When bits get wet: introduction to microfluidics networking

DIPARTIMENTO DI INGEGNERIA DELL'INFORMAZIONE

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Most of experimental pictures in this presentations are complimentary from Prof. Mistura (Univ. of Padova)

Purposes

1. **Introduction to microfluidics networking**

2. **Research challenges**

3. Grow the interest on the subject… and **increase my citation index** ☺

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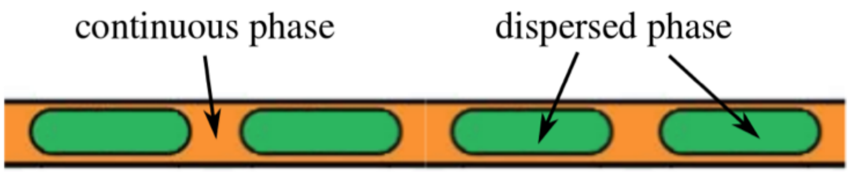
MICROFLUIDICS…

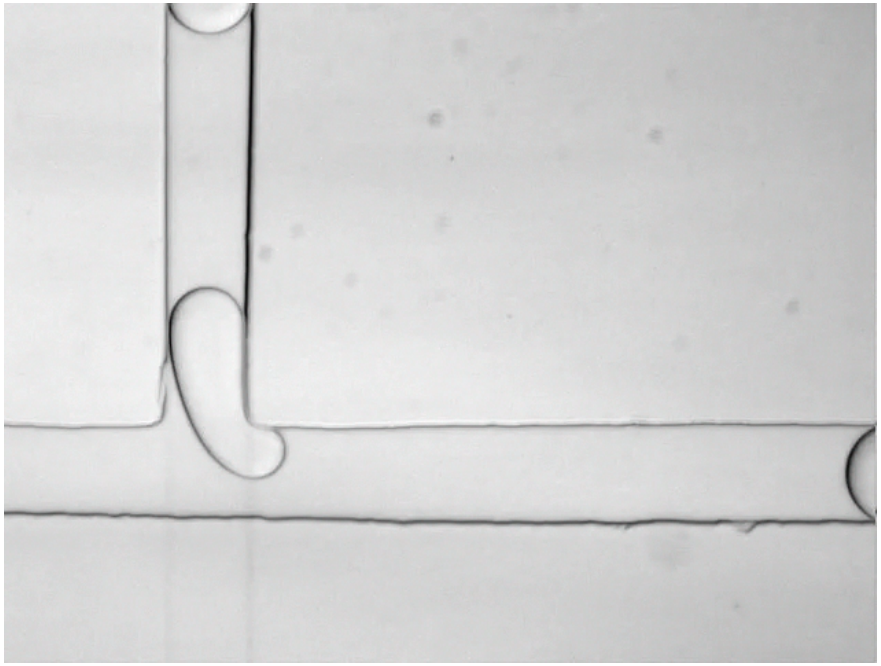
WHAT IS IT ALL ABOUT?

- Microfluidics is both a **science** and a **technology** that deals with the control of small amounts of fluids flowing through microchannels



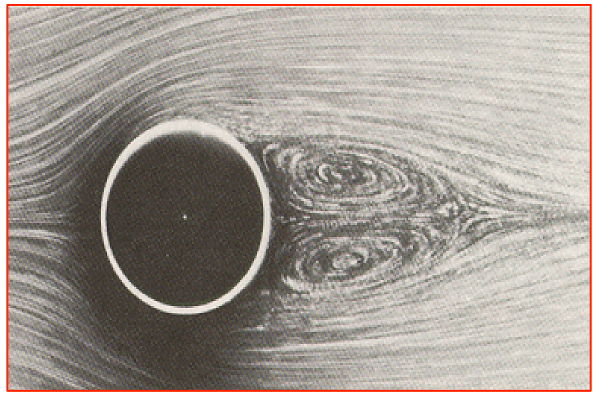
Droplet microfluidics

- Droplets (dispersed phase) encapsulating samples and reagents are dispersed into an immiscibile fluid (continuous phase) and carried throughout microchannels



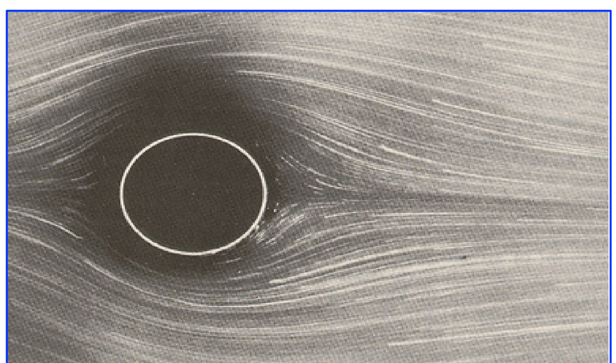
Features

MACROSCALE: inertial forces >> viscous forces



turbolent flow

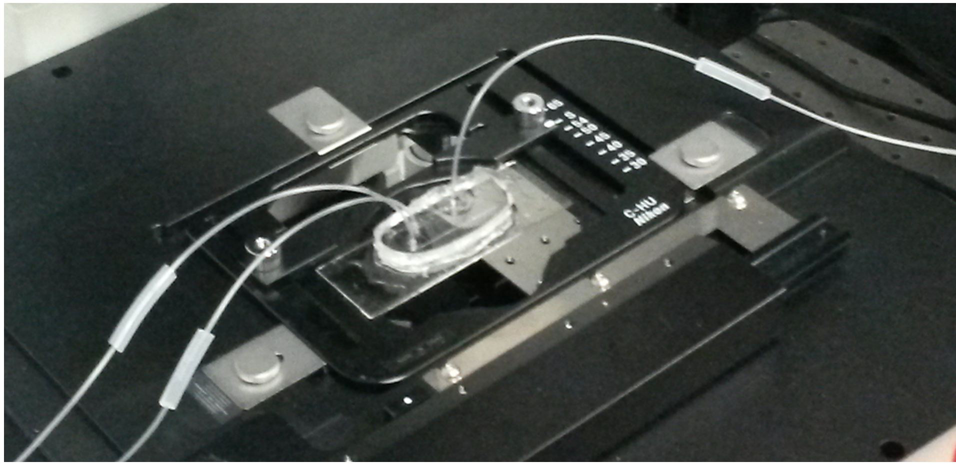
microscale: inertial forces ≈ viscous forces

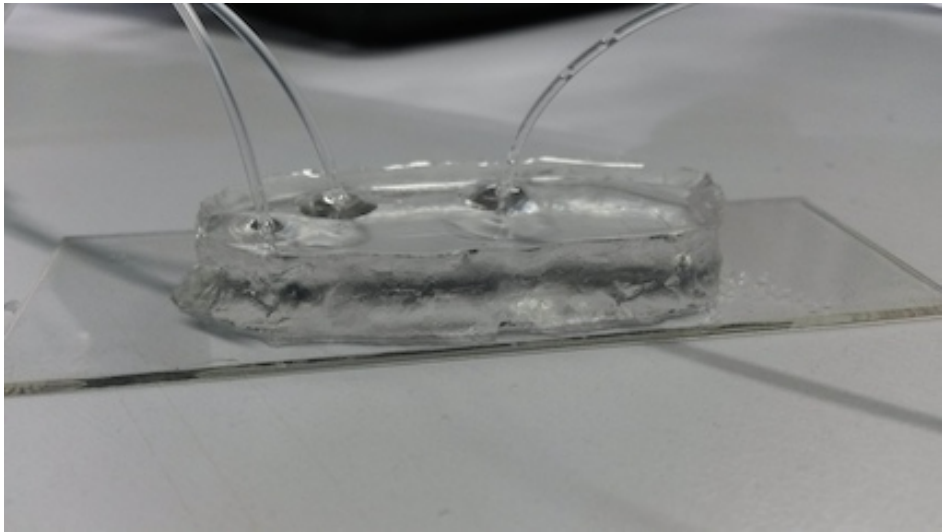


laminar flow

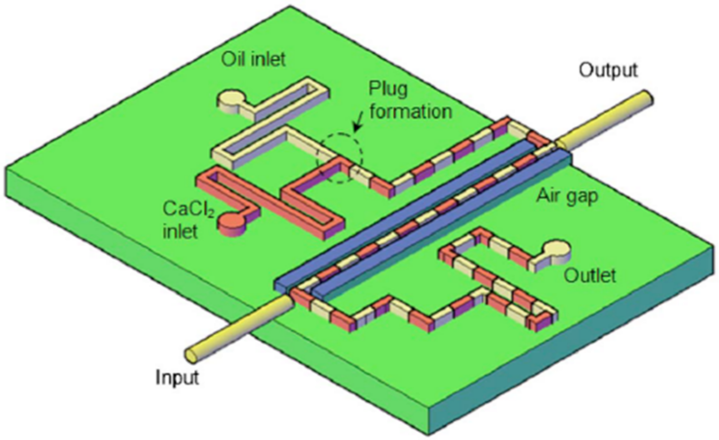
Advantages

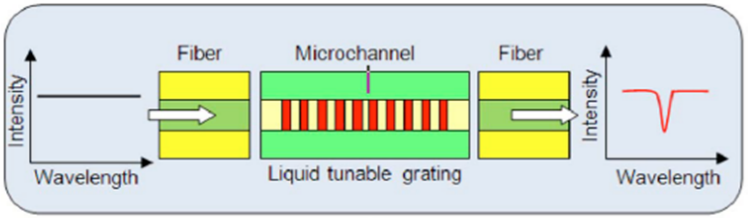
- Optimum flow control
  - Accurate control of concentrations and molecular interactions
- Very small quantities of reagents
  - Reduced times for analysis and synthesis
  - Reduced chemical waste
- Portability



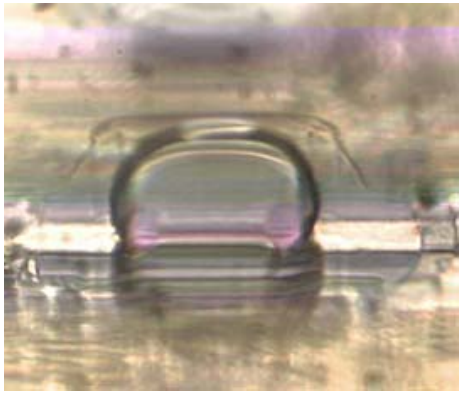


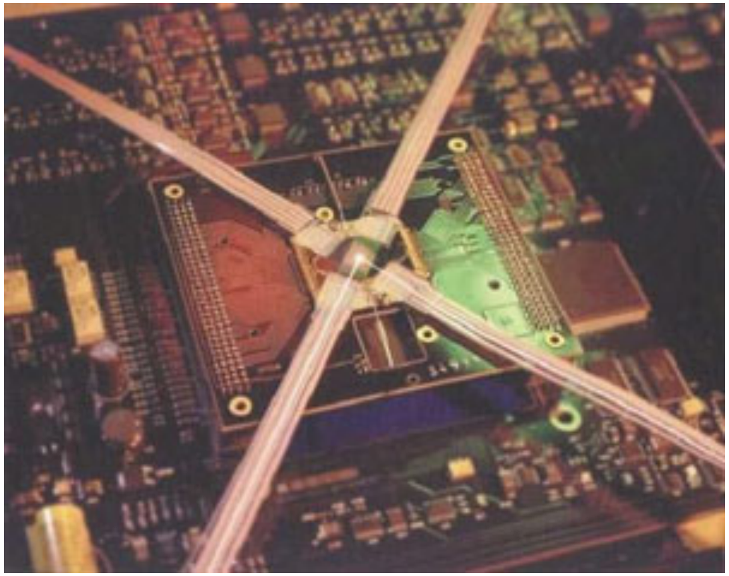
Microfluidic research: Tunable filters, Optical Switches,…





] Chin, L. K.; Liu, A.Q.; Zhang, J.B.; Lim, C. S.; Soh, Y. C., "An on-chip liquid tunable grating using multiphase droplet microfluidics," *Applied Physics Letters* , vol.93, no.16, pp.164107,164107-3, Oct 2008

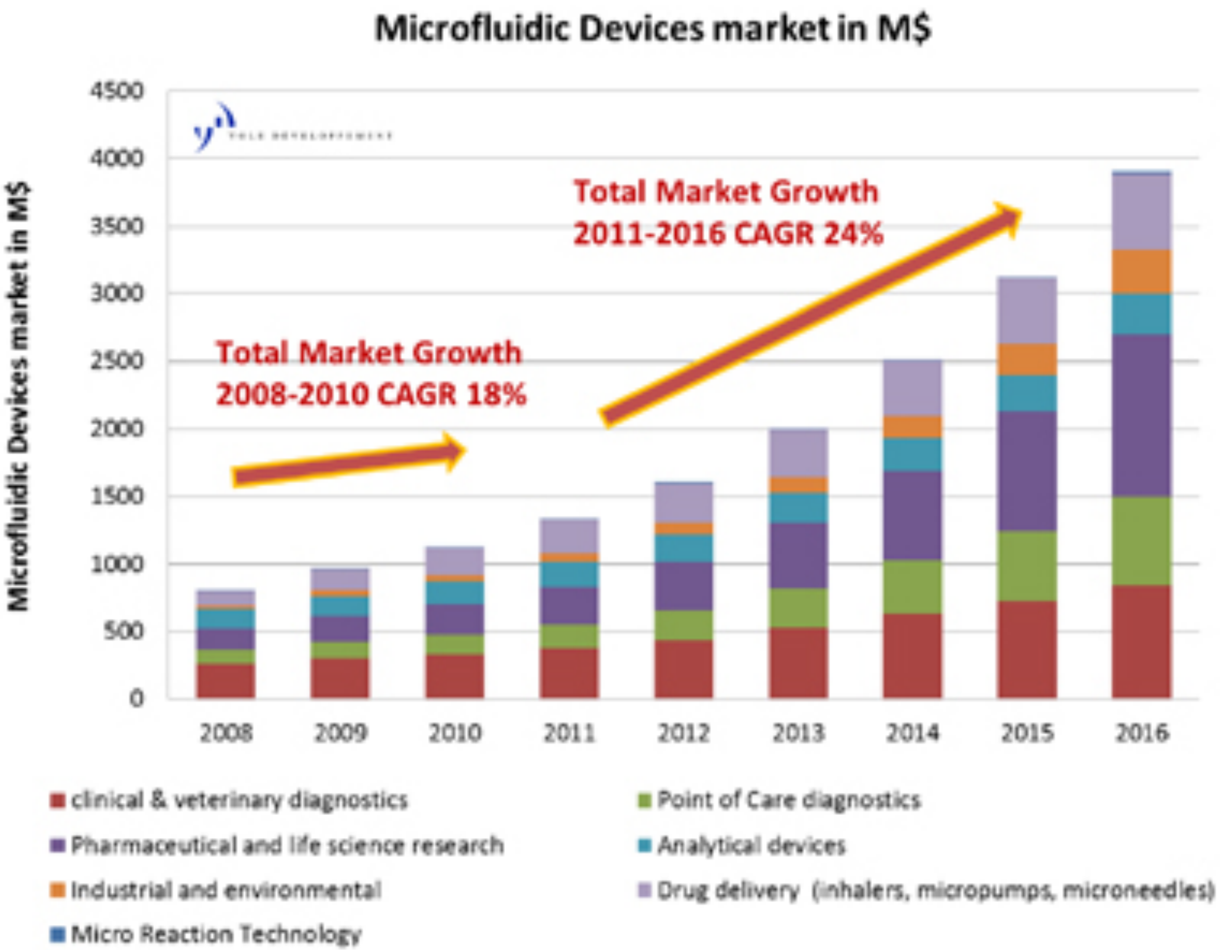




Switching Fiber-Optic Circuits with **Microscopic Bubbles** John Uebbing, Agilent Technologies

Market

- Inkjet
- Biolo
- Chem
- Pharr
- Medi
- ...



