Imbibition of a wetting liquid in pump-less microfluidic networks

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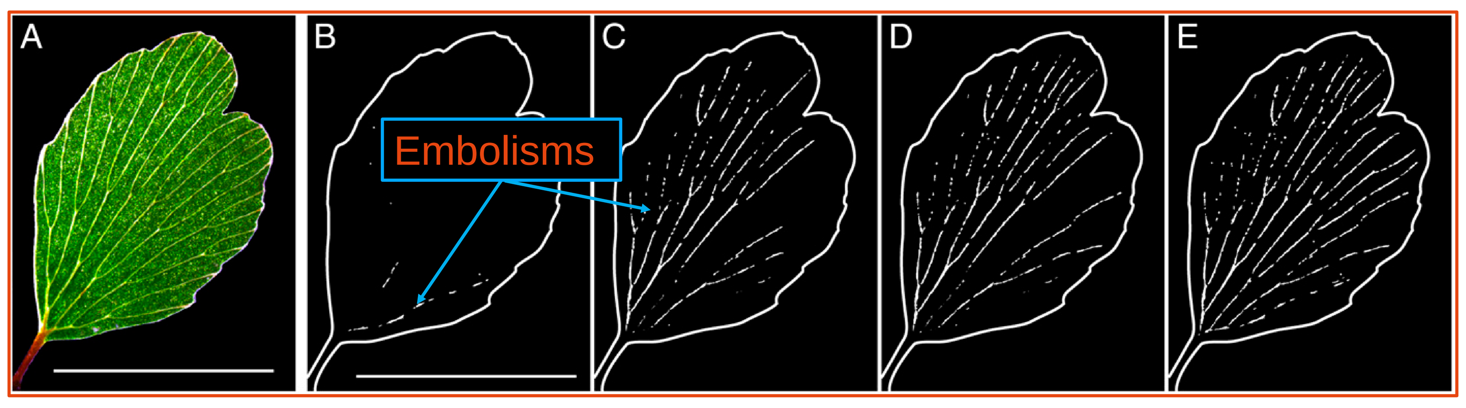
Motivation

