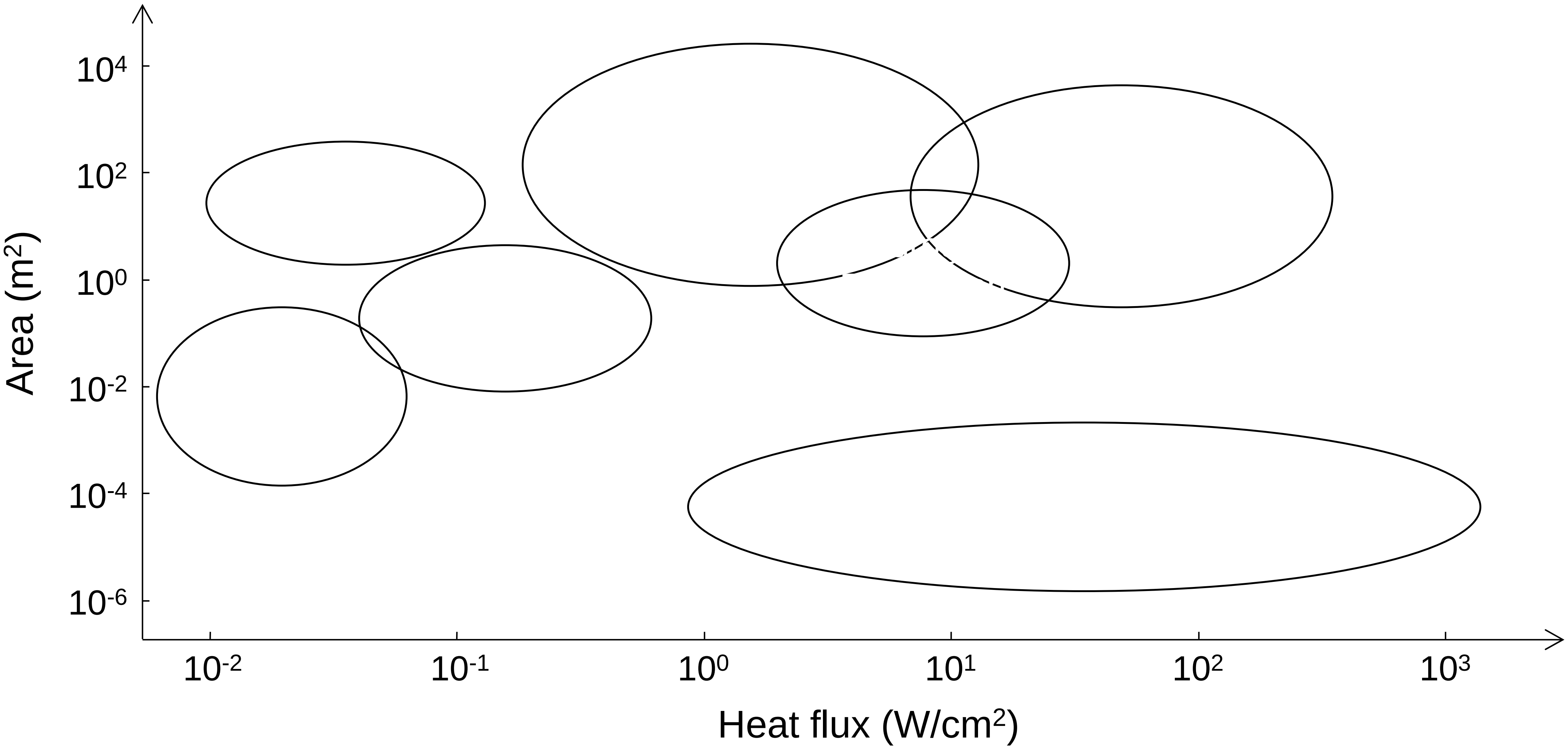
HEATING BITS

EPFL Sustainability Project

https://heatingbits.epfl.ch

Broad Applications of Liquid-Vapor Phase Change

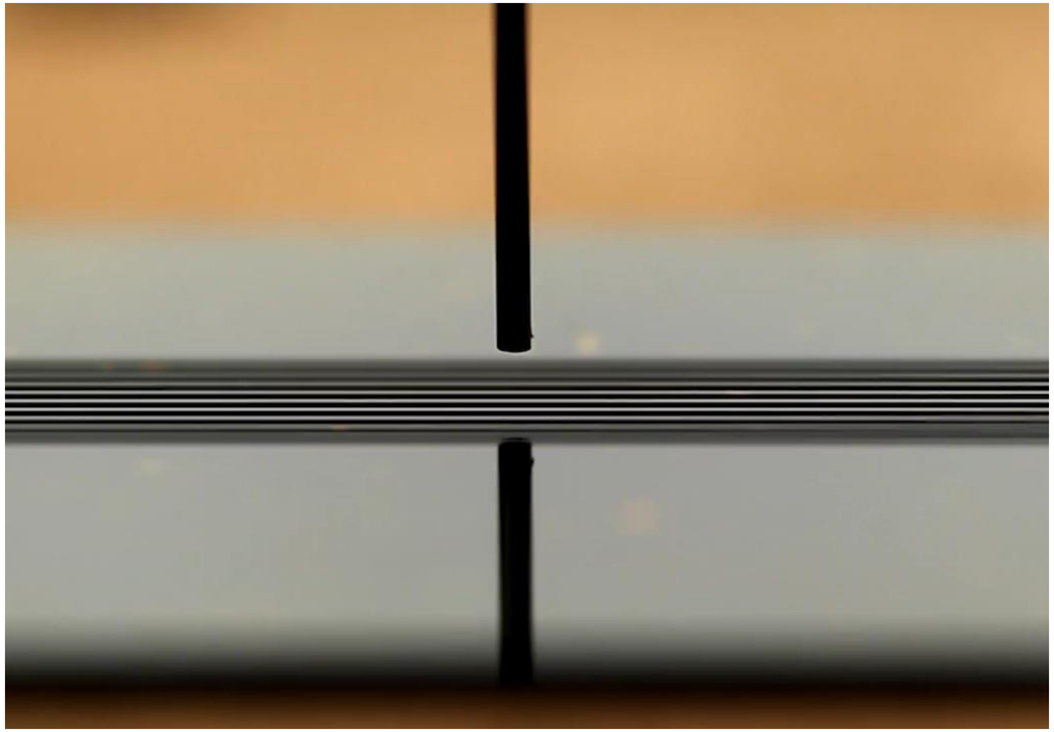
ETA-Lab
Energy Transport Advances



What We Study in ME-446

- 1. Capillarity and wetting
- 2. Evaporation physics
- 3. Pool boiling
- 4. Gas evolution electrochemical reaction
- 5. Condensation