Source: Yole Développement (www.micruxfluidic.com)

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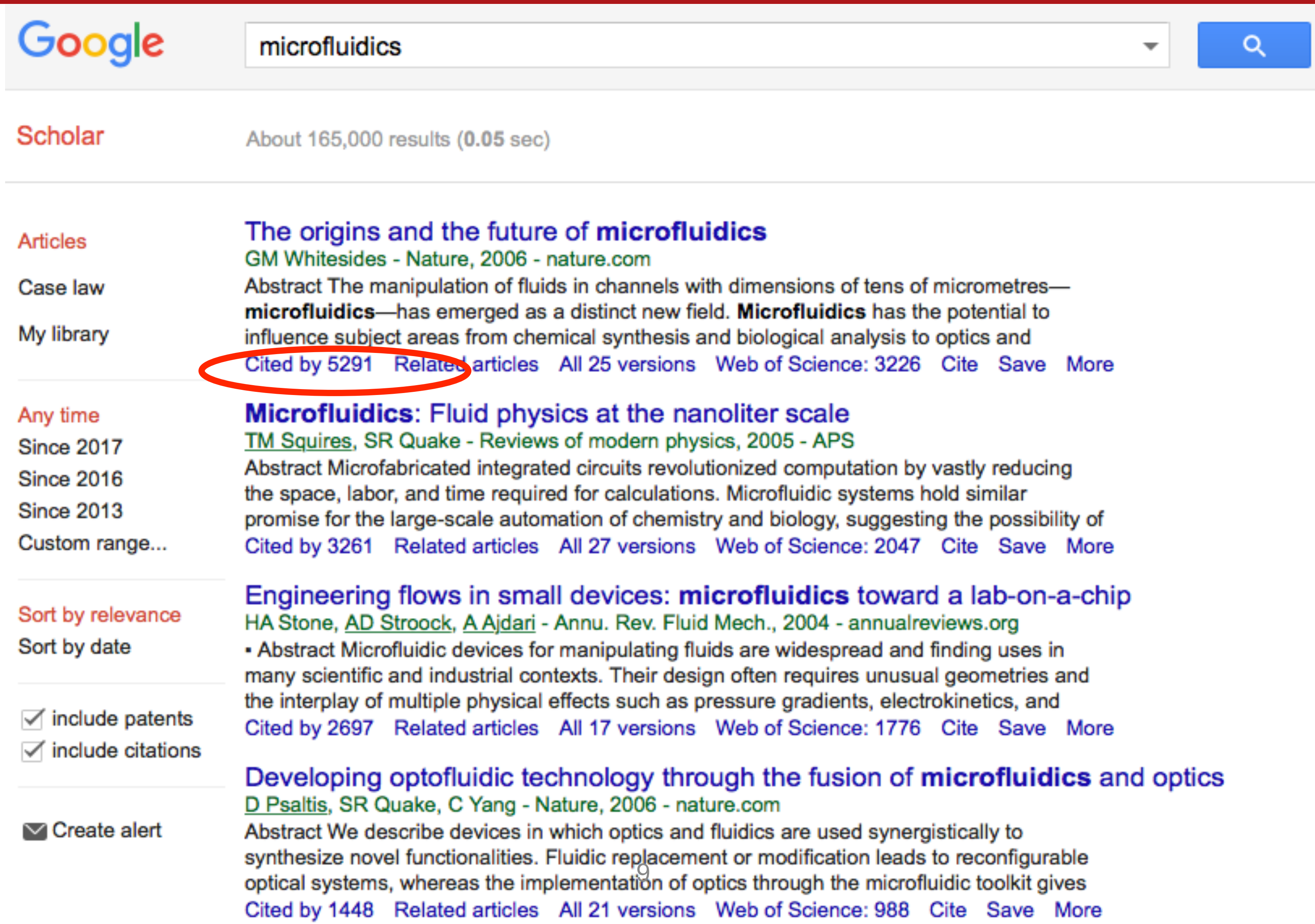
Popularity

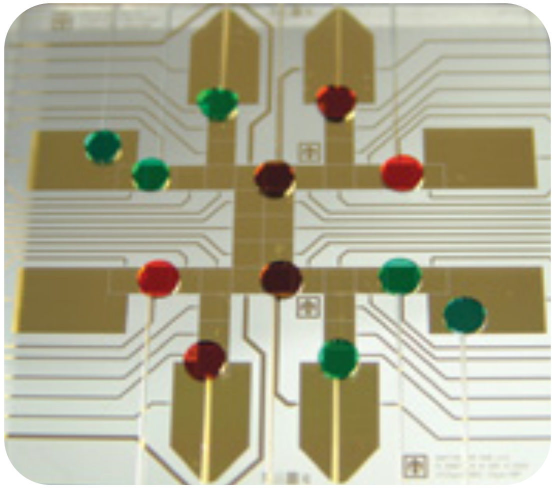


LoC Internetworking

- Currently, most LoC are special-purpose devices
- Attention is now on **LoC internetworking**
  - **Versatility**
    - same device for different purposes
  - **Capability**
    - Can concatenate multiple LoCs to realize more complex analysis/functionalities
  - **Economy**
    - Cost saving
    - Energy saving

The challenge of integration

- Today's commercial available programmable microfluidic devices (PMS) exploit **active manipulation** methods (es. Agilent, Advanced Liquid Logic).



Active Droplets handling (Electrowetting on Dielectrics)

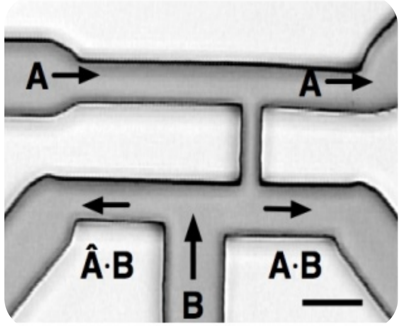
- relies on integrated valves and electrodes
- requires a complex and costly multilayer microfabrication process for the chip

Active droplets handling… Problems?

- Expensive fabrication process
- Biocompatibility of electrical signals on cells and biomolecules

M. Prakash, N. Gershenfeld
Microfluidic Bubble Logic,
Science, 315(5813), 2007

Bubble logic is a first attempt to design a passive PMS



Passive droplets handling

- exploits only pure hydrodynamic forces to control the droplets through an appropriate design of microchannels
- cheap and simple fabrication process

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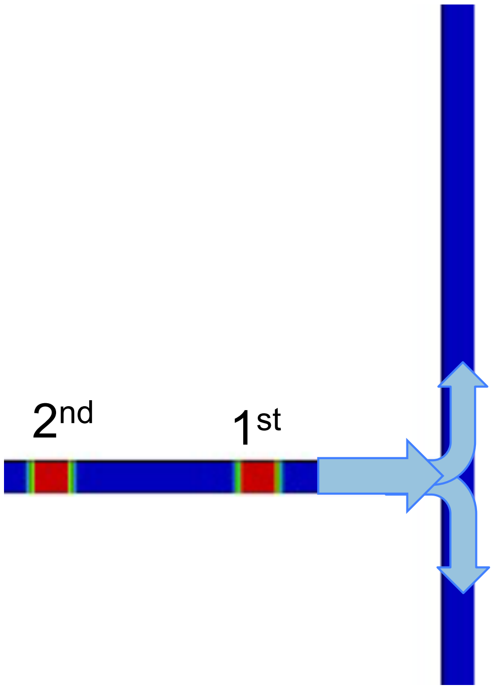
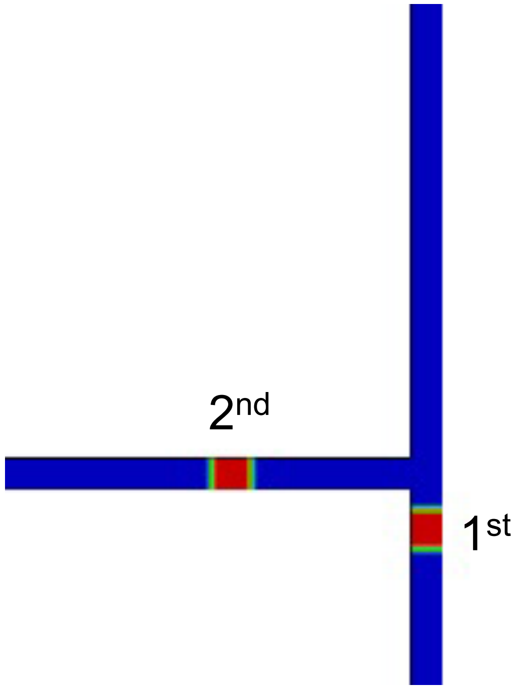
Pure hydrodynamic switching principle

① Droplets flow along the path with minimum hydraulic resistance

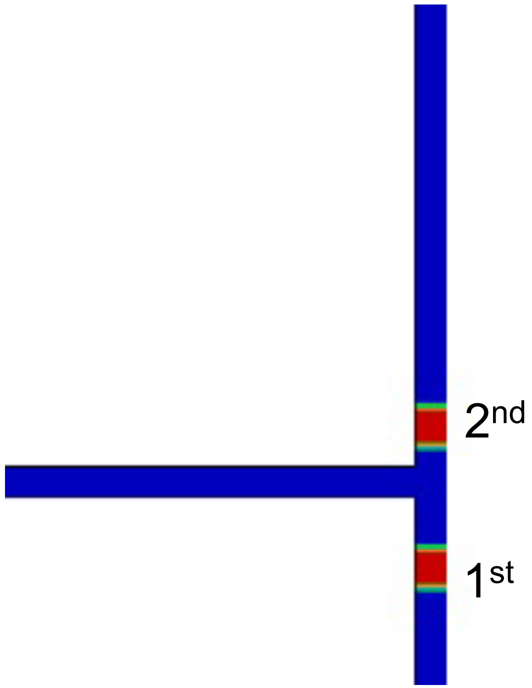
② Channel resistance is increased by droplets



Two close droplets arrive at the junction



First drop "turns right"



Second drop "turns left"

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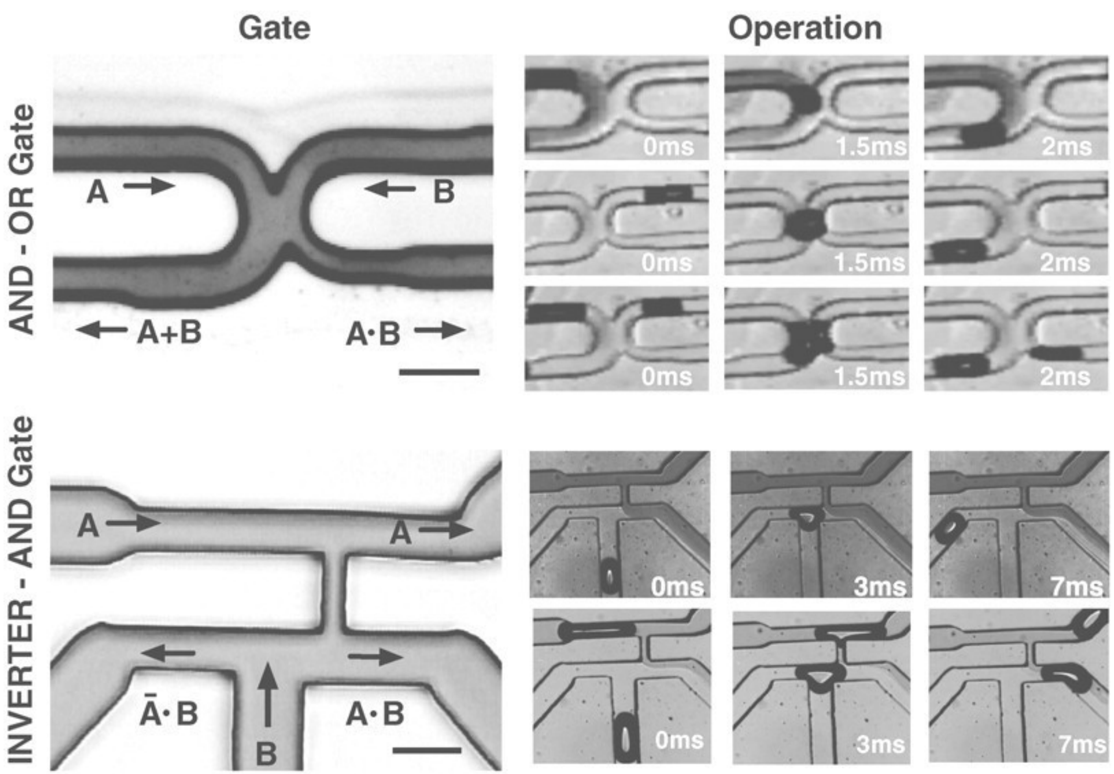
Microfluidic bubble logic

- Droplet microfluidics systems can perform basic Boolean logic functions, such as AND, OR, NOT gates



A	B	A+B	AB
1	0	1	0
0	1	1	0
1	1	1	1

See: Microfluidic **bubble logic,** M Prakash, N Gershenfeld - Science, 2007

OUR APPROACH

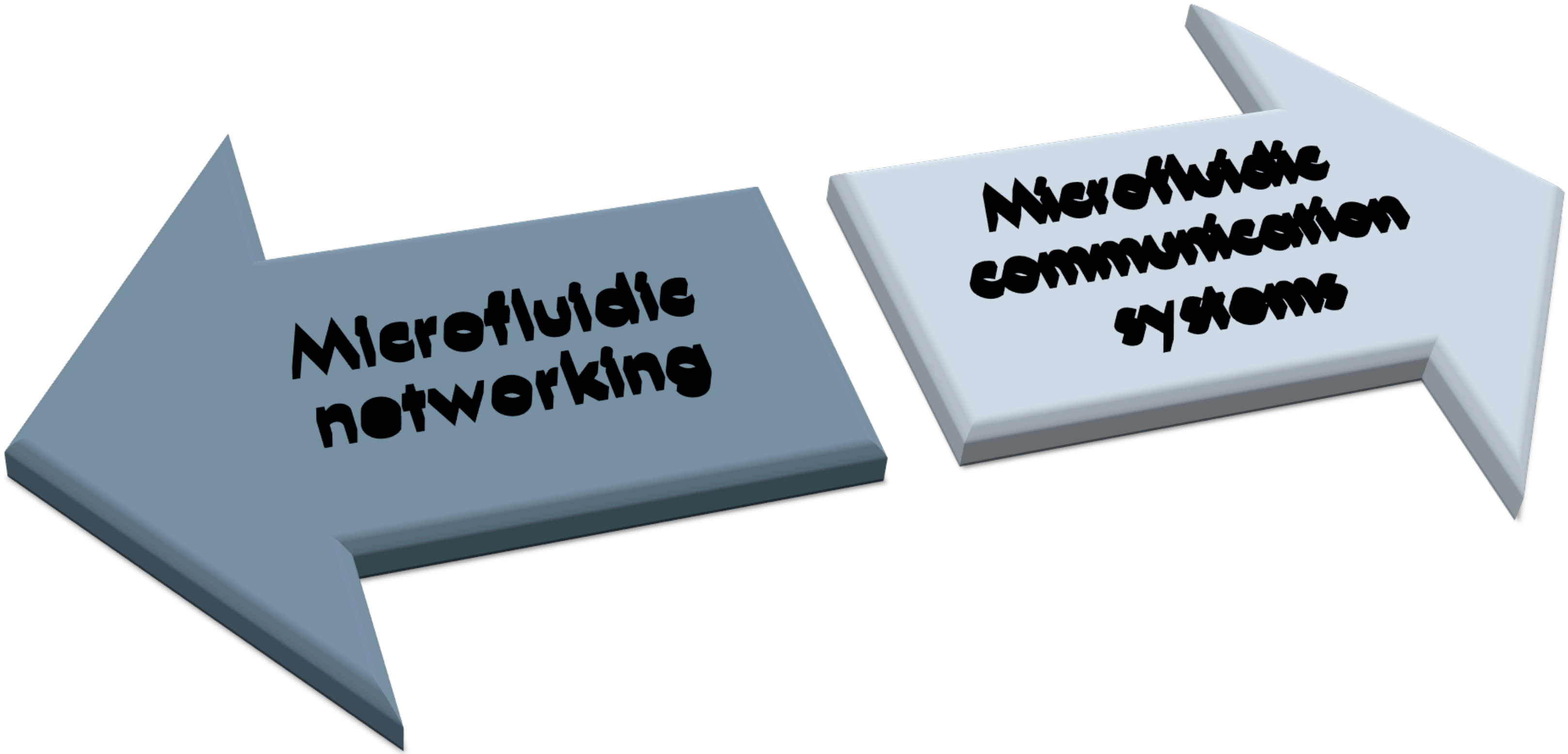
Purely hydrodynamic LoC internetworking

- **Simple fabrication**
  - No mixed materials
  - 3D printer-made circuits
- **Simple control**
  - Act only at board periphery (mainly, syringes/pumps)
- **Bio compatibility**
  - No electronics → no undesired biological interactions
  - Possibility to implant in living tissues