Keywords: Biomimetics, microfluidics, capillarity

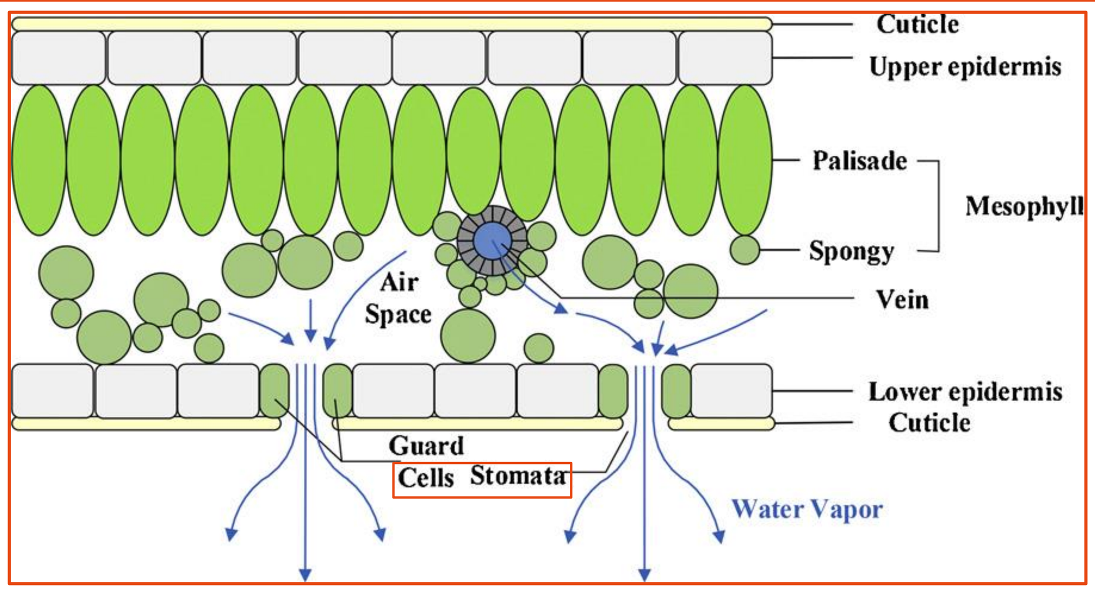


A: Illuminated fern leaf. B-E: Progression of air embolism, via image analysis. *Brodribb et al., PNAS, 113 (17) 4865-4869, 2016*

- **Refilling a leaf's xylem after embolism**
  - ⇒ During drought, spontaneous cavitation occurs in the xylem
  - ⇒ Cavitation grows into an embolism
  - ⇒ **What are the conditions for refilling channels after they were filled with air?**

Approach - Goals

- Water diffuses from the xylem to the lower epidermis and exits through the **stomata**

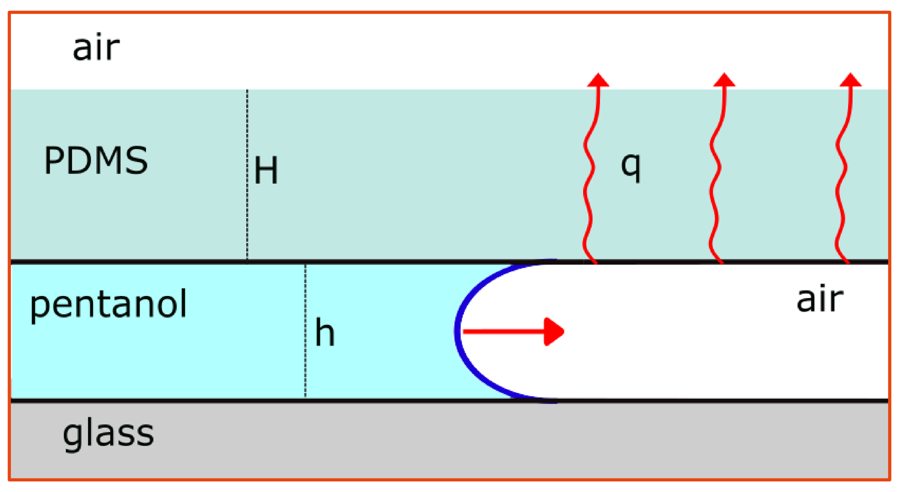


Sketch of a leaf cross-section. The blue arrows show the flow of water.
Xu et al., Journal of Plant Physiology, 234-235 (2019) 138-144

«artificial leaf»

Bio-Mimetism

Microfluidic channels in thin PDMS layer, allowing transpiration of water and diffusion of air



Sketch of our approach: A single channel is etched in PDMS and deposited on a glass slide. Pentanol displaces the air (embolism), which escapes through the pores of the PDMS (stomata)

- Pump-less networks with one entrance and **no exit**
- Pores of PDMS allow for the escape of the trapped air (mimicking the role of the stomata)
- Liquid: **Pentanol** due to its perfect wetting with PDMS
- Only driving force: **the interfacial pressure between liquid and air**