Capillarity and Wetting



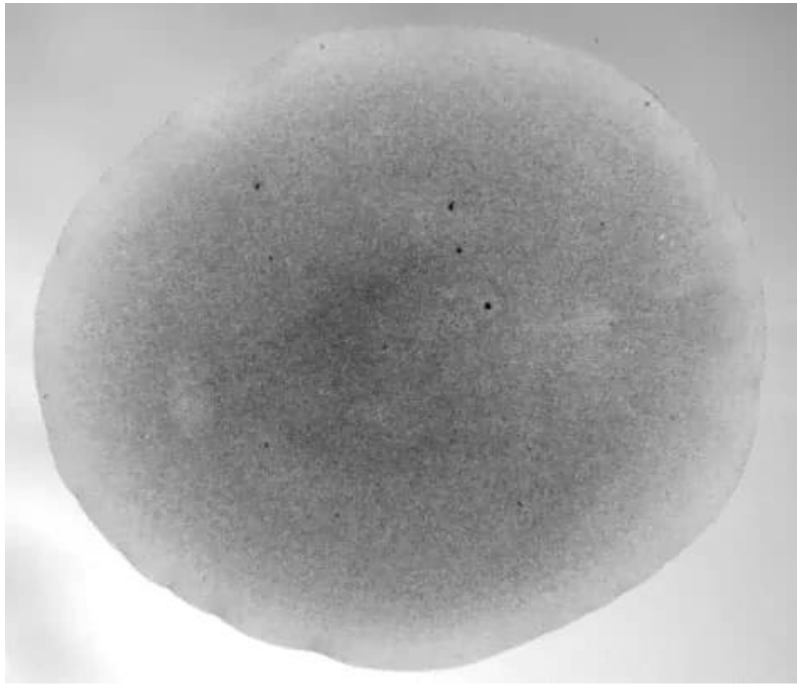
Capillary Wicking

Wilke *et al.*, *PNAS* 2021

Hydrophobicity

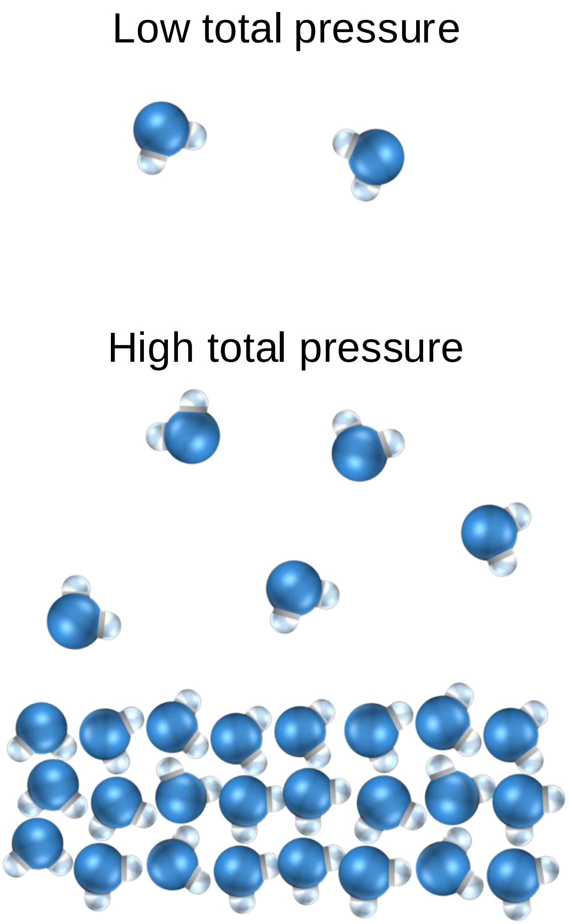
http://davewirth.blogspot.com/2011/11/final-lotus-of-year.html

Evaporation Physics



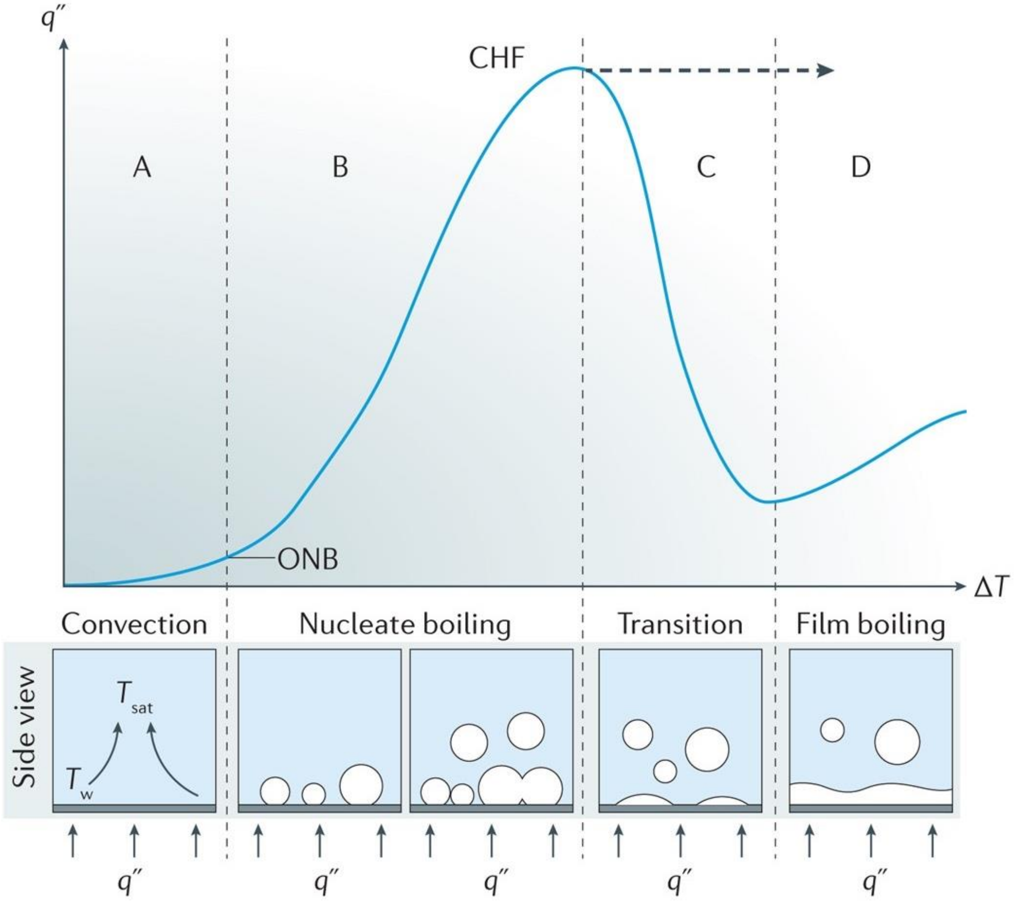
Yunker *et al.*, *Nature* (2011)