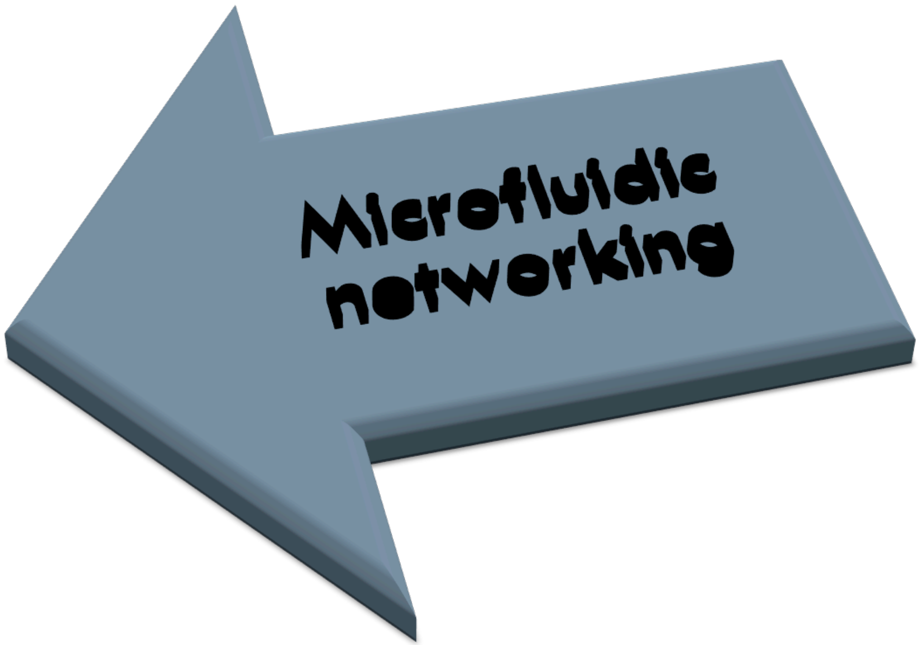
Challenges

- Droplets behavior is affected by various intertwined factors
  - flows in each channel depend on the properties of the entire system
    - Topology & geometrical parameters
    - Fluids characteristics (density, viscosity, …)
    - Obstacles, imperfections, …
- Time evolution of a droplet-based microfluidic network is also difficult to predict
    - the speed of the droplets depends on the flow rates, which depend on the hydraulic resistance of the channels, which depend on the position of the droplets…

OUR GOALS


Microfluidic networking
Microfluidic communication systems

OUR GOALS

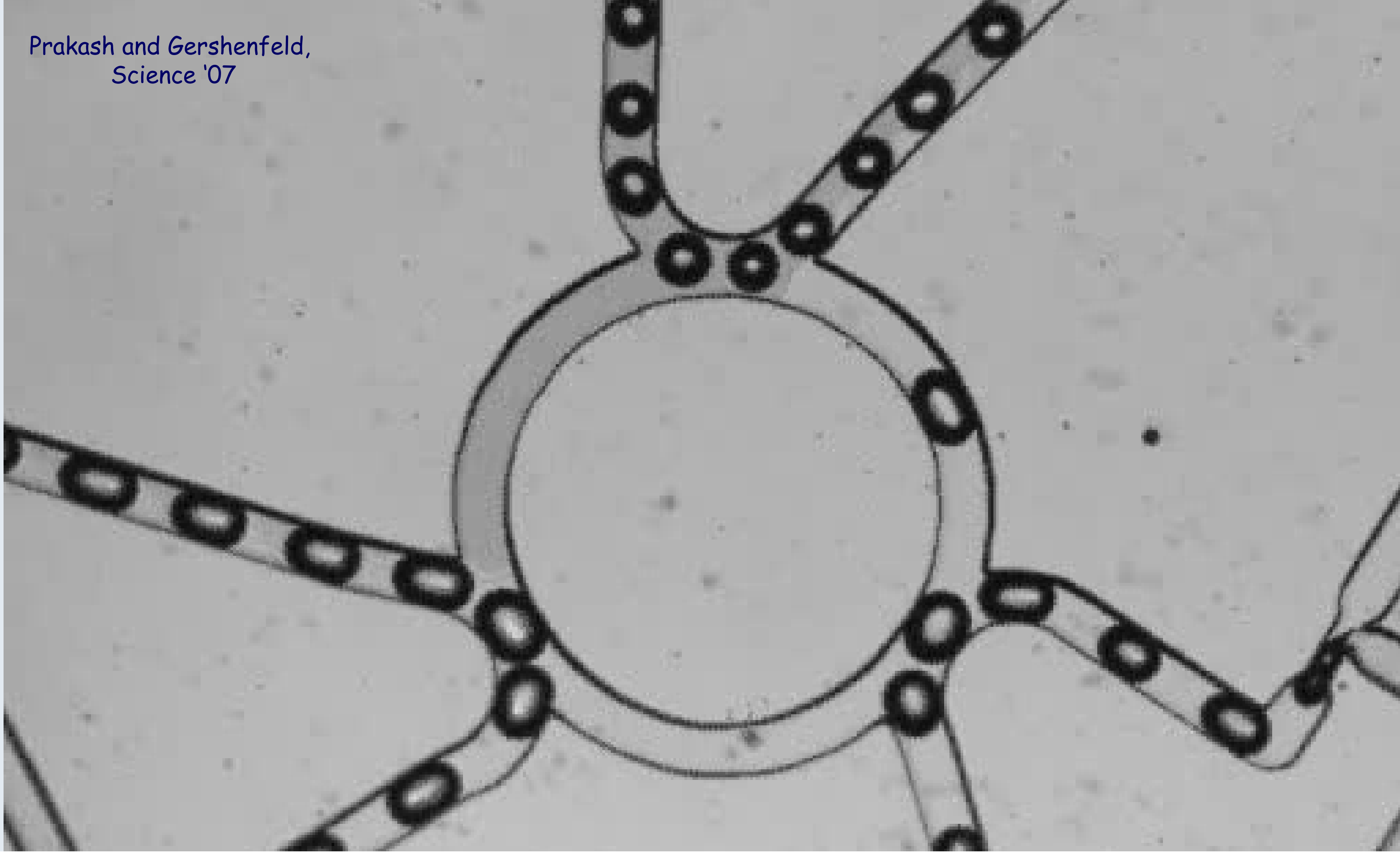


Our contributions

① Derive simple ``**macroscopic models**" for the behavior of microfluidic systems as a function of the system parameters

② Define a simple Microfluidic Network Simulator framework

③ Apply the method to study the performance of a microfluidic network with **bus topology**



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① "Macroscopic" models

Basic building blocks

① Droplet source

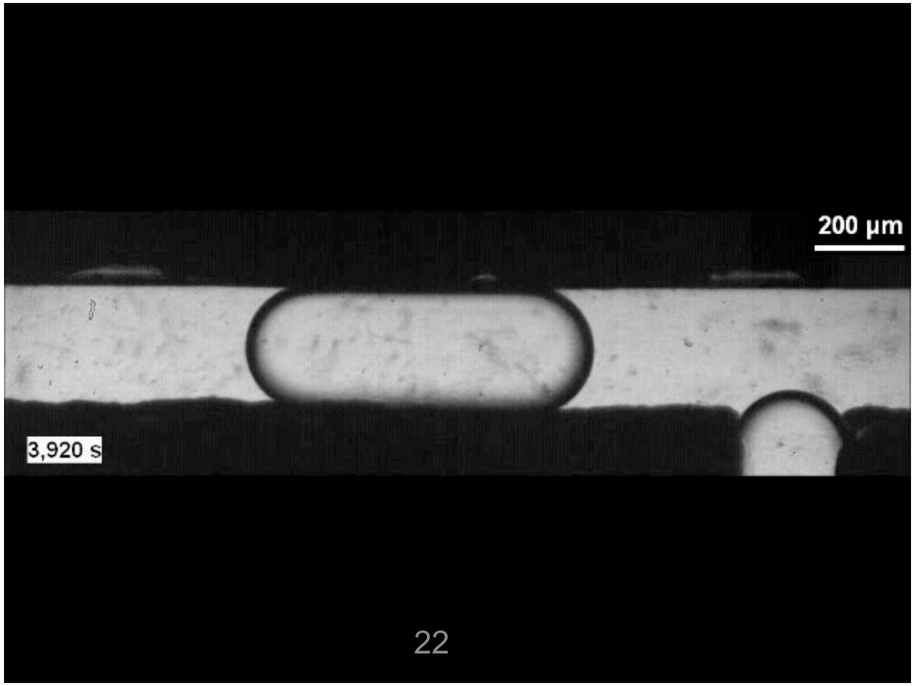
② Droplet switch

③ Droplet use (microfluidic machines structure)

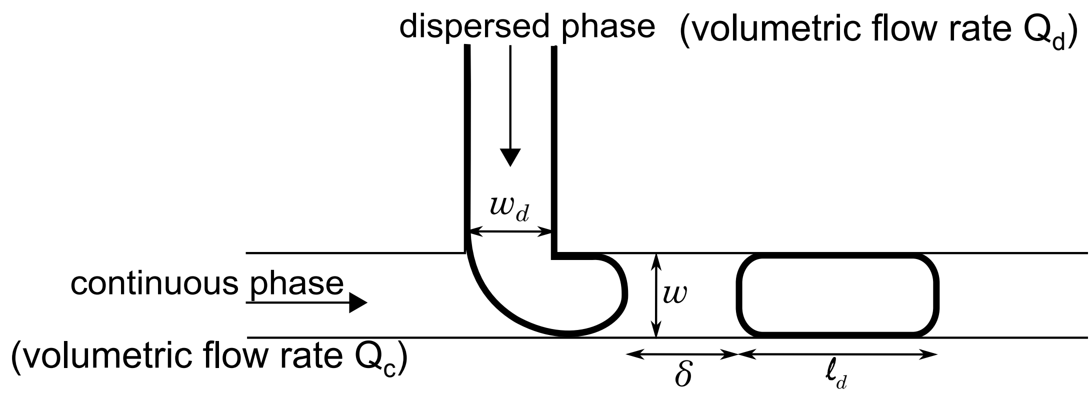
Droplets generation

Capillary number: captures the relative magnitude of the viscous shear stress compared with the interfacial tension

$C_a < C_a^* \approx 10^{-2}$ ➔ **Squeezing regime** ➔ **droplet formation**



Droplets generation



$$L_d = w\left(1 + \xi \frac{Q_d}{Q_c}\right) \qquad \delta = L_d \frac{Q_c}{Q_d} + \frac{\pi w^3/6 - w^2 h}{Q_d w h}(Q_d + Q_c)$$

Constant (~1)

- By changing input parameters, you can control (average) droplets length and spacing, but NOT independently!

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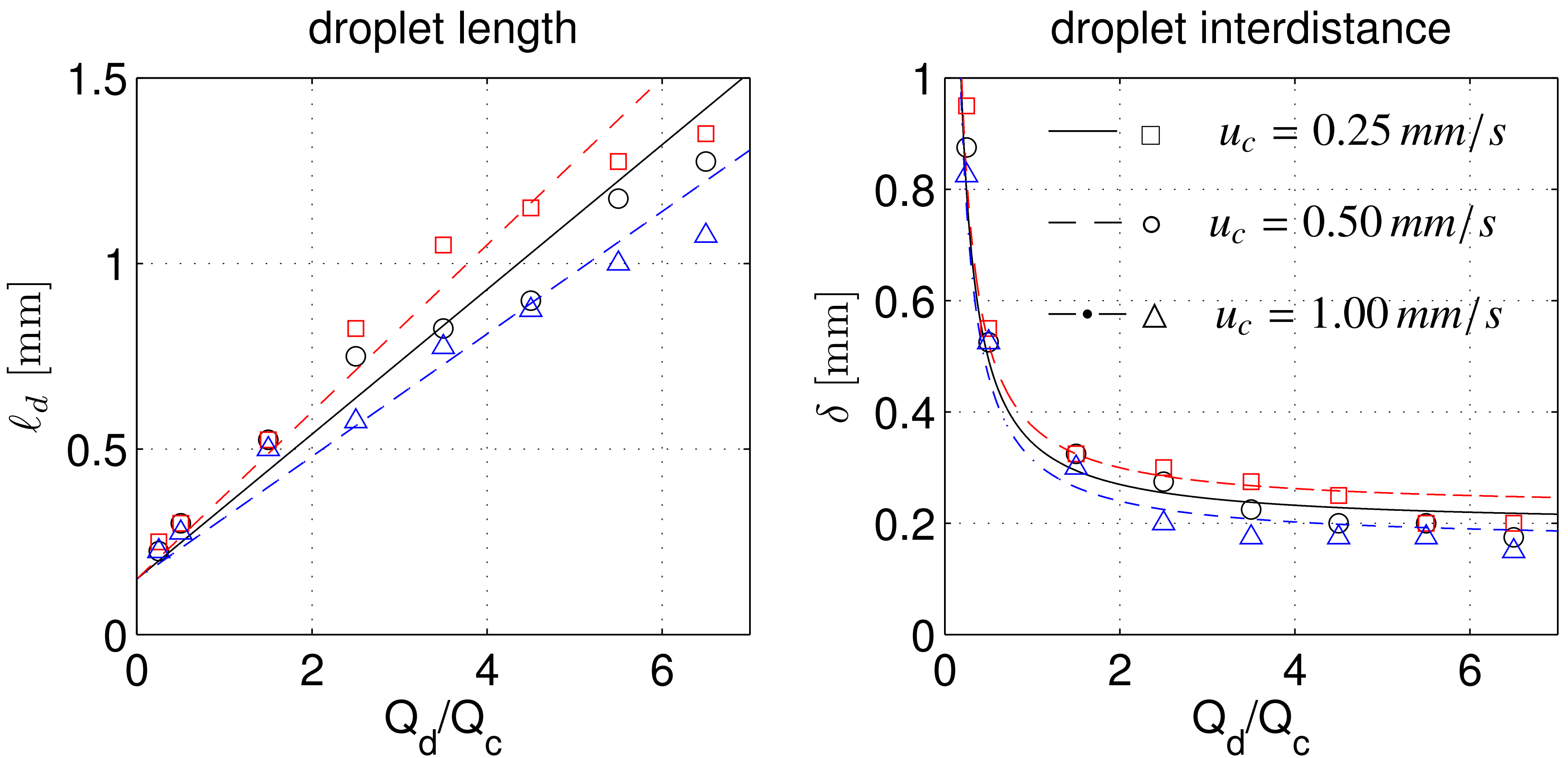
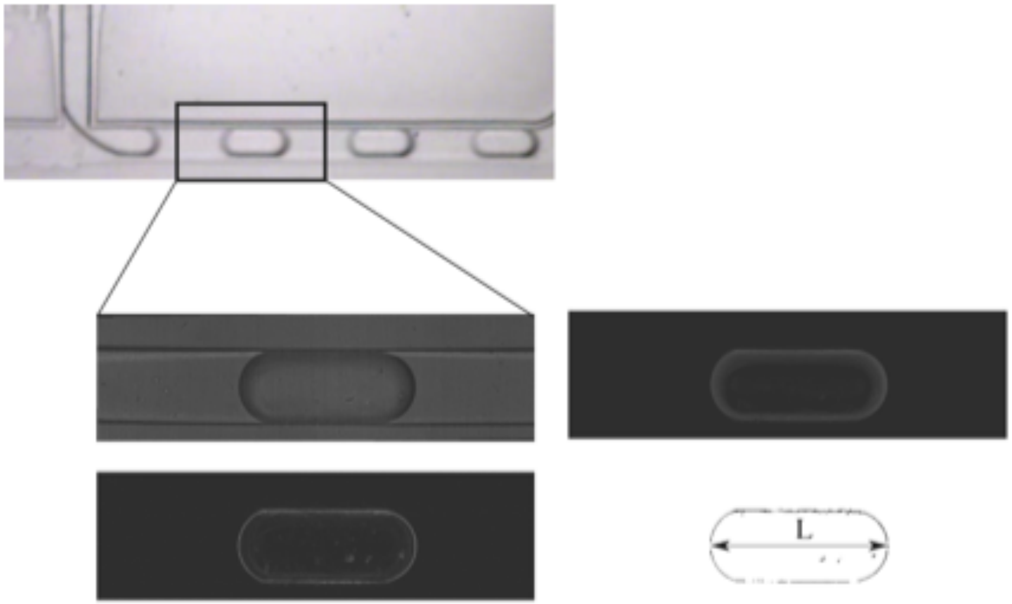
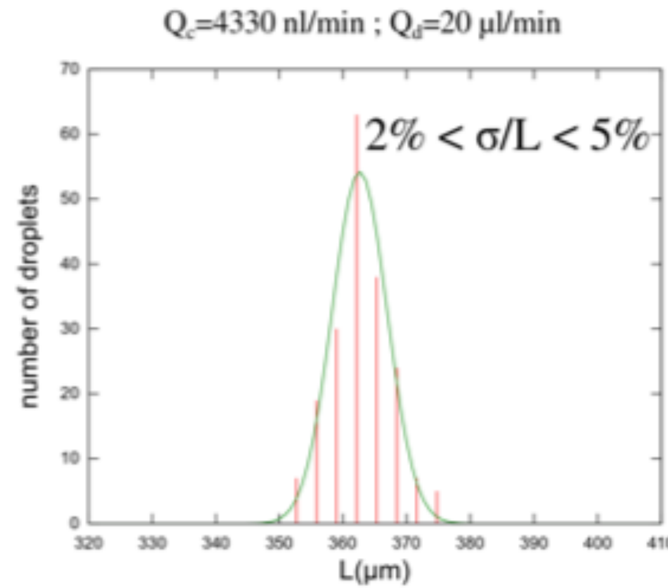
Droplets generation (2)



