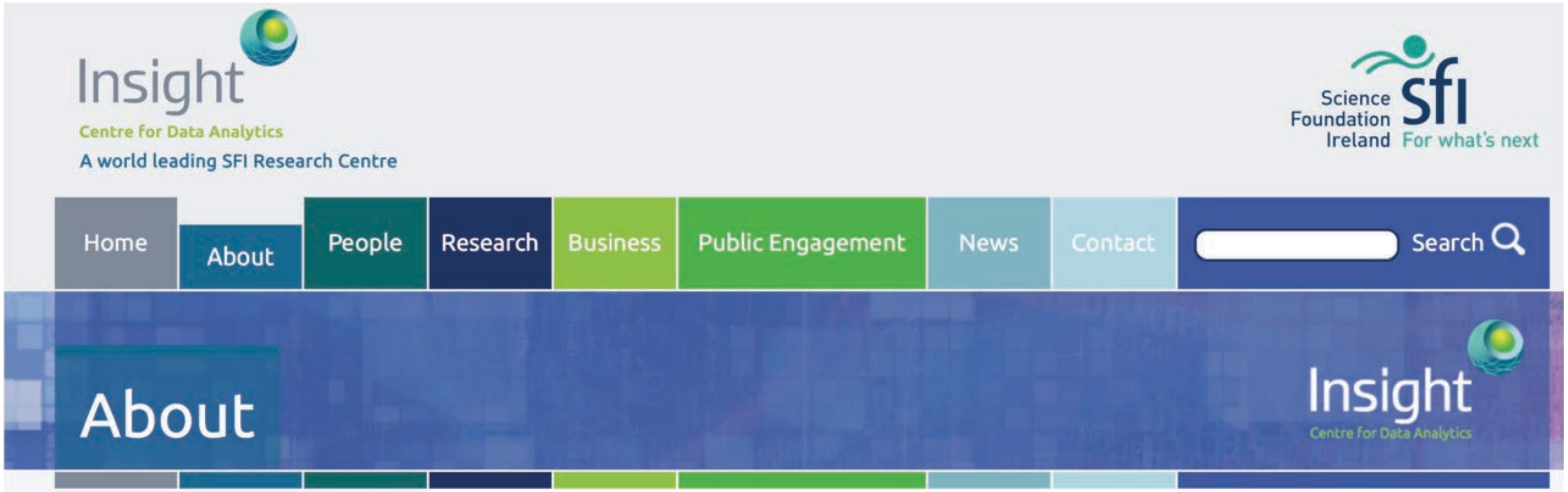
Merging the Digital and Molecular Worlds: From Crazy Idea to Realistic Possibility?

Prof. Dermot Diamond
INSIGHT Centre for Data Analytics, National Centre for Sensor Research
Dublin City University

Invited Silklab "Cocoon" Lecture and Conversation presented at

Tufts University
Medford, MA
21 August 2019

The Insight Centre for Data Analytics



Insight is one of the biggest data analytics centres in Europe. It undertakes high-impact research, seeks to derive value from Big Data and provides innovative technology solutions for industry and society by enabling better decision-making.

With **€88 million (ca.50% Industry)** in funding, Insight has 400 researchers across areas such as connected health, decision analytics, social media analytics, smart cities and the semantic web.

http://www.sfi.ie/sfi-research-centres/insight/

2nd Phase funding approved (ca. €50 million SFI) commencing autumn 2019

Internet of (Biochemical) Things $IO_{BC}T$

- **Bridging the Molecular and Digital Worlds**
  - Emergence of 'Internet of Analytical Things', Internet of 'Molecular Things', 'Internet of Biochemical Things'
- **Long-Term "Deploy and Forget" use model**
  - Embedded 'smartness'
    - Sensing (temperature, light-level, imaging, vibration)
    - Communications (wireless)
    - Power (10-year battery life-time, energy scavenging capability)
  - Awareness of
    - Surrounding environment
    - Internal (functional) condition

Keynote Article: Anal. Chem., 76 (2004) 278A-286A

internet scale sensing

Dermot Diamond
Dublin City University
(Ireland)