Molecular gas dynamics

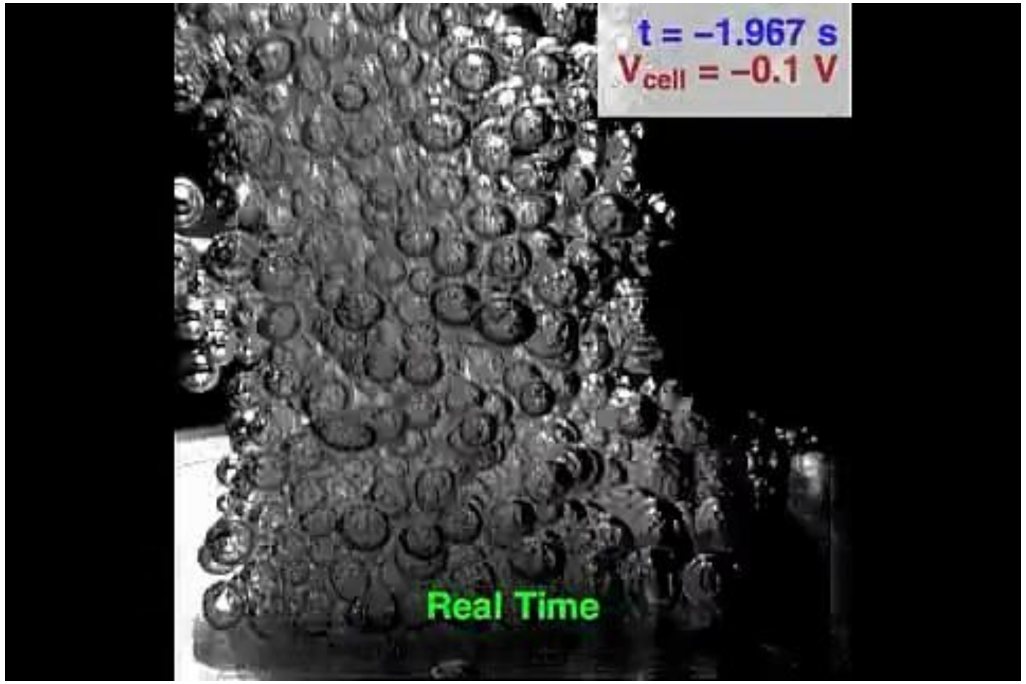


Lu *et al.*, *Nat. Comm.* 2019

Pool Boiling

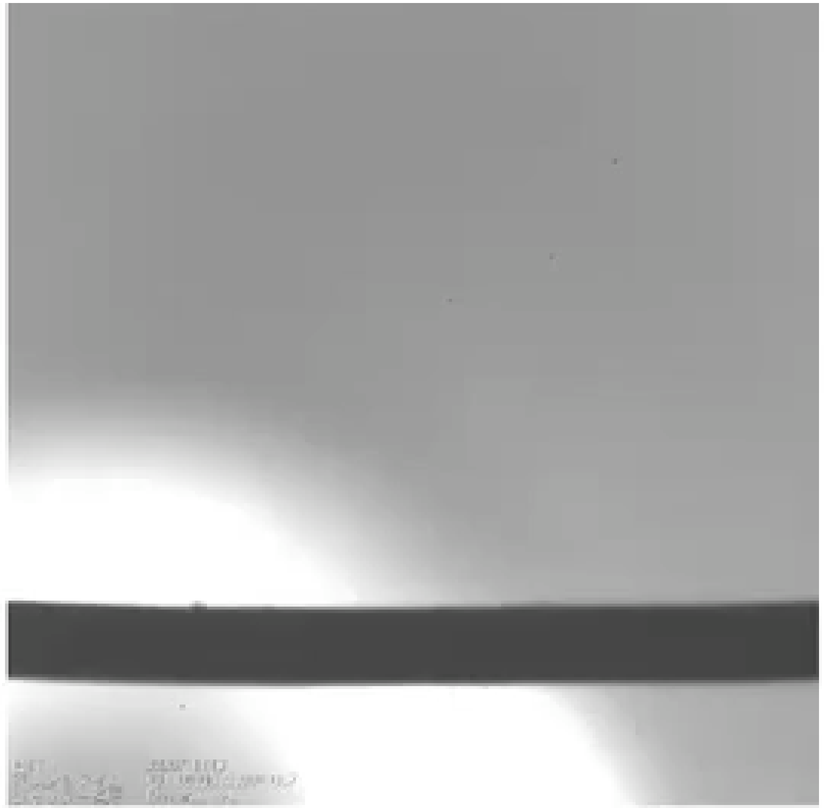


Cho *et al.*, *Nature Reviews Materials* 2016

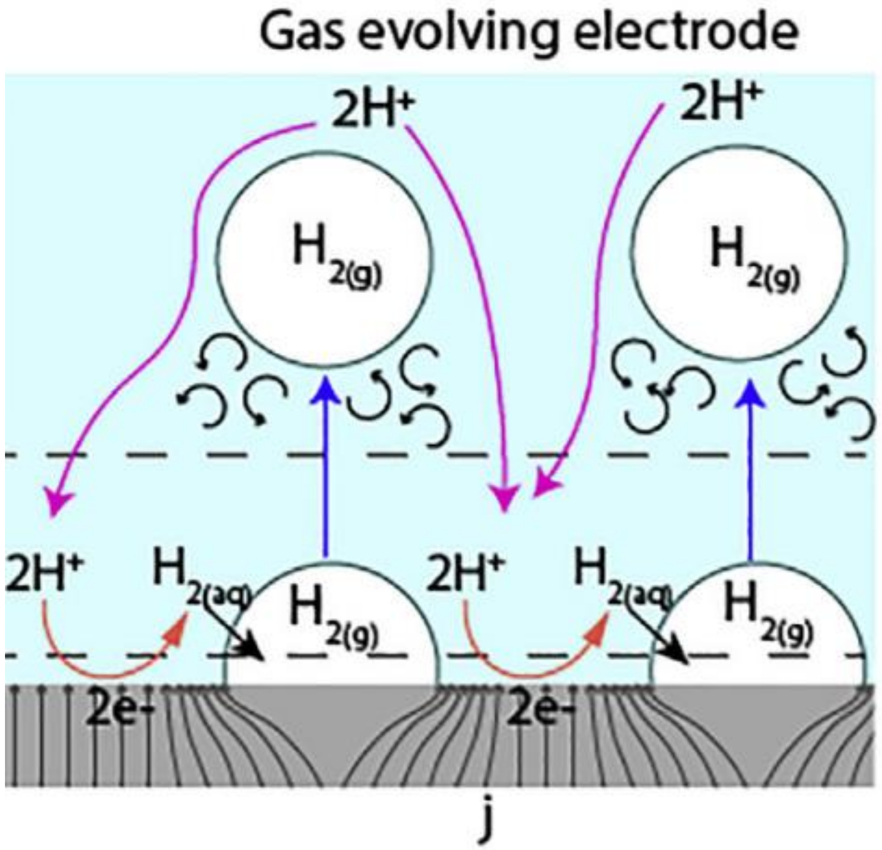


Cho *et al.*, *Nat. Comm* (2016)