Experimental results

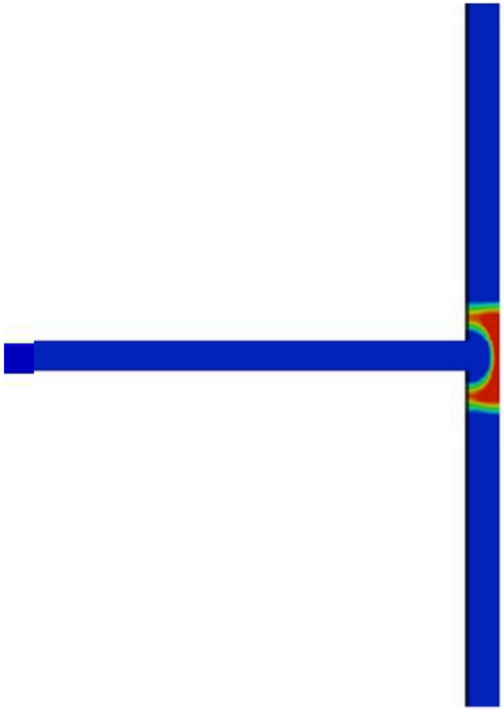




- varying Q_d for each 4 values of Q_c
- $Ca \sim 10^{-4}$
- ~ 150 droplets

Junction breakup

- When crossing a junction a droplet can **break up…**

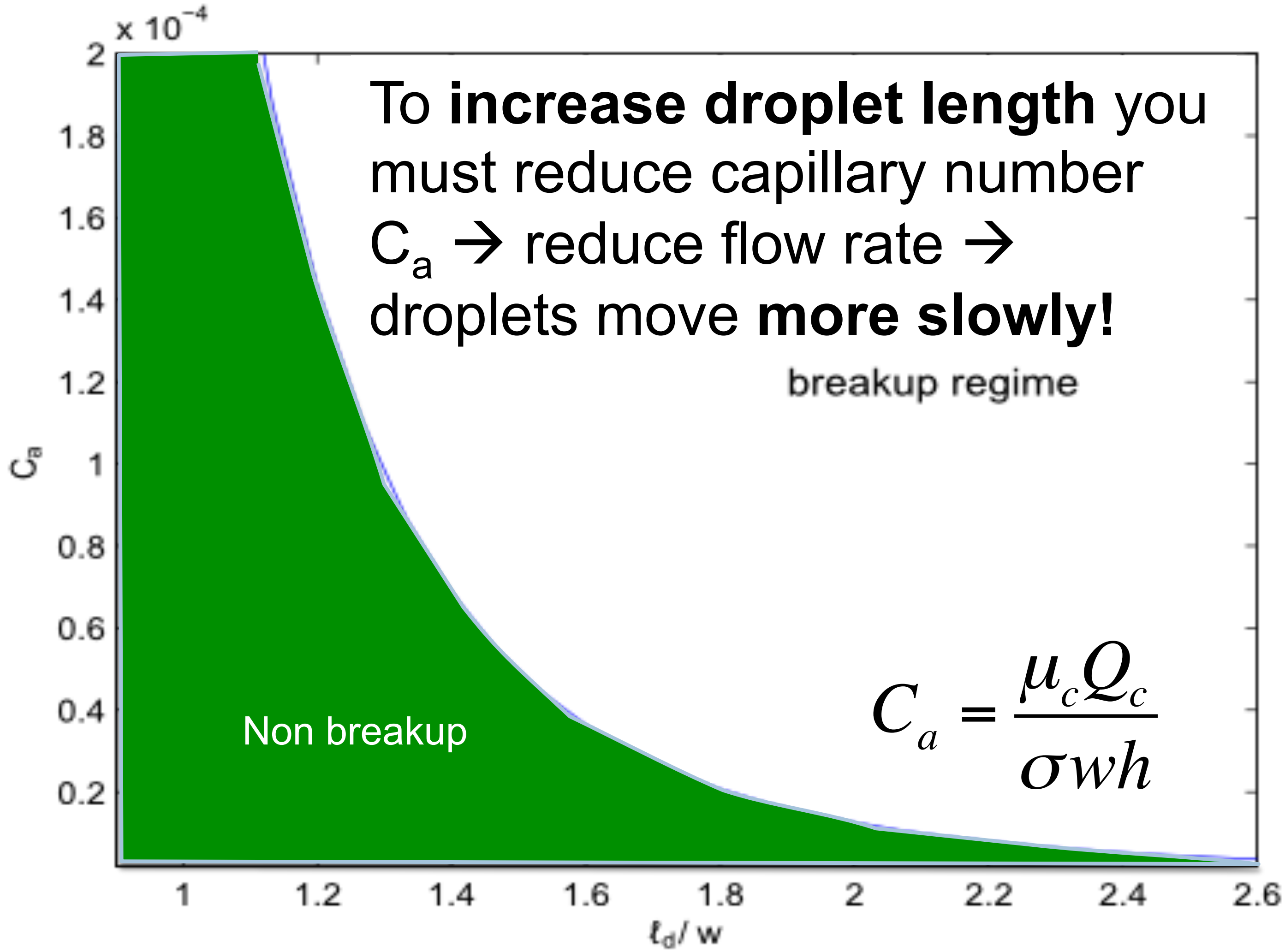


To avoid breakup, droplets shall not be too long [1]

$$\ell_d < \ell_d^* \approx \chi w C_a^{-0.21}$$

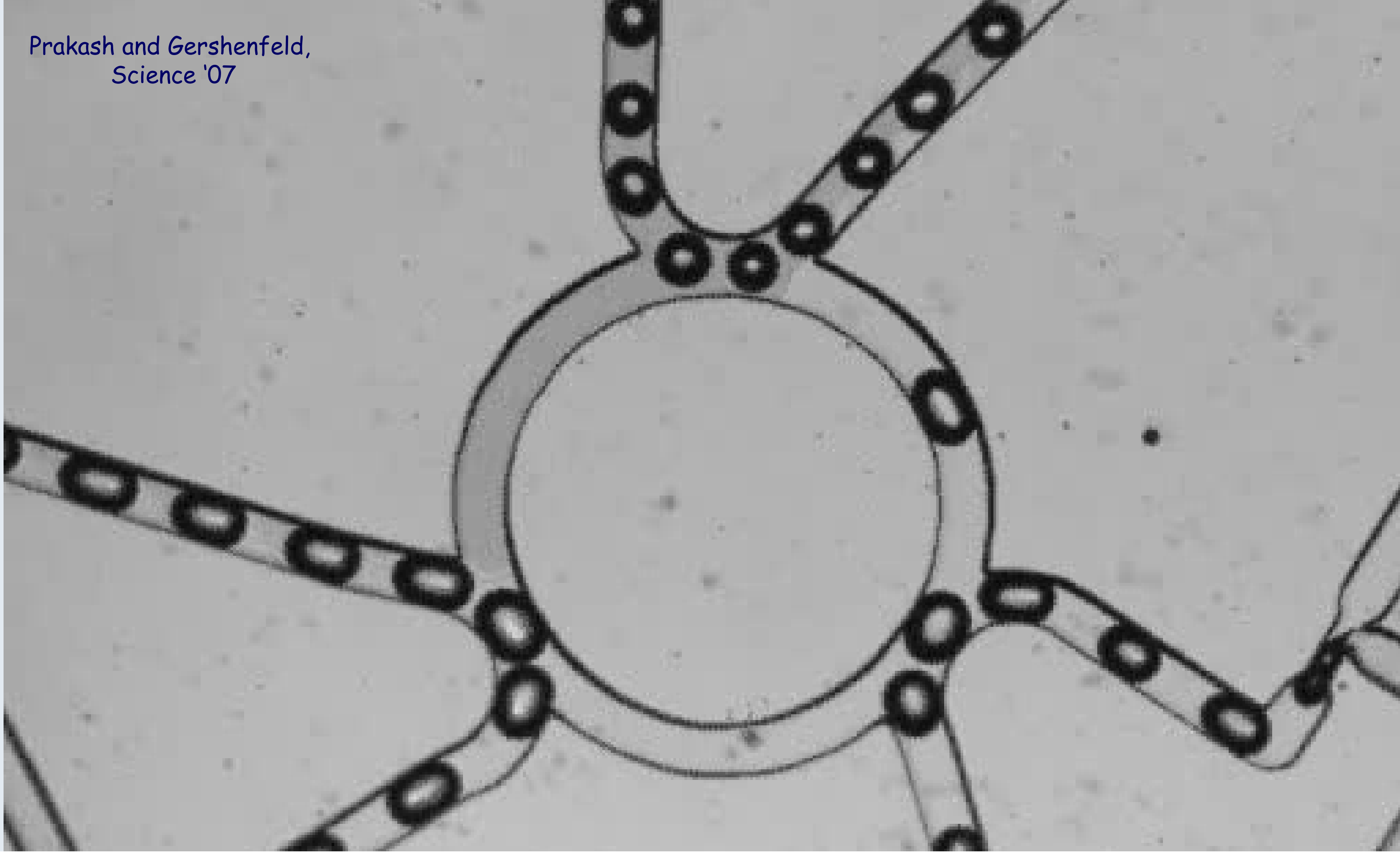
[1] A. M. Leshansky, L. M. Pismen, "Breakup of drops in a microfluidic T-junction", *Phys. Fluids*, 21.

Junction breakup



To **increase droplet length** you must reduce capillary number C_a → reduce flow rate → droplets move **more slowly!**

$$C_a = \frac{\mu_c Q_c}{\sigma w h}$$



Prakash and Gershenfeld, Science '07

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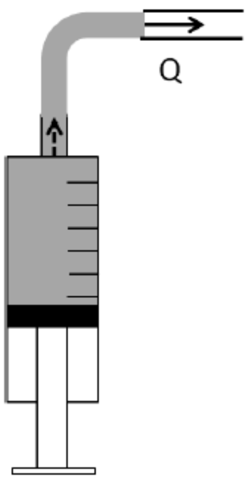
② Microfluidic Network Simulator

Microfluidic/electric duality

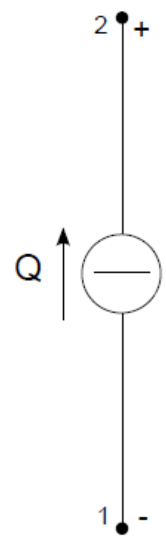
Microfluidic domain	Electric domain
	
Volumetric flow rate Q	Current intensity I
Pressure difference ΔP	Voltage drop ΔV
Hagen-Poiseuille law $\Delta P = RQ$	Ohm law $\Delta V = RI$
Flow and energy conservation $\Sigma\, Q = 0;\quad \Sigma\, \Delta P = 0$	Kirchhoff laws $\Sigma\, I = 0;\quad \Sigma\, \Delta V = 0$

Microfluidic/electrical analogy (I)

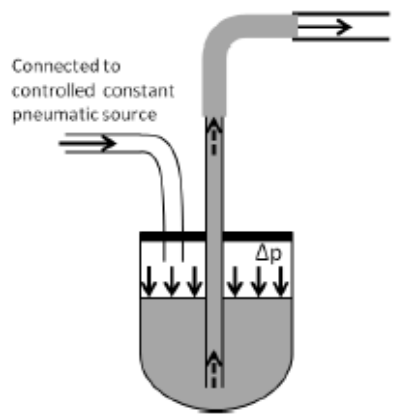
Syringe pump → current generator



→



Pneumatic source → voltage generator



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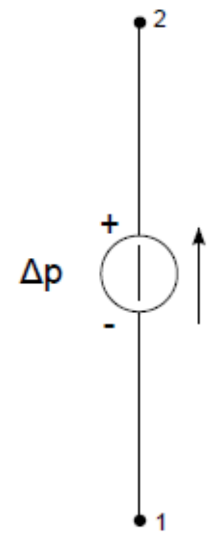
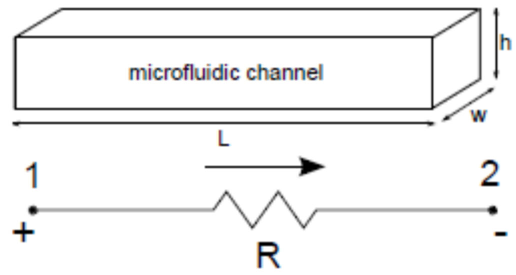


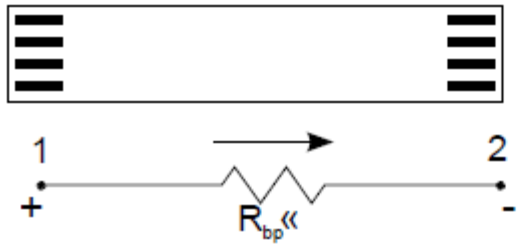
Microfluidic/electrical analogy (II)



Microfluidic channel filled only by continuous phase

↓

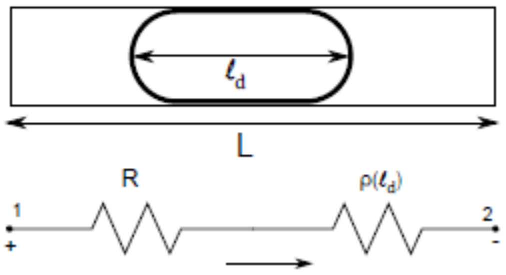
resistor



Bypass channel (ducts that droplets cannot access)