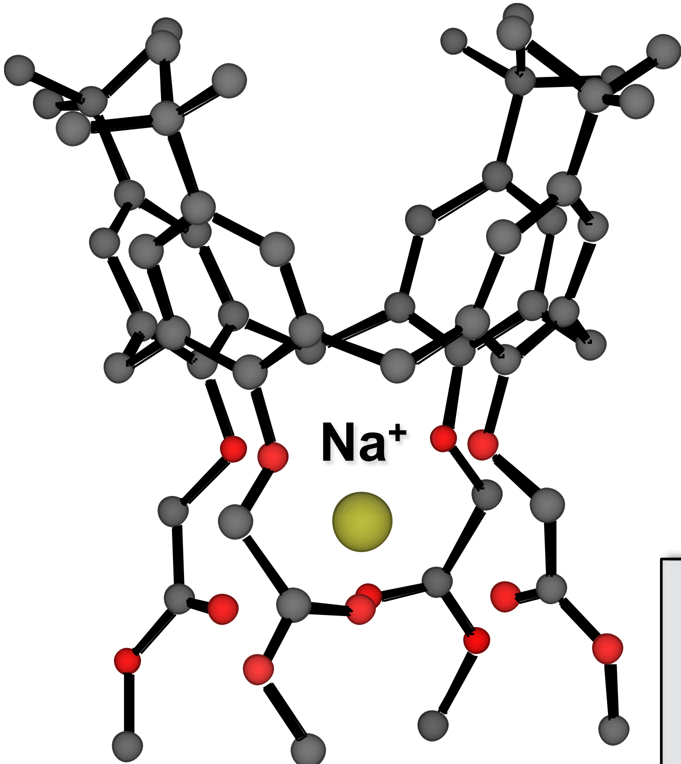
Incredible advances in digital communications and computer power have profoundly changed our lives. One chemist shares his vision of the role of analytical science in the next communications revolution.

Digital communications networks are at the heart of modern society. The digitization of communications, the development of the Internet, and the availability of relatively inexpensive but powerful mobile computing technologies have established a global communications network capable of linking billions of people, places, and objects. Email can instantly transmit complex documents to multiple remote locations, and websites provide a platform for instantaneous notification, dissemination, and exchange of information globally. This technology is now pervasive, and those in research and business have multiple interactions with this digital world every day. However, this technology might simply be the foundation for the next wave of development that will provide a seamless interface between the real and digital worlds.

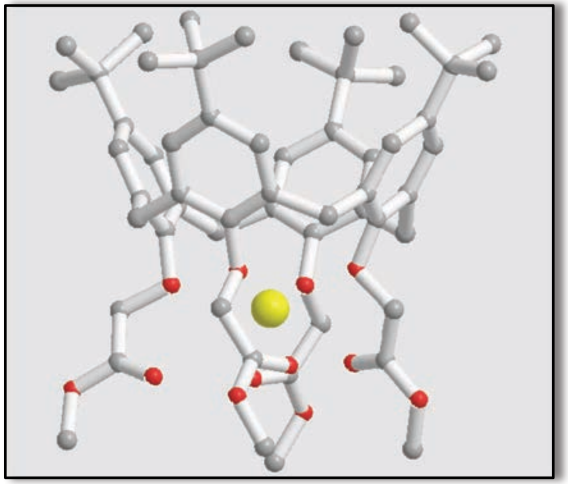
The crucial missing part in this scenario is the gateway through which these worlds will communicate: How can the digital world sense and respond to changes in the real world? Analytical scientists—particularly those working on chemical sensors, biosensors, and compact, autonomous instruments—are

Ron Ambrosio & Alex Morrow, IBM TJ Watson

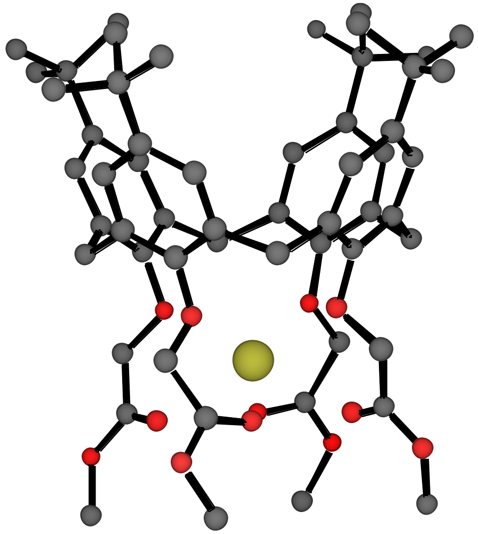
Calixarene Ionophores – controlling the selectivity