Gas Evolution Electrochemical Reaction

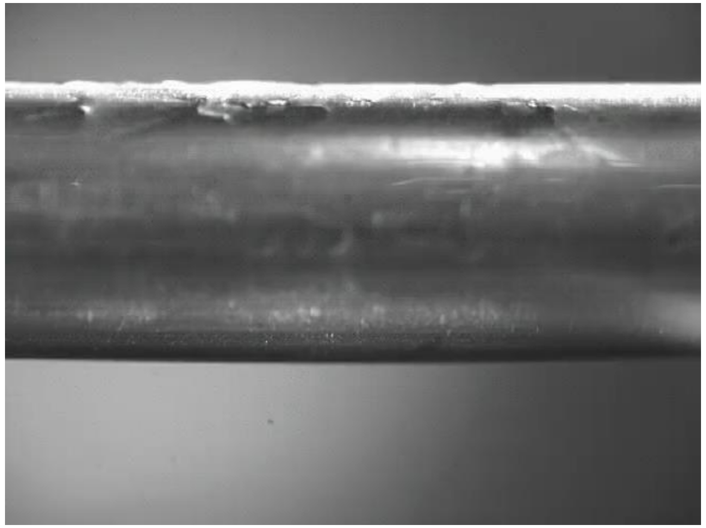


Ikeda *et al.*, International Journal of Hydrogen Energy 2022

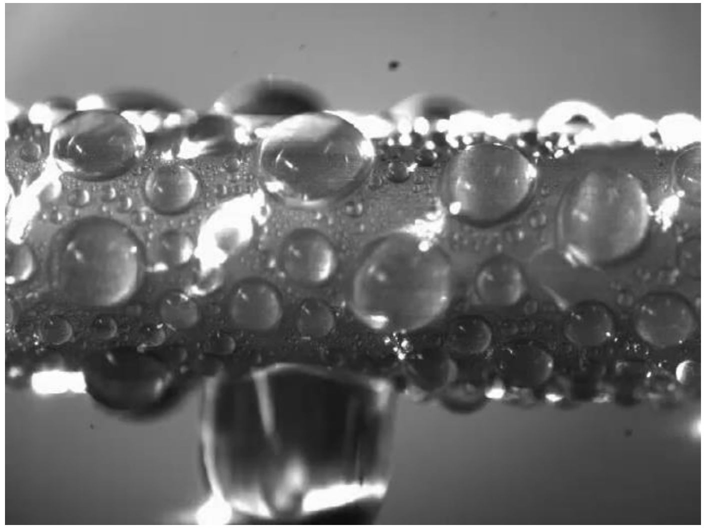


Angulo, *Joule* 2020

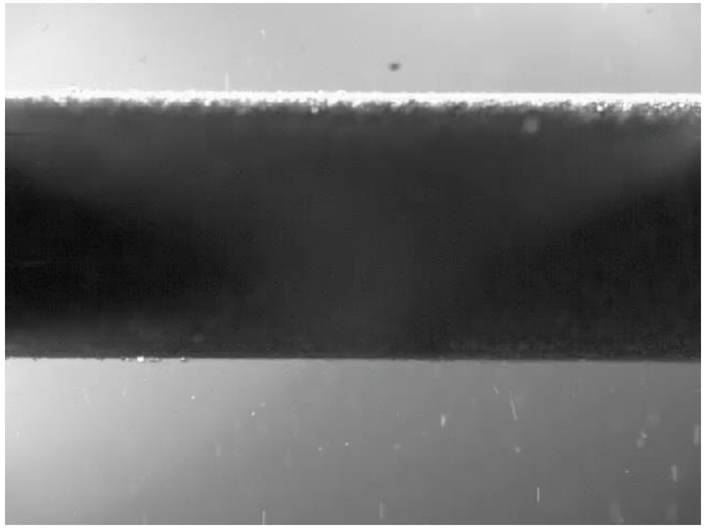