↓

resistor with negligeable resistance

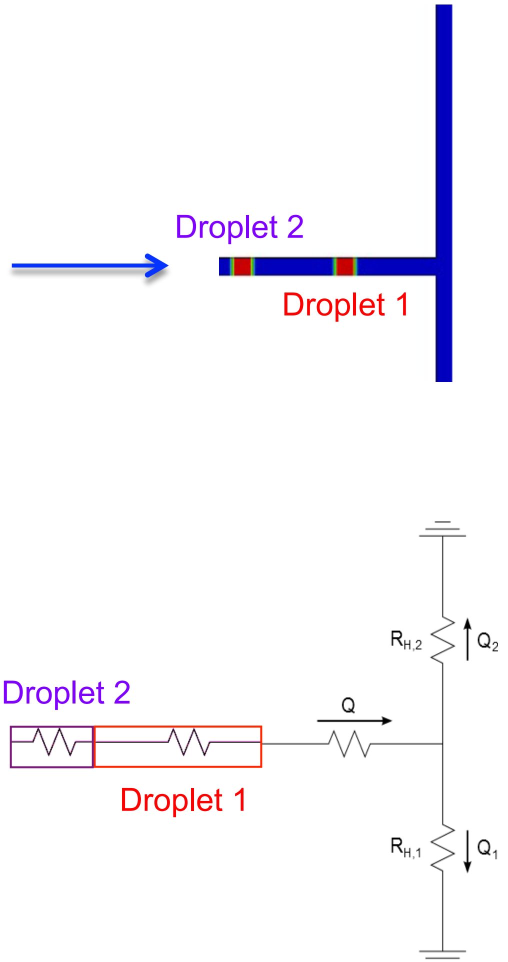


Microfluidic channel containing a droplet

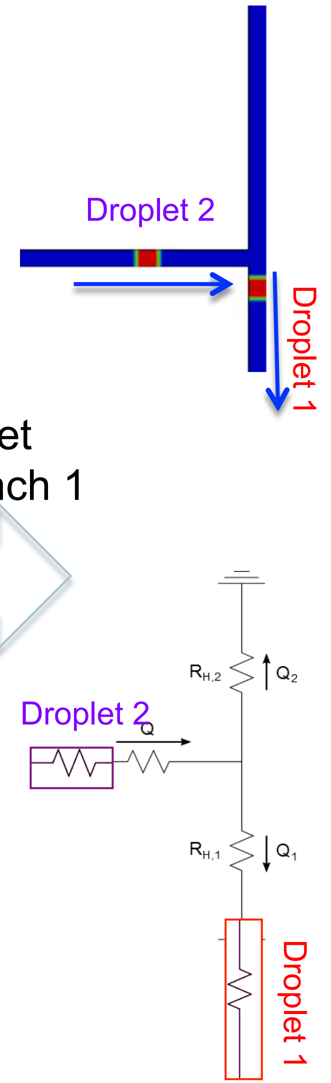
↓

series resistor

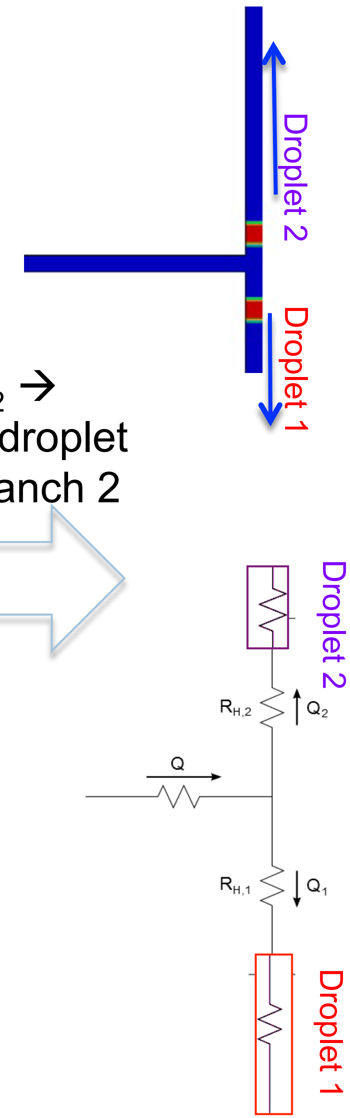
Example



$R_1 < R_2$ → First droplet takes branch 1

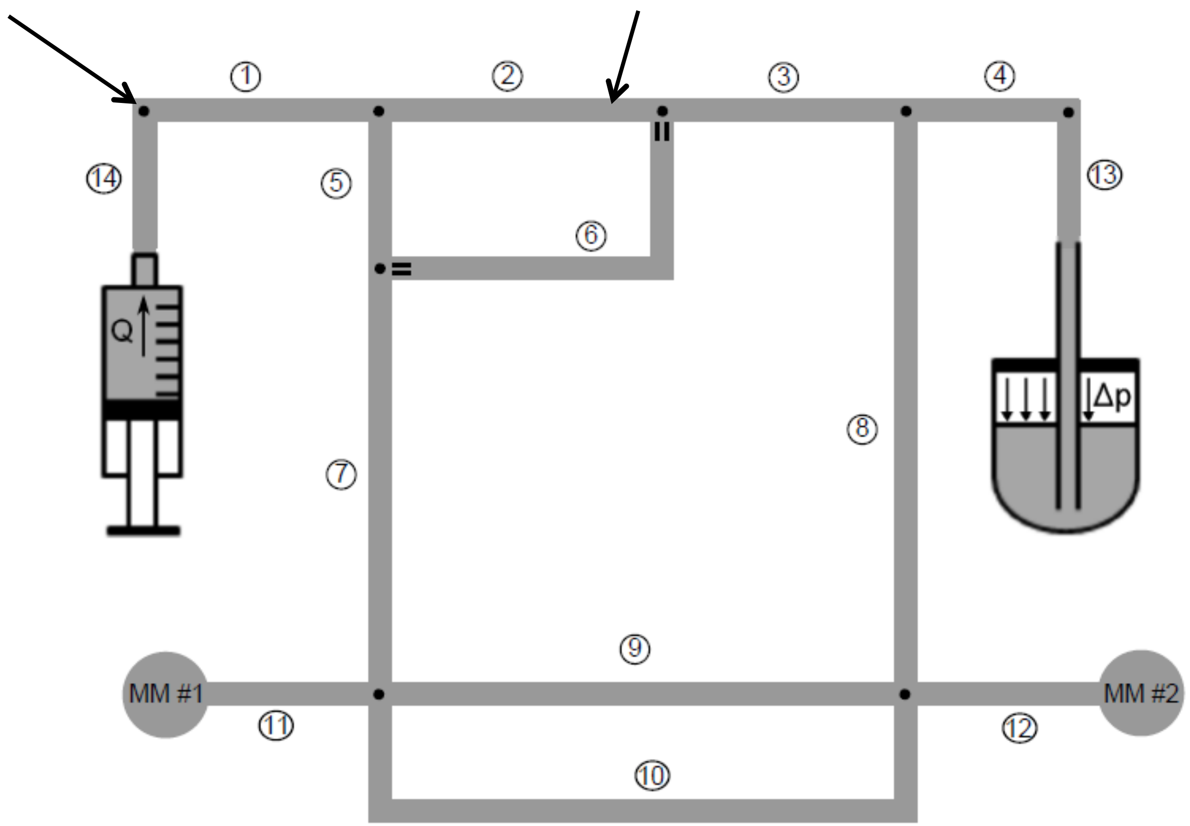


$R_1 + \delta > R_2$ → Second droplet takes branch 2



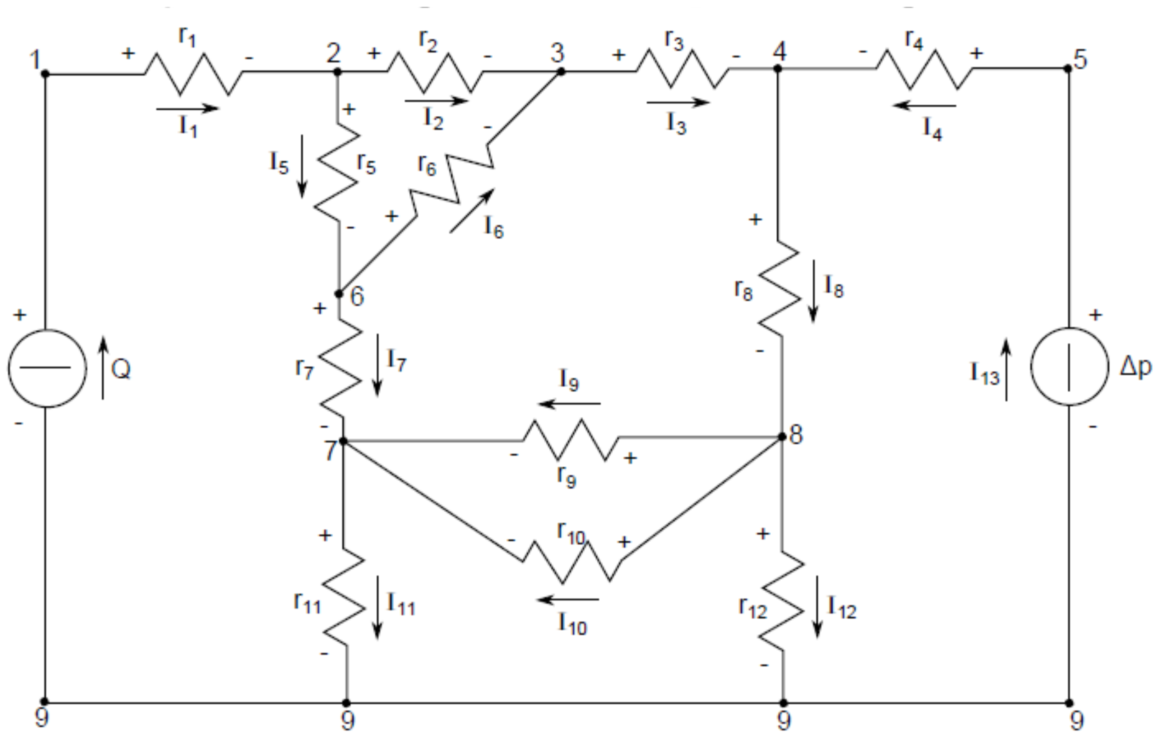
Microfluidic Network Model

- $G(t)=(\underline{V},\underline{E})$
  - $\underline{V}=\{v_1,\ldots,v_{N_{nodes}}\}$
  - $\underline{E}=\{e_1,\ldots,e_{N_{edges}}\}$

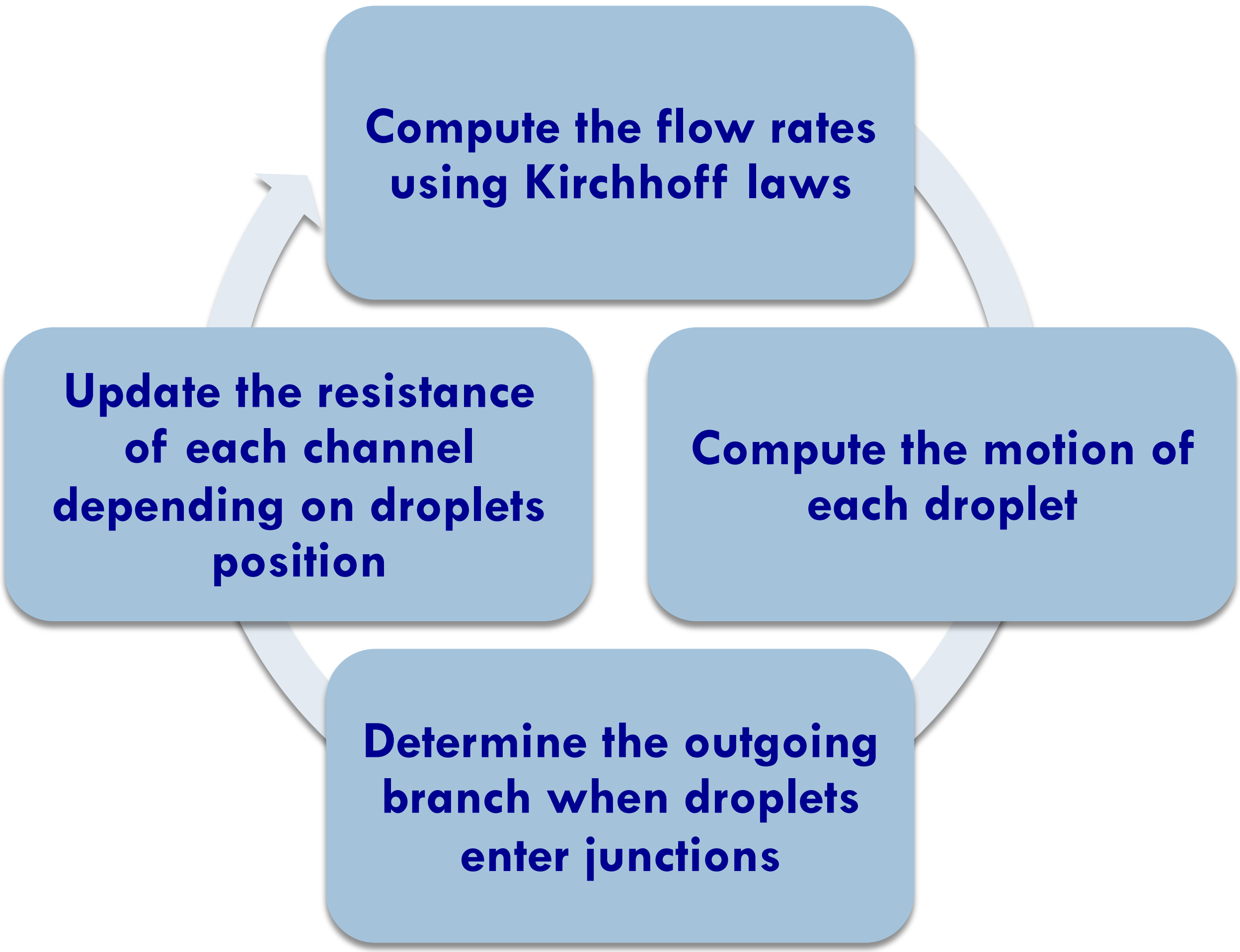


Parallel with electrical network

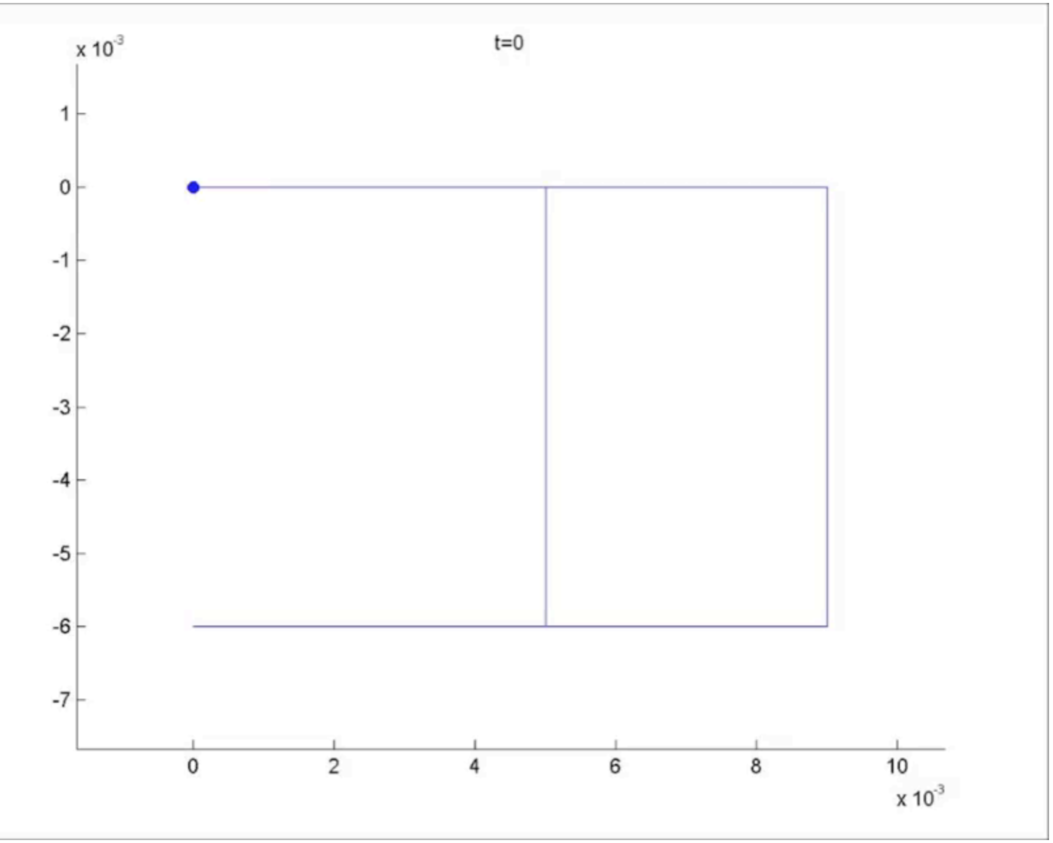
- Static MN graph is mapped into the dual electric circuit
  - flow generator
  - pressure generator
  - microfluidic channel
  - bypass channel