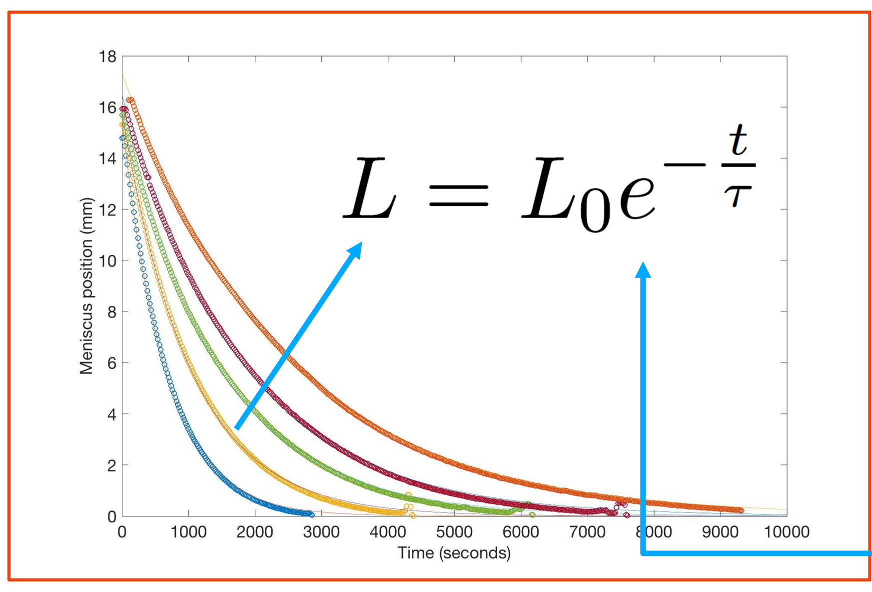
Goals:
I. Understanding pump-less liquid flows
II. Determining the "rules" of flows in networks

I. Understanding imbibition in single channels

I.1) Imbibition in single channel of constant width and height

- The escaping air flux q is proportional to the gas over-pressure $\Delta P = P_{gas} - P_{atm}$.
- The over-pressure is given by the Young-Laplace equation, as a function of the surface tension and geometrical characteristics of the channel. (γ: surface tension, w: channel width)

$$q \propto \Delta P \propto \frac{\gamma}{w}$$



$$L = L_0 e^{-\frac{t}{\tau}}$$

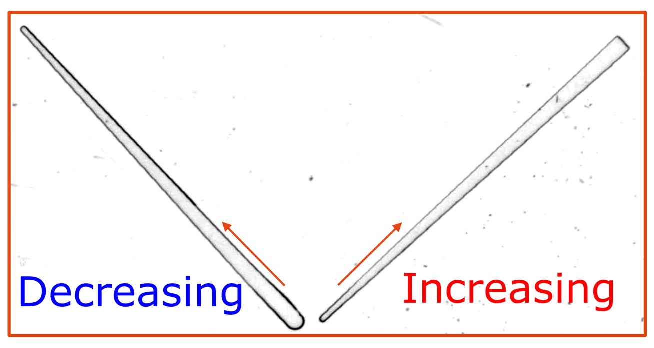
Air column length vs time for 5 channels of increasing width (blue to orange). L_0 is the total channel length.

- The volumetric flux, Q:
  - Is proportional to the channel length, L. $\quad Q = qL$
  - Is determined through the conservation of volume of the air pocket (h: channel height) $\quad Q = -hw\dot{L}$