Condensation



Filmwise condensation



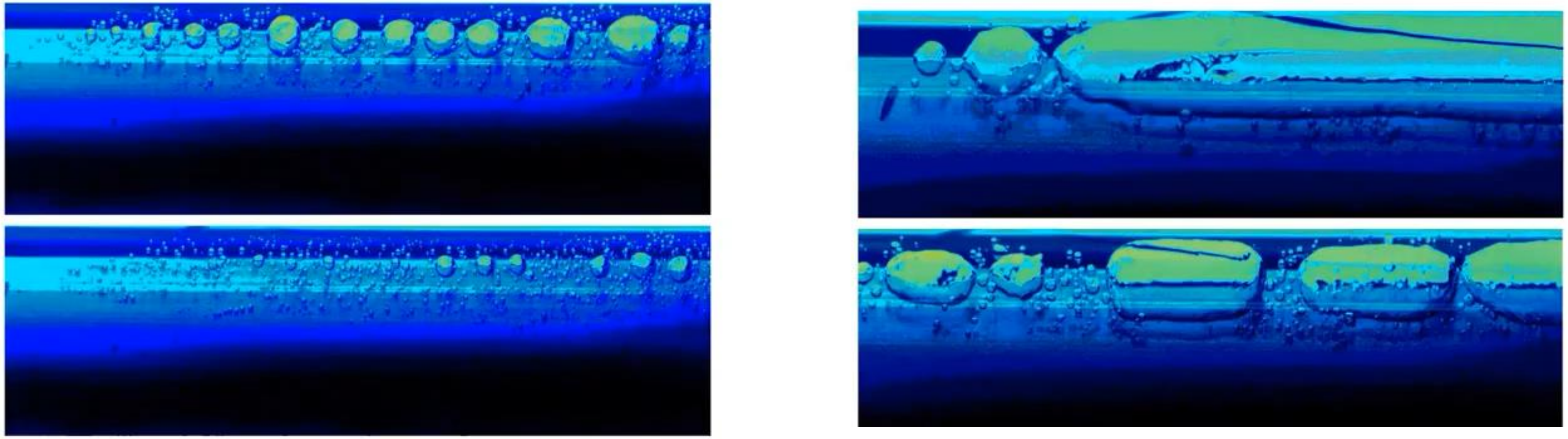
Dropwise condensation



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)

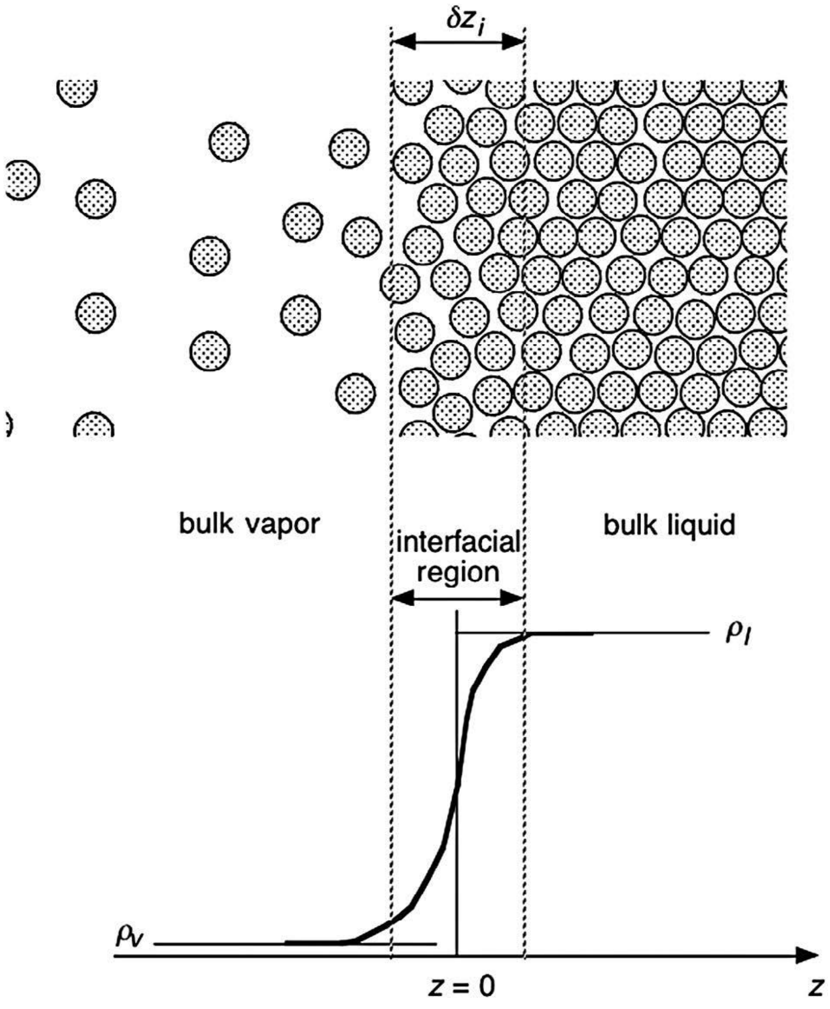
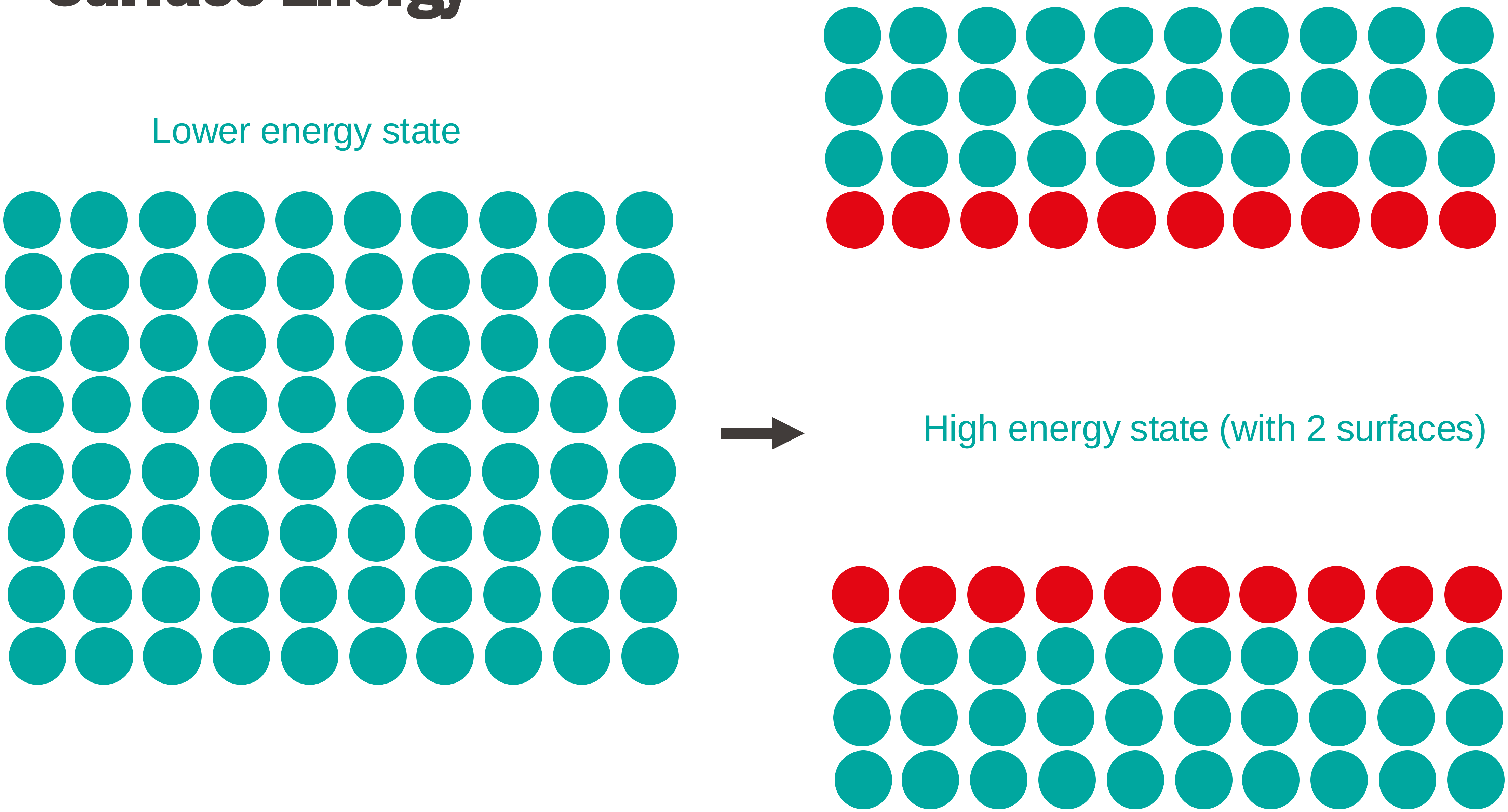