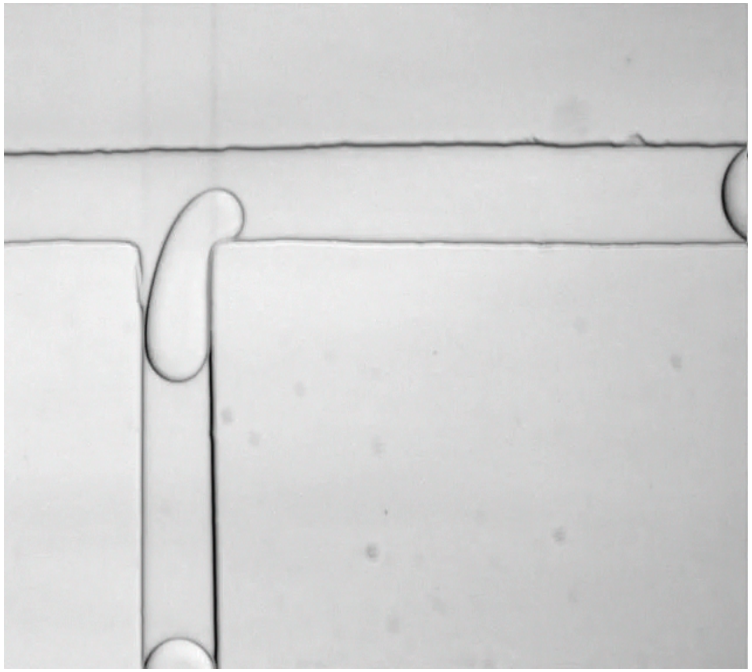


Simulation cycle

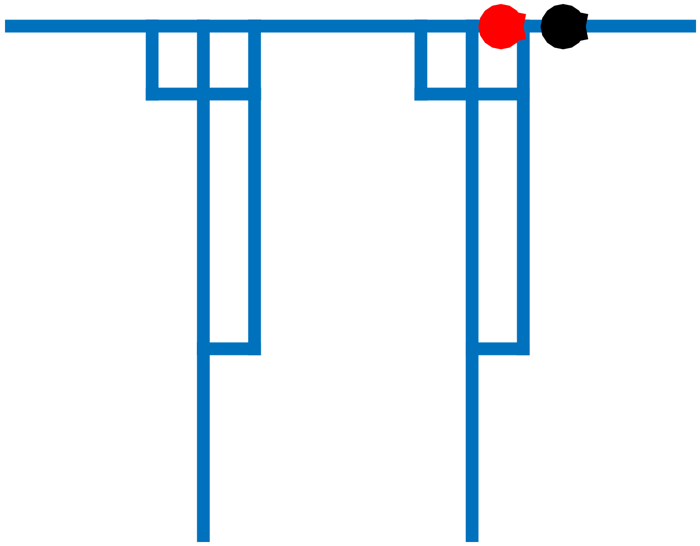


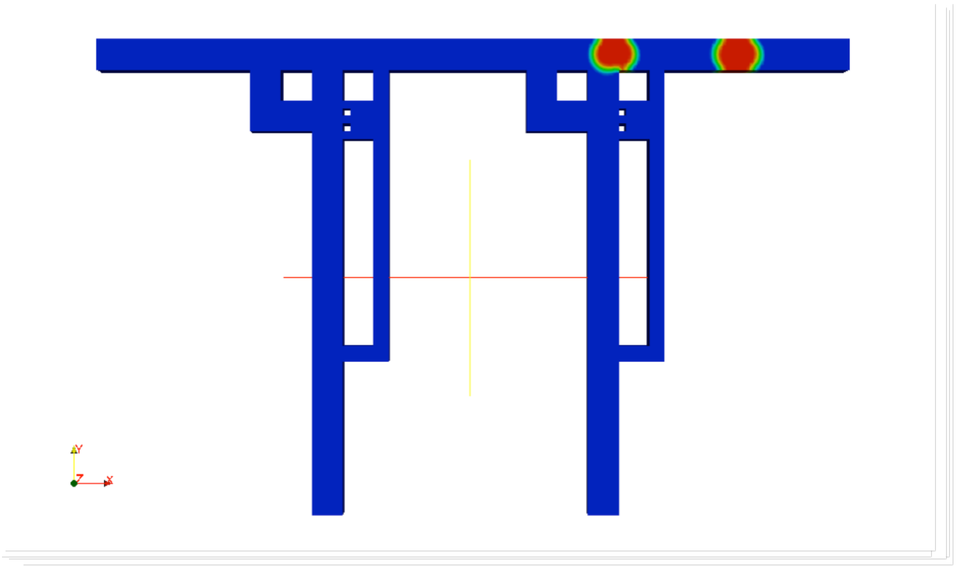
Simulation vs experimentation

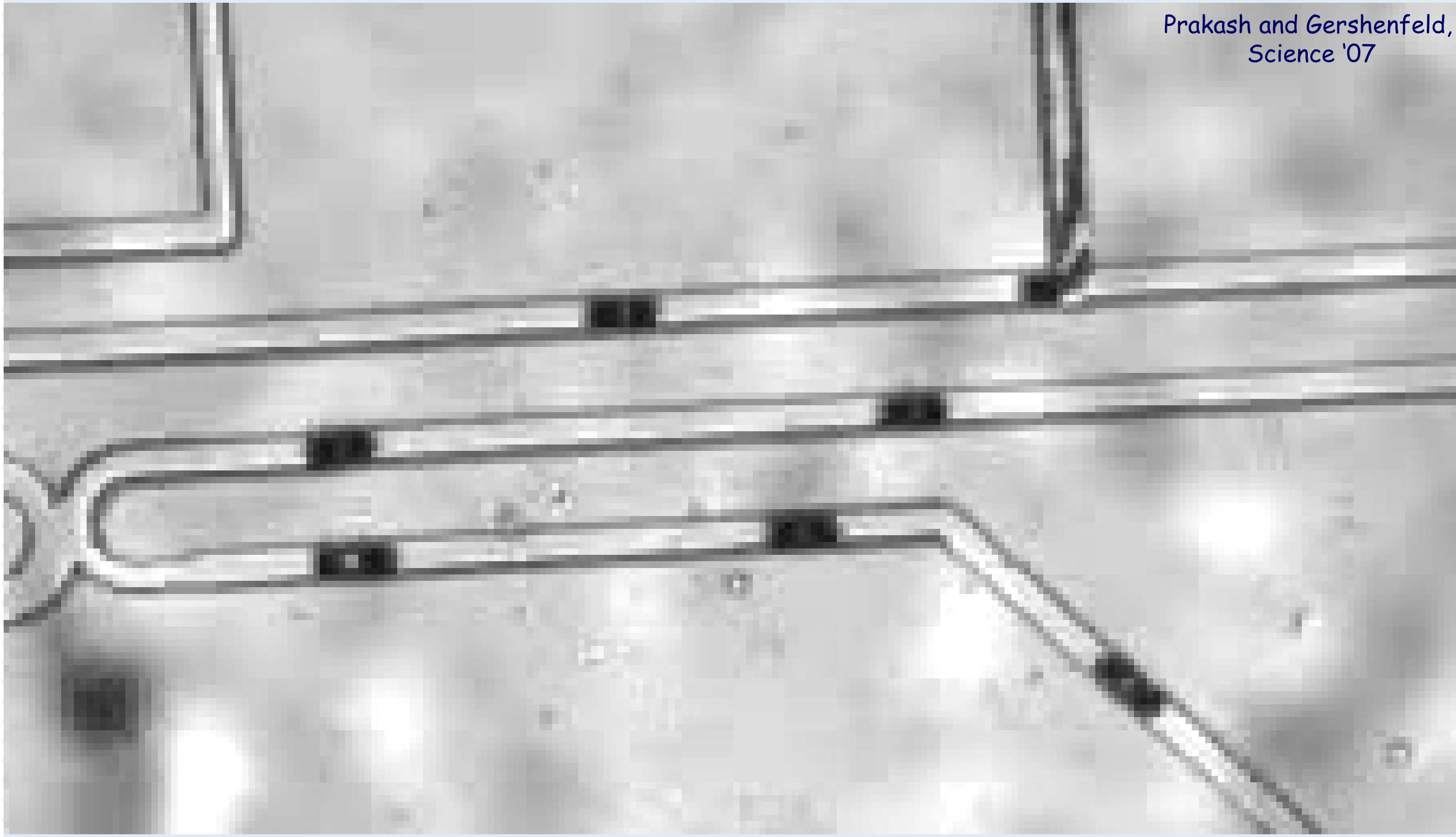




Simulation vs simulation







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Bus Network analysis

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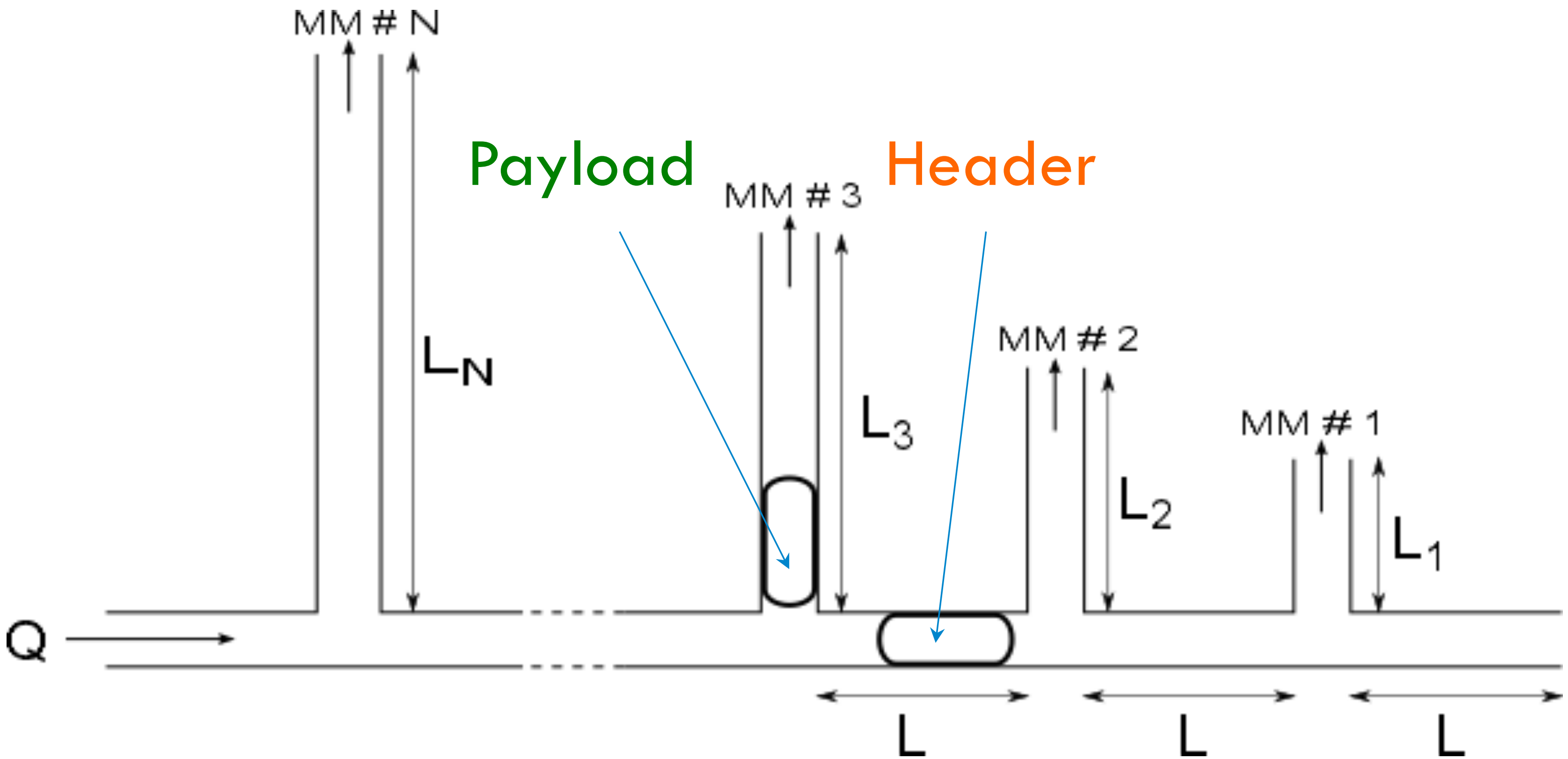
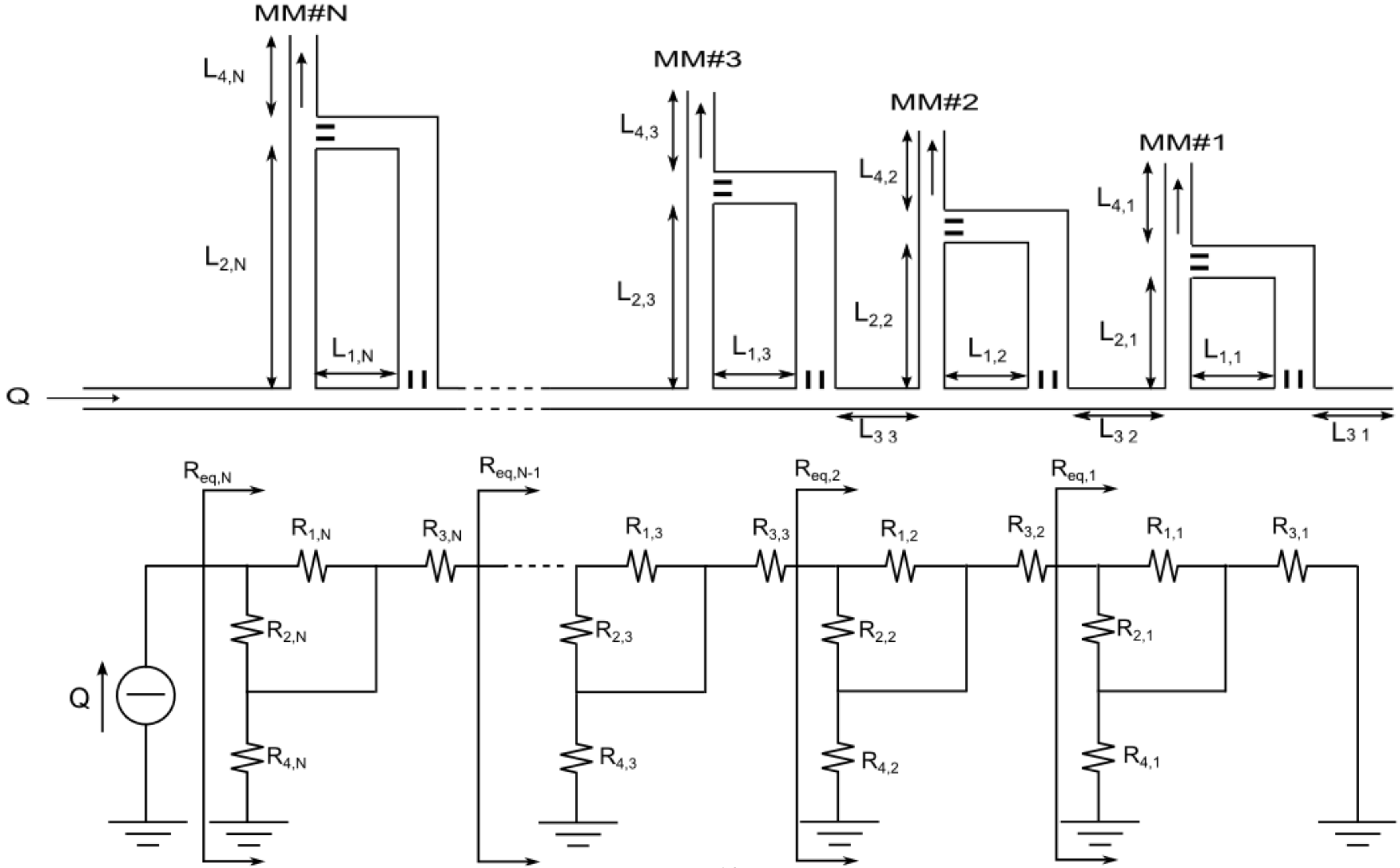
Case study: microfluidic network with bus topology