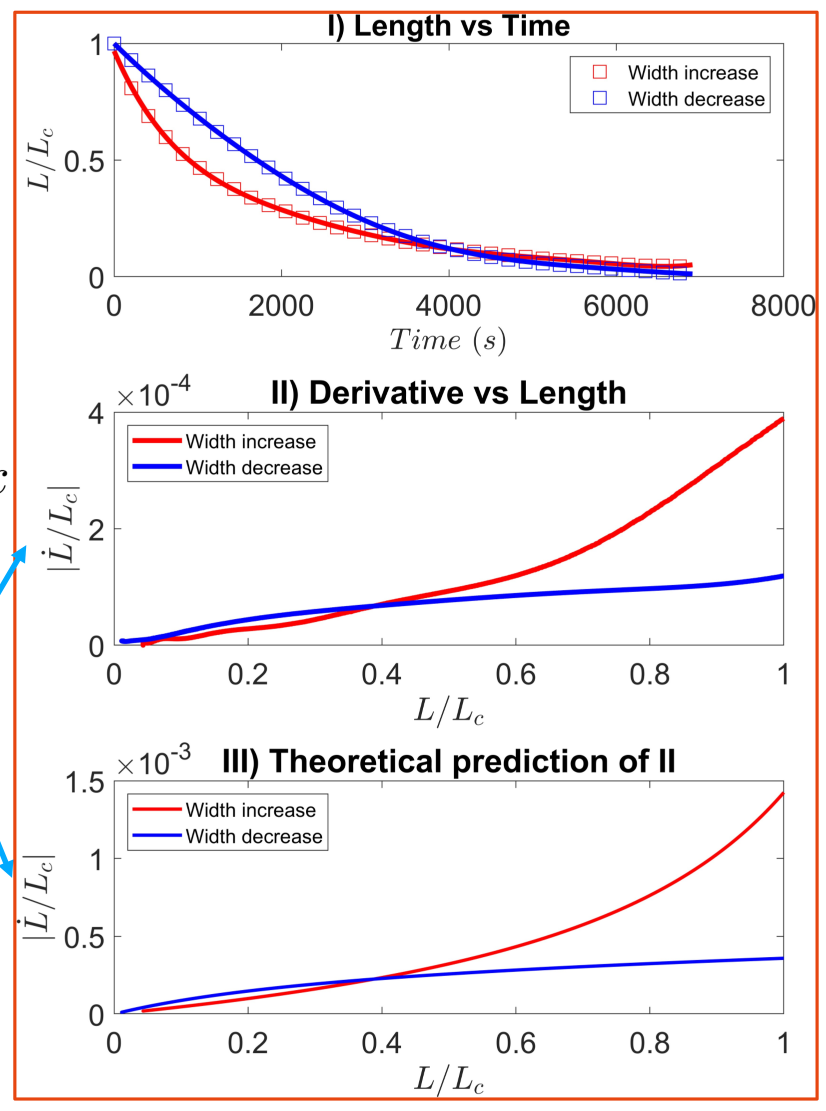
$$\frac{\dot{L}}{L} = -\frac{hw}{q} = -\tau$$

I.2) Imbibition in single channel of linear width profile and constant height

- q now a function of the local width: $\quad q = q(w(x))$
- Q has to be solved as an integral of q over the length of the channel, L_c: $\quad Q = \int_0^{L(t)} q(w(x))\, dx$
- The length vs time is not an exponential: $\quad \dot{L} = F(L)$