Figure 1.3 in Carey

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/m²)**
- Surface energy depends on the intermolecular interaction

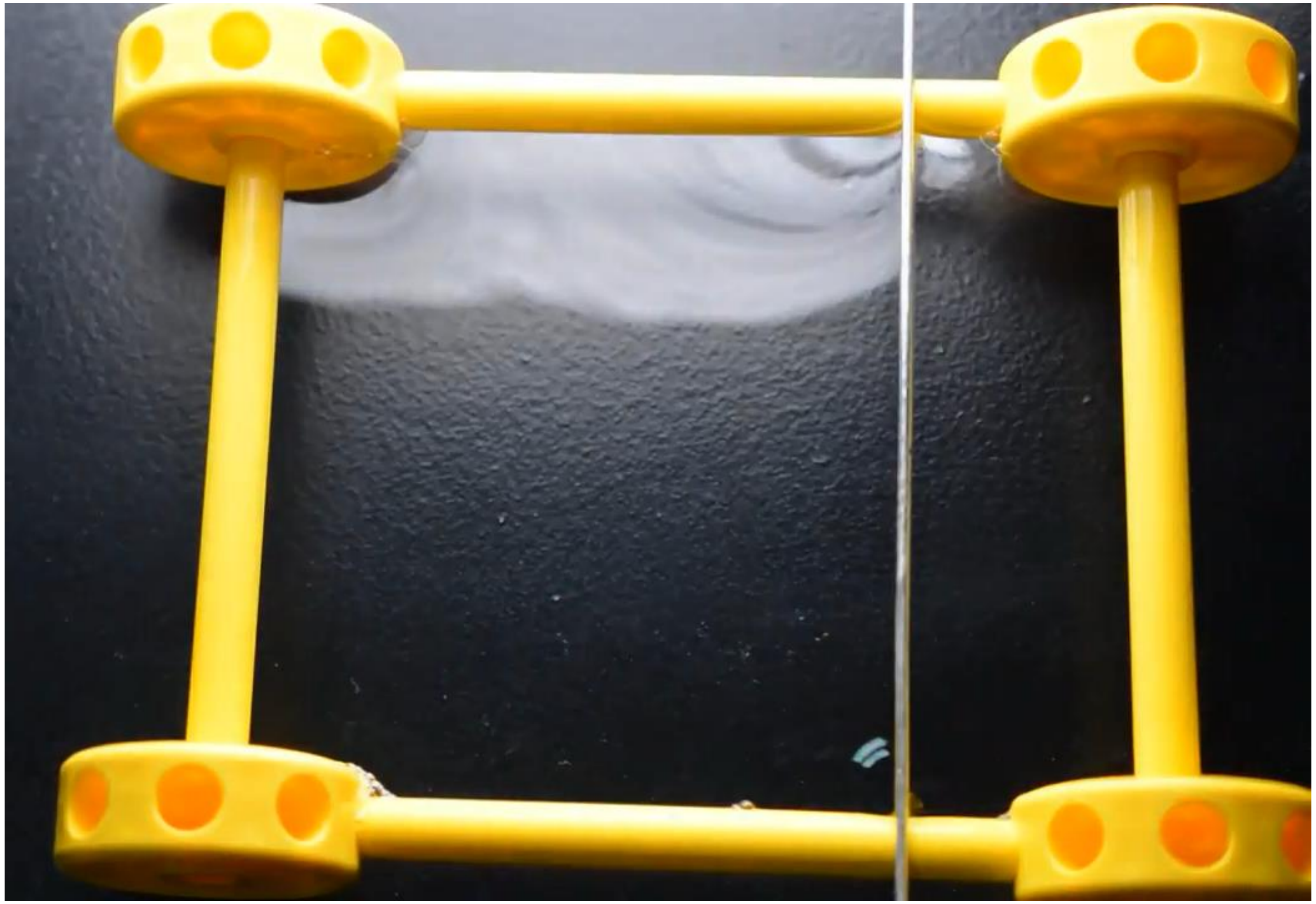
Force per length or energy per area?