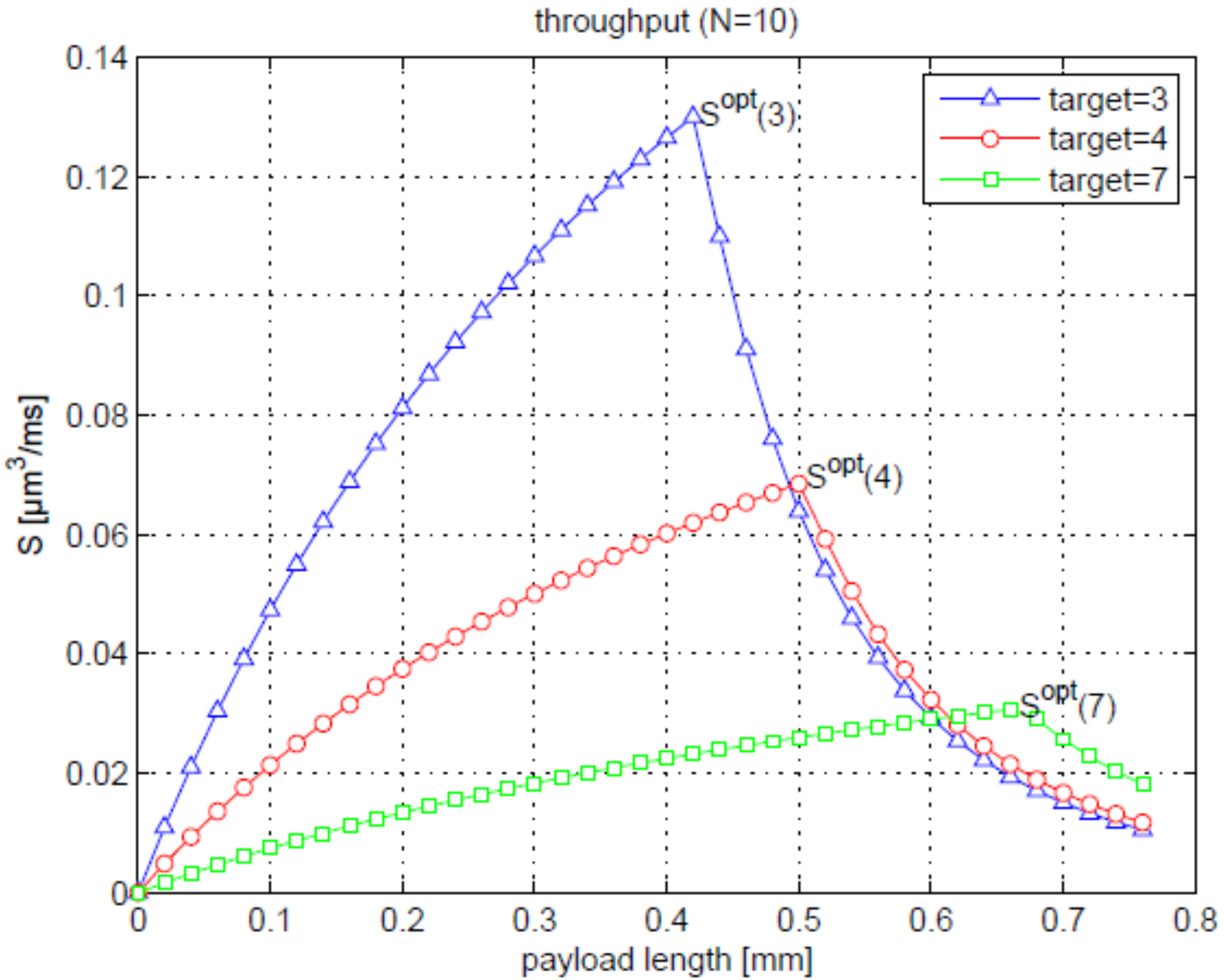
Microfluidic bus network with bypass channels



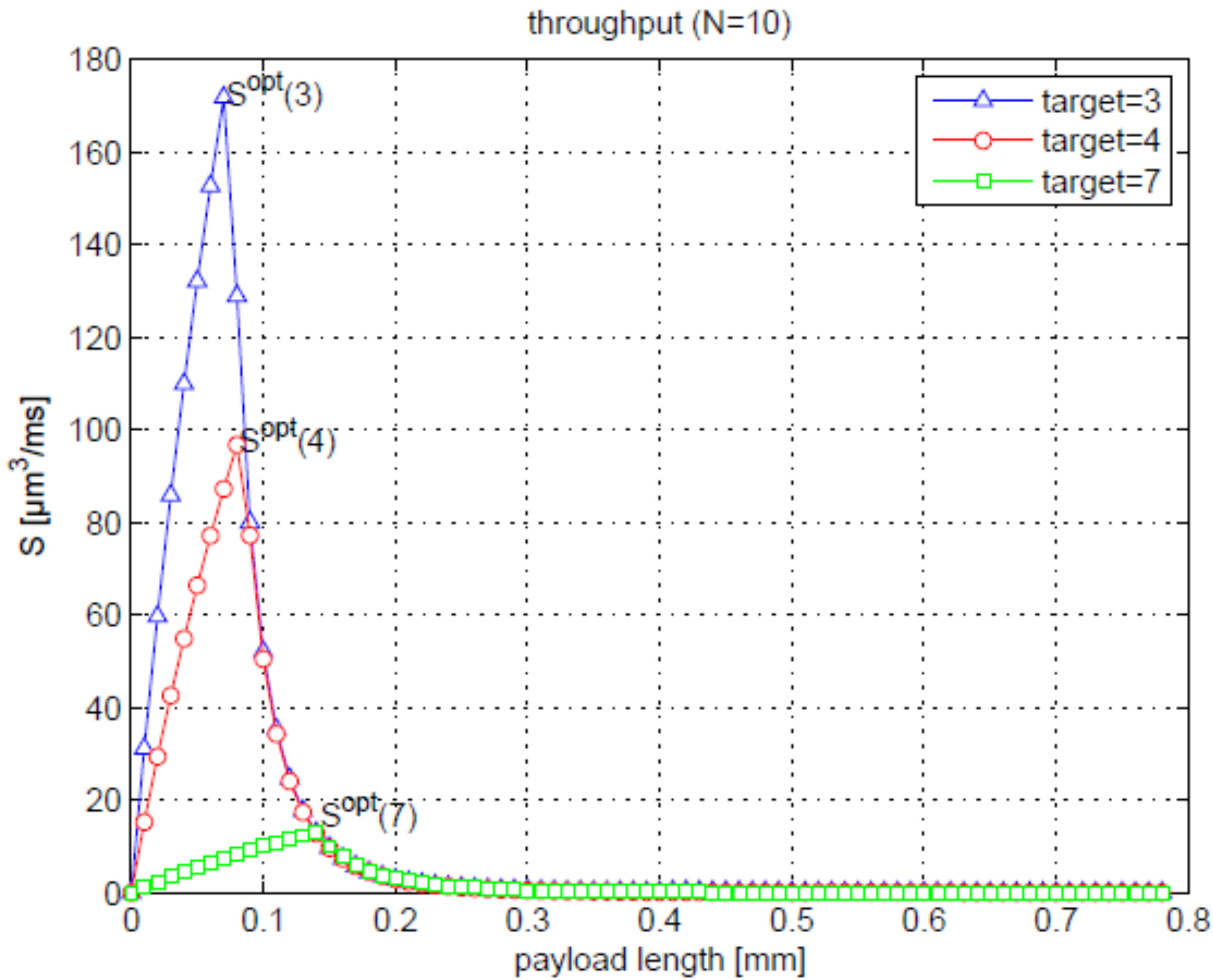
Performance

- Throughput
  - **volume** of fluid conveyed to a generic MM per time unit (S [$\mu m^3/ms$])
- Access strategy
  - "exclusive channel access": one header-payload at a time!

Bus network with simple T-junctions



Bus network with bypass channels



Conclusions and future developments

- Addressed Issues:
  - Definition of a **totally passive** droplet's **switching model**
  - Design of a macroscopic droplet-based **Microfluidic Network Simulator**
  - Analysis of **case-study: microfluidic bus network**

- Looking further ahead:
  - Joint design of network topology and MAC/scheduling protocols
  - Design and analysis of data-buffer devices
  - Proper modeling of microfluidics machines
  - Characterization of microfluidics traffic sources
  - Information-theory approach to microfluidics communications
  - …

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OUR GOALS

Our contribution

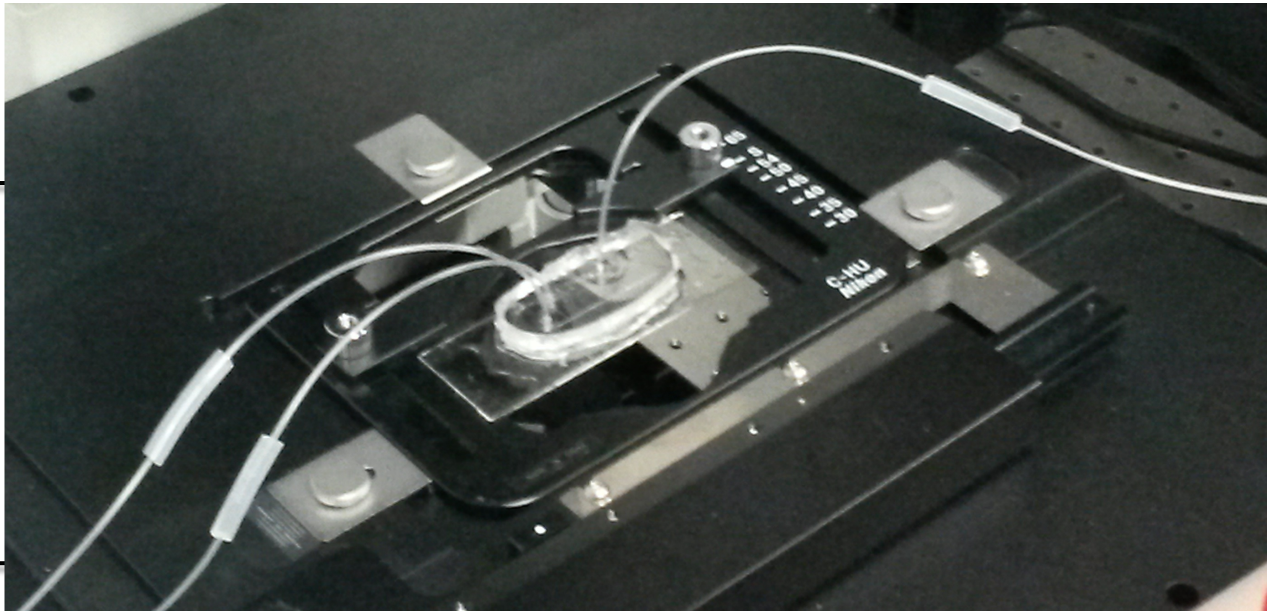
- Add communication capabilities in microfluidic systems
- Transmit information in a microfluidic channel by means of a PAM like modulation
- Use droplet length/interdistance to code the information
- Evaluate system performance on a real case scenario

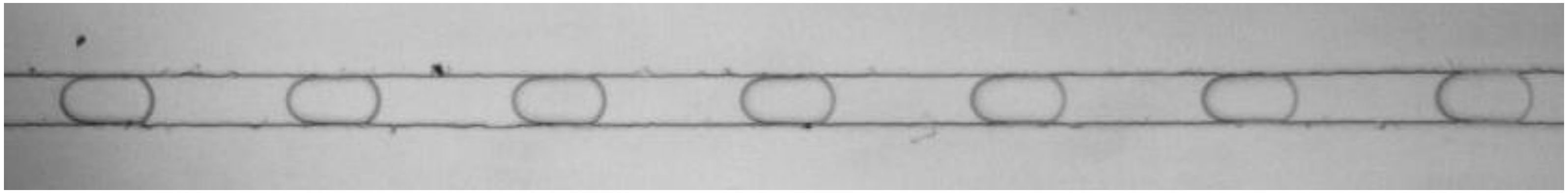
Modulation

Bit string	00	01	10	11	
	⇩	⇩	⇩	⇩	
PAM symbols	0	1	2	3	
	⇩	⇩	⇩	⇩	
Droplet length	$L_d^{(0)}$	$L_d^{(1)}$	$L_d^{(2)}$	$L_d^{(3)}$	
	⇩	⇩	⇩	⇩	
Dispersed phase flow	0.5	1	1.5	2	[μl/min]

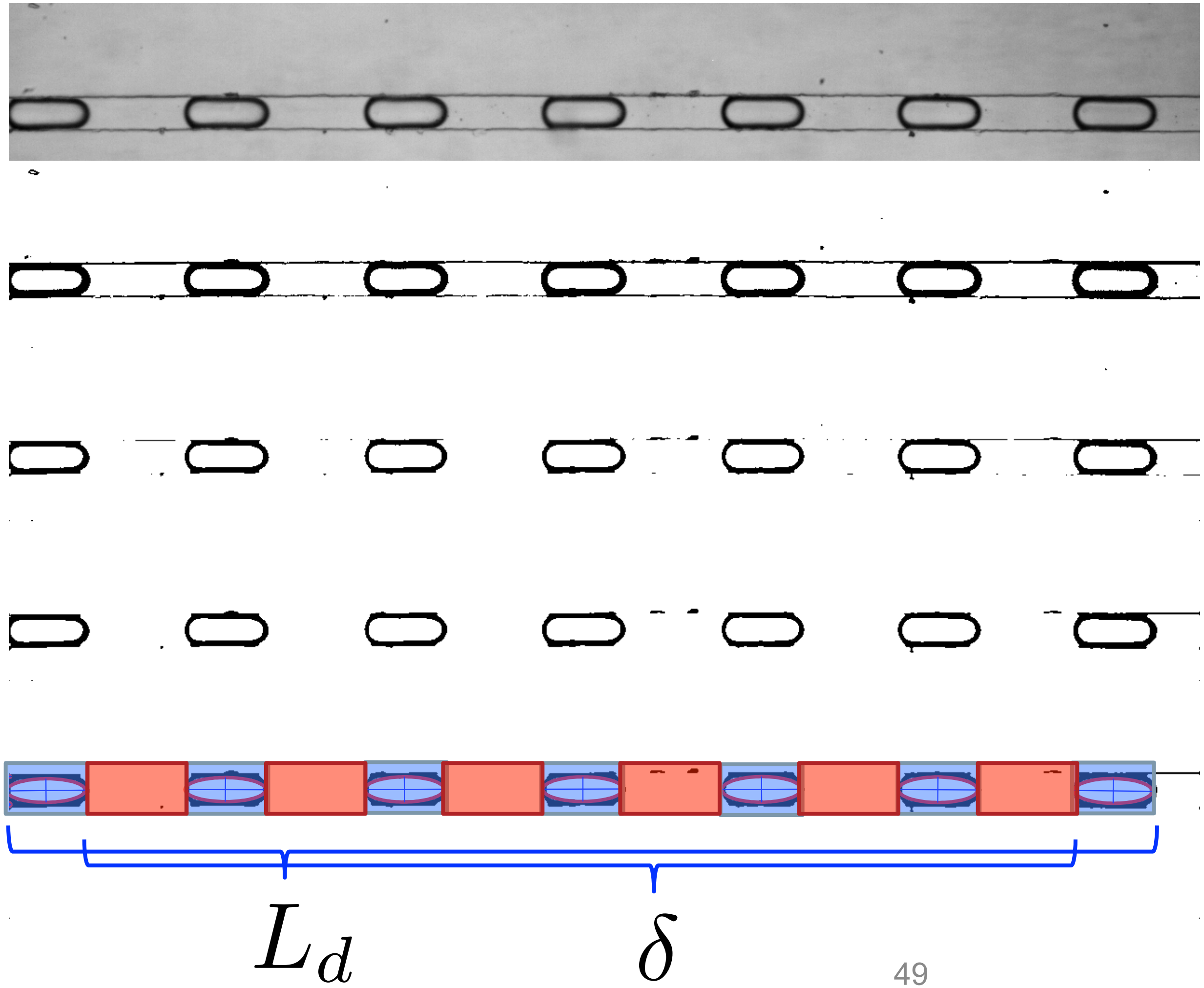
Continuous phase flow 5 [μl/min]