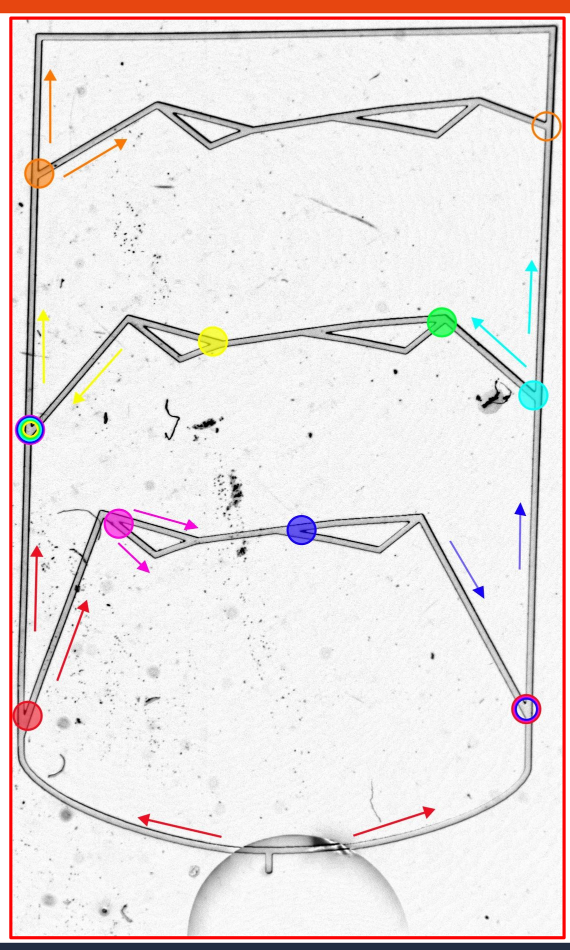
Two channels of linear width profiles



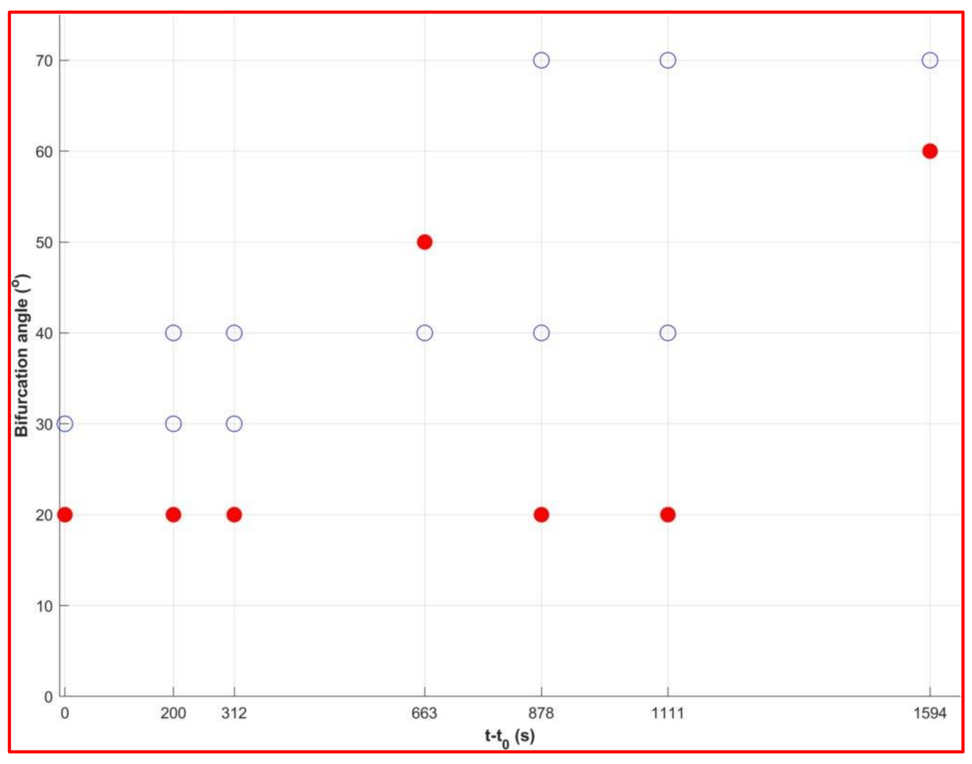
Length vs time and derivative vs normalized length

II. A "rule" for the design of networks with deterministic flow

- **Bifurcation angle "rule":** When two or more anchored menisci are competing to split in bifurcations, the one in the most acute bifurcation will split first.



The "ladder" network. All bifurcations are designed with increasing angles, from 20º to 70º. Arrows indicate the flow of pentanol. Circled bifurcations indicate a competition event there. Unfilled circle: Meniscus remained anchored after the competition. Filled circle: Meniscus "won" the competition. Seven events are pictured, color coded as: red, violet, blue, cyan, green, yellow, orange.



Graph of every splitting competition event. Red circle signifies a "win", blue circle a "loss".

Perspectives

- ➢ Modelling of imbibition in more complex networks (e.g. of multiple width profiles).
- ➢ Development of pump-less microfluidic chips for practical purposes (Lab-on-a-Chip).
- ➢ Bio-mimetism route: Using water with biopolymers as our materials. Designing networks in which imbibition begins via condensation on the outside of the chip, instead of our current approach in which the liquid enters through a single opening.