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

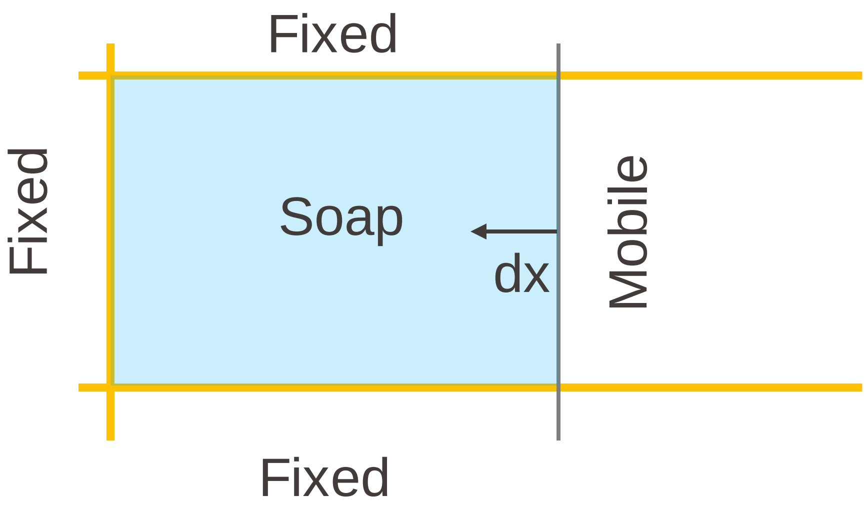
Liquid	Temperature (°C)	Surface Tension (mN/m)
Silver (Ag)	1100	878
Mercury (Hg)	20	484
Hydrazine (N_2H_4)	25	91.5
Water (H_2O)	20	72.8
Ethylene glycol ($C_2H_6O_2$)	20	48.4
Ammonia (NH_4)	–40	35.4
Carbon tetrachloride ($CC1_4$)	20	27.0
n-Butanol ($C_4H_{10}O$)	20	24.6
Acetone (CH_3COCH_3)	20	24.0
Ethanol (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

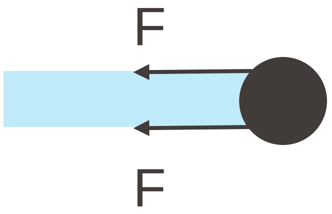
Carey, Table 2.1

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:

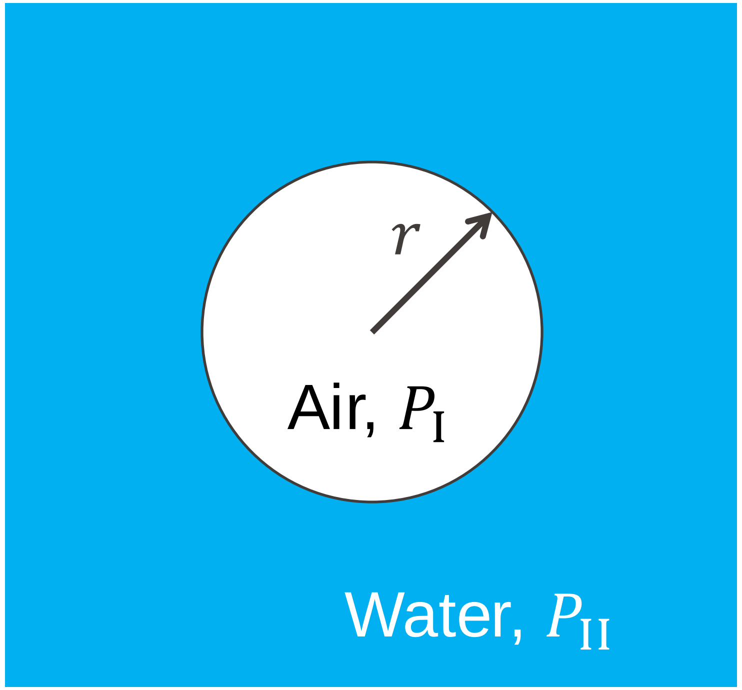
$$2Fdx = 2\sigma L dx$$

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

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

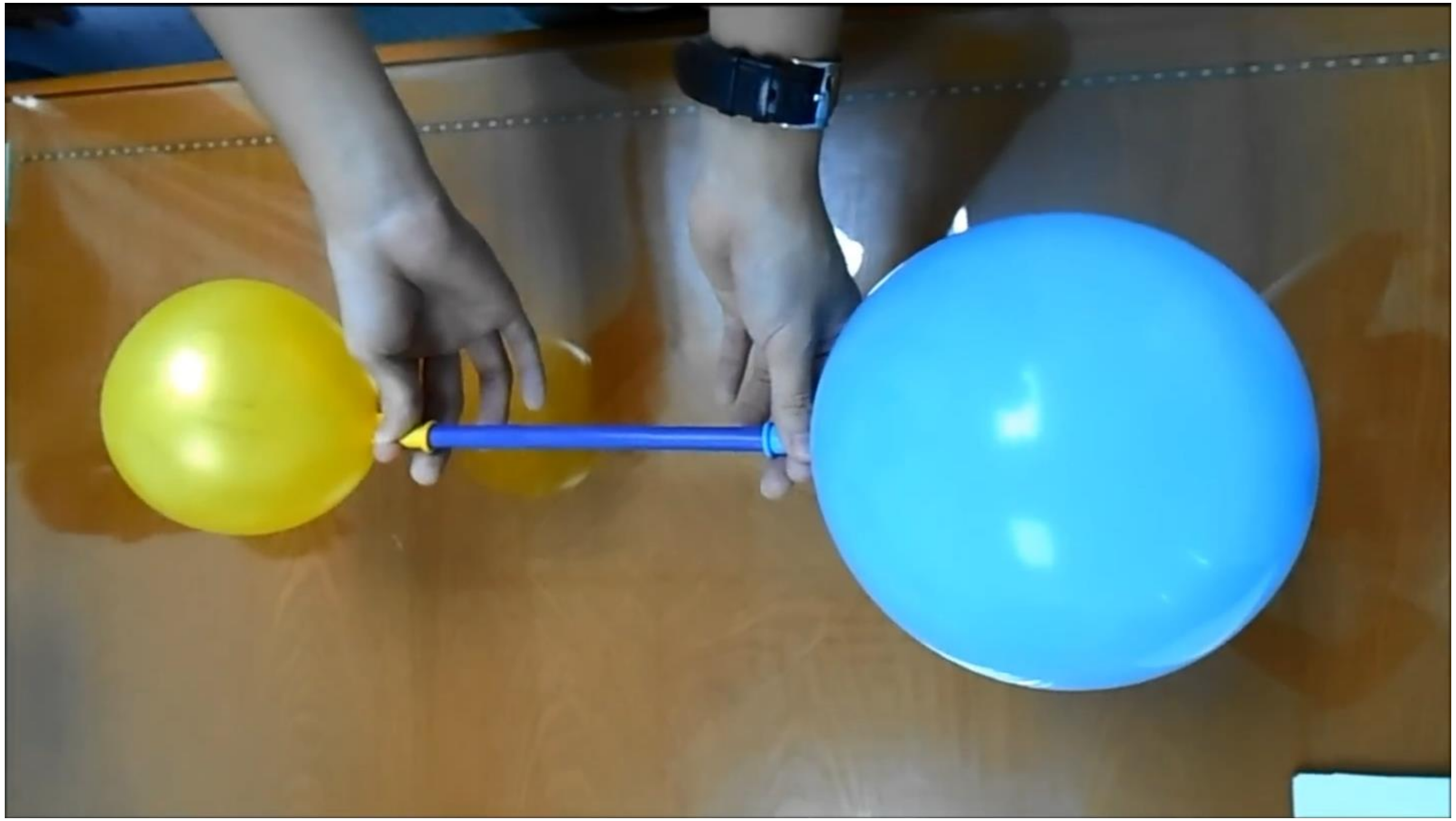
Laplace Pressure

Air bubble in water



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

Laplace Pressure

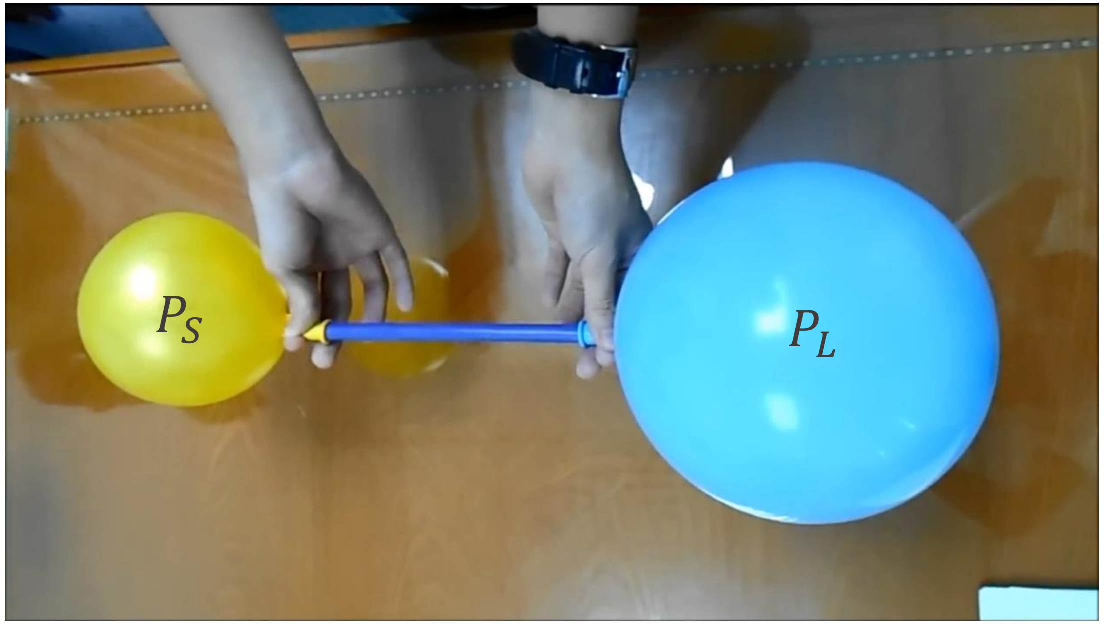


https://www.youtube.com/watch?v=_btWTwDVRj8&t=100s

Assuming balloon surfaces have the same surface tension

Laplace Pressure

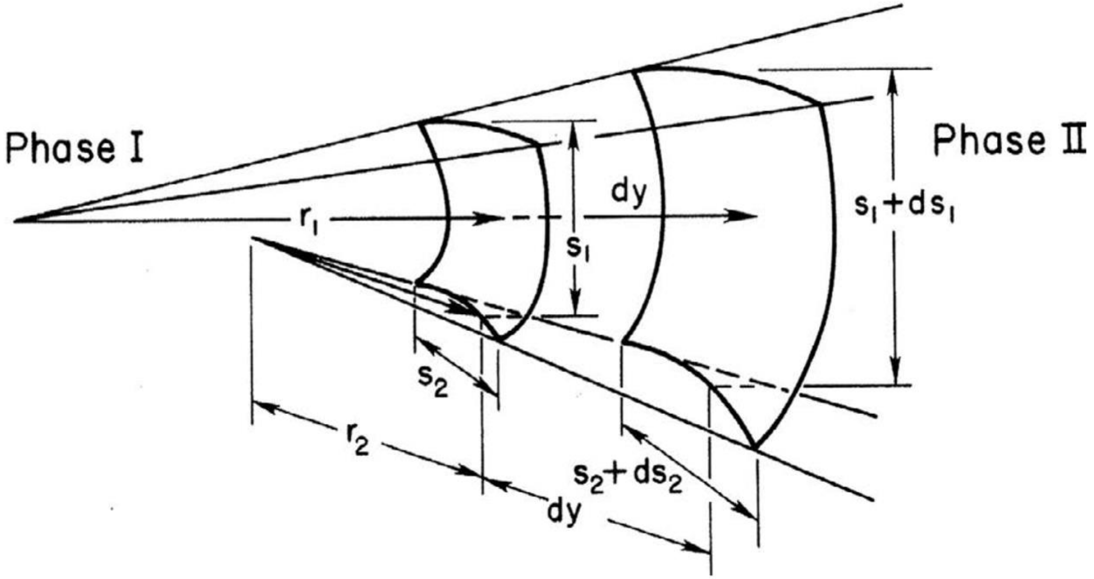
Small balloon empty itself into larger balloon



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

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

Non-Spherical Interface Shape



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

Young-Laplace Equation

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