Experimental setup



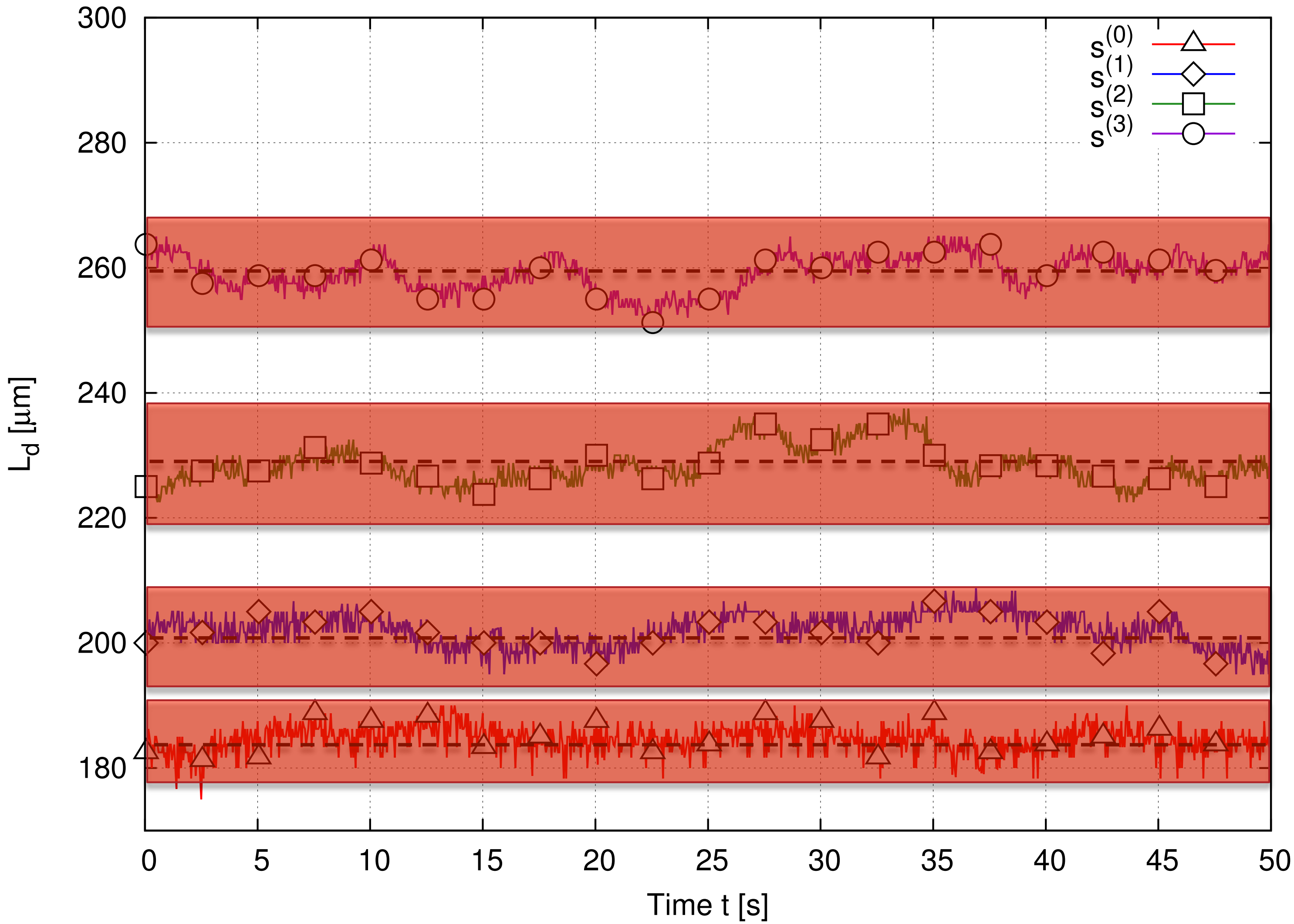


Frame processing



- Camera frame
- Binary image
- Lowpass Wiener filter
- Median filter
- Connected components identification

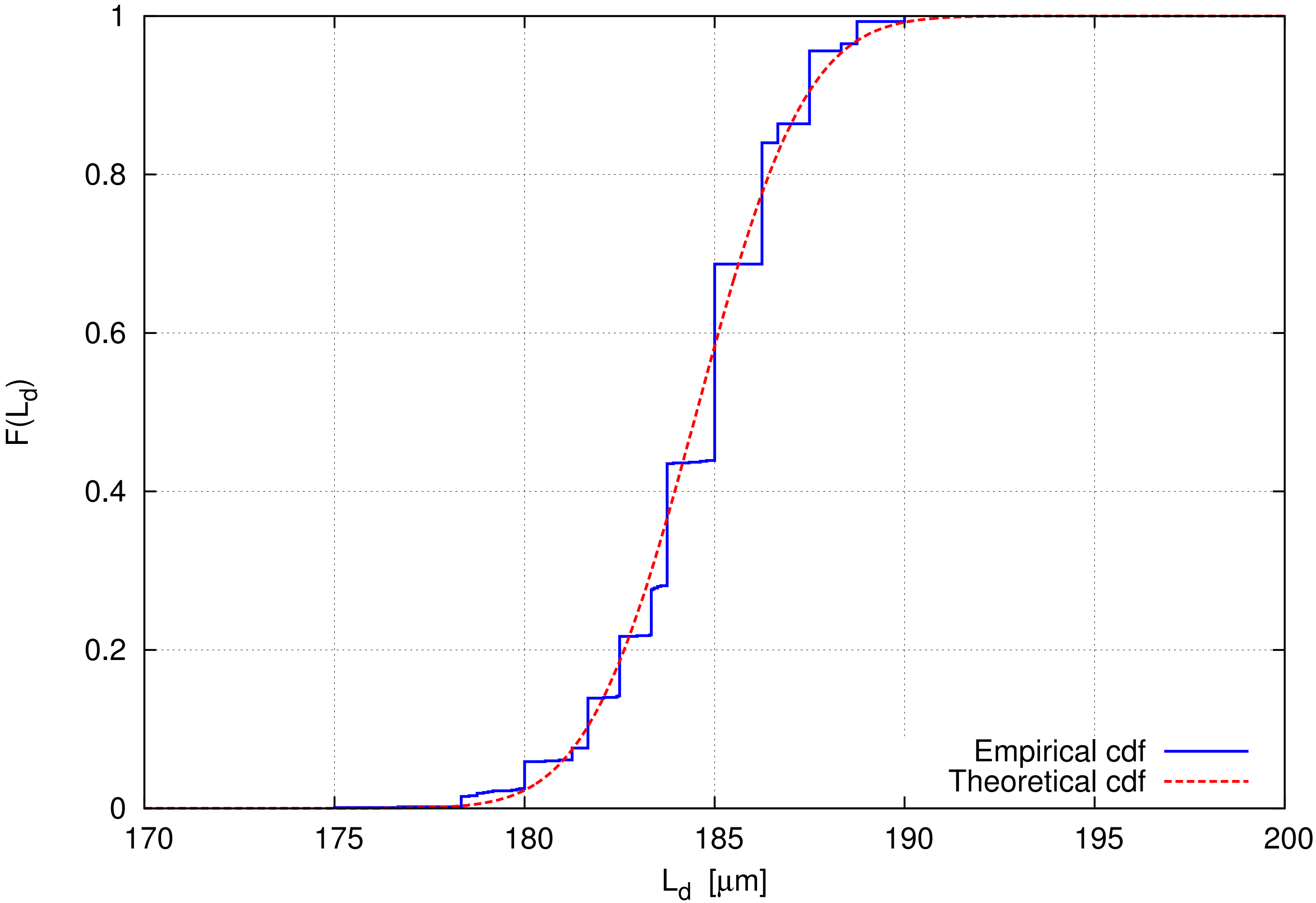
Droplet lengths



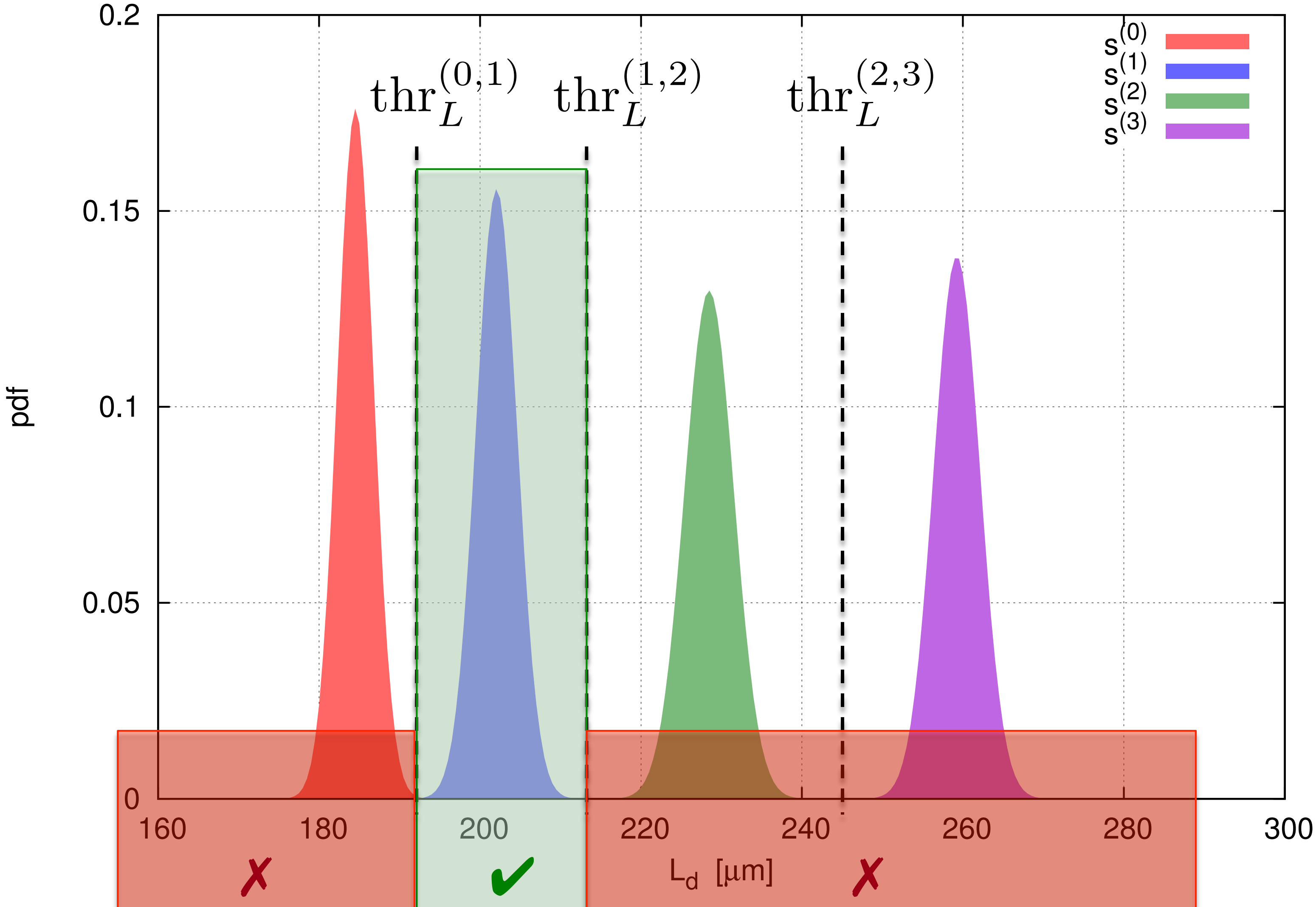
$$\bar{L}_d^{(i)}$$

$$\sigma_d^{(i)}$$

Droplets length distribution



Symbols PDFs



Error probability

- Assuming equally likely symbols

$$e = \frac{1}{4} \sum_{i=0}^{3} P(E|s^{(i)})$$

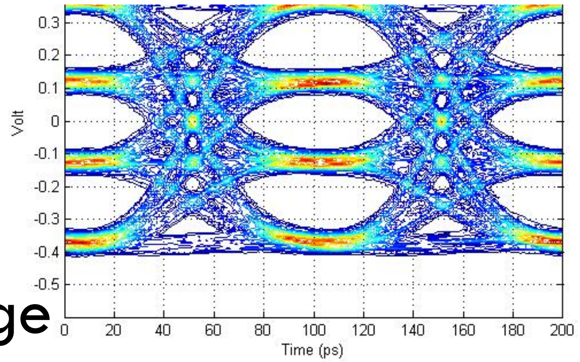
i	$\bar{L}_d^{(i)}$	$\sigma_d^{(i)}$	$\text{thr}_L^{(i,i+1)}$	$\bar{\delta}^{(i)}$	$\sigma_\delta^{(i)}$	$\text{thr}_\delta^{(i,i+1)}$
	Droplet-length PAM			Inter-droplet distance PAM		
0	184.52	2.26	193.29	769.65	14.04	679.5107
1	202.05	2.56	215.26	589.37	15.30	513.0877
2	228.47	3.08	243.85	436.80	9.44	397.8275
3	259.24	2.88	/	358.85	4.09	/
e_L	$1.80 \cdot 10^{-5}$			e_δ	$8.95 \cdot 10^{-7}$	

Wrapping up

- This work:
  - investigated the feasibility of extending communication concept to microfluidics
  - implemented basic modulation technique based on length/interdistance
  - evaluated system performance with experimental data
    - Both droplet length and inter-droplet distance can carry information bits
    - Inter-distance is generally preferable BUT, in complex network, it can vary as droplets stream along the channels
      - See Biral & Zanella, NanoComNet 2013

Looking forward…

- Transient characterization
  - Time to change modulated symbol
    - Related to *symbol period*
    - Depends on the physical "distance" between symbols → **symbol-dependent transmission rate**



- more sophisticated modulations
  - Combining length and distance
  - Using other circuits to dynamically change droplet inter-distance
- consider other performance indexes
  - throughput, delay, energy consumption

And YES... you can publish this stuff!

- W. Haselmayr, A. Biral, A. Grimmer, A. Zanella, R. Wille, A. Springer, "Addressing Multiple Nodes in Networked Labs-on-Chips without Payload Re-injection" in the Proceedings of the 2017 International Conference on Communications (ICC) Paris, France, 21-25 May 2017
- A. Biral, D. Zordan, A. Zanella, "Modeling, simulation and experimentation of droplet-based microfluidic networks" IEEE Transactions on Molecular, Biological, and Multi-Scale Communications, vol. 1, no. 2, pp. 122-134, June 2015.
- A. Biral, A. Zanella, "Introducing purely hydrodynamic networking functionalities into microfluidic systems" Nano Communication Networks, Elsevier, vol. 4, n0. 4, pp 205-215, 2013. DOI: 10.1016/j.nancom.2013.09.001
- A. Biral, D. Zordan, A. Zanella, "Simulating macroscopic behavior of droplet-based microfluidic systems" in the Proceedings of IEEE Global Communications Conference Dec. 6-10, 2015, San Diego, CA, USA
- A. Biral, D. Zordan, A. Zanella, "Transmitting information with microfluidic systems" in the Proceedings of the IEEE International Conference on Communications (ICC 2015), June 8-12, 2015, London, UK.
- A. Zanella, A. Biral, "Design and Analysis of a Microfluidic Bus Network with Bypass Channels" in the Proceedings of IEEE ICC 2014 10-14 June, 2014, Sydney, Australia.

Transmitting Information with Microfluidic Systems

Andrea Biral, Davide Zordan,
Andrea Zanella

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DI INGEGNERIA
DELL'INFORMAZIONE

Any questions?