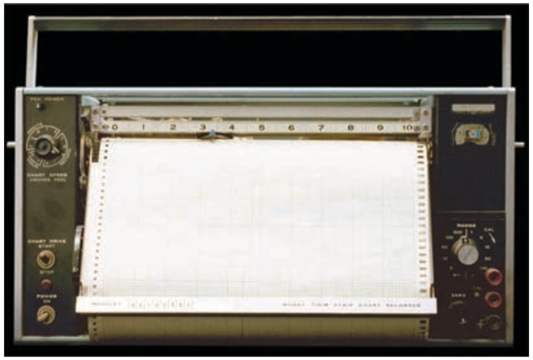


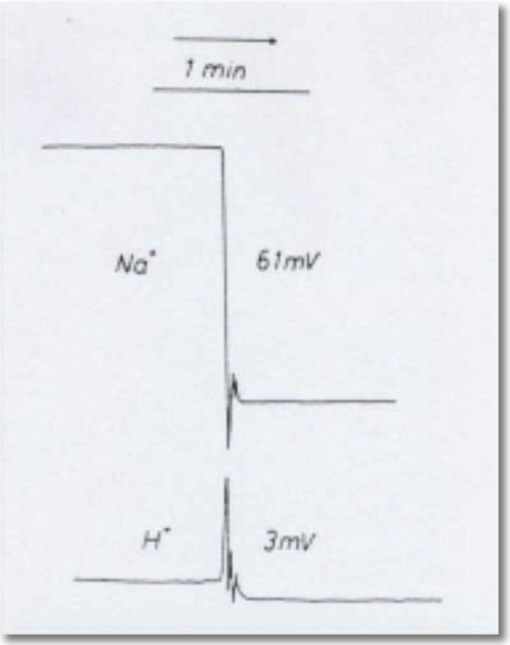
$H_3C-O-C(=O)-CH_2-$

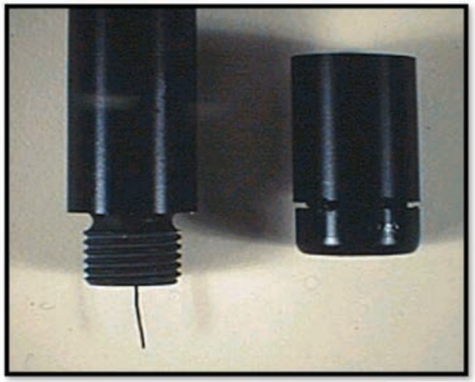


And…….





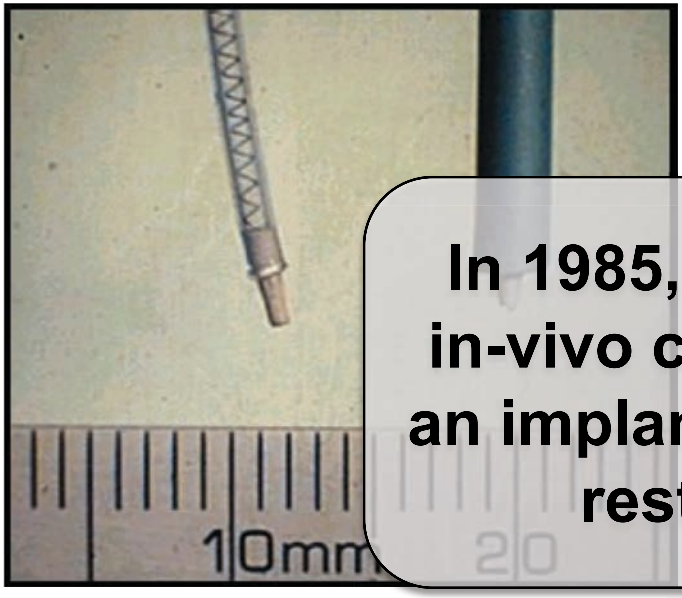




Neutral Carrier Based Ion-Selective Electrodes, D.Diamond, Anal. Chem. Symp. Ser., 25 (1986) 155.

A sodium Ion-Selective Electrode based on Methyl p-t-Butyl Calix[4]aryl Acetate as the Ionophore, D.Diamond, G.Svehla, E.Seward,and M.A.McKervey, Anal. Chim. Acta., 204 (1988) 223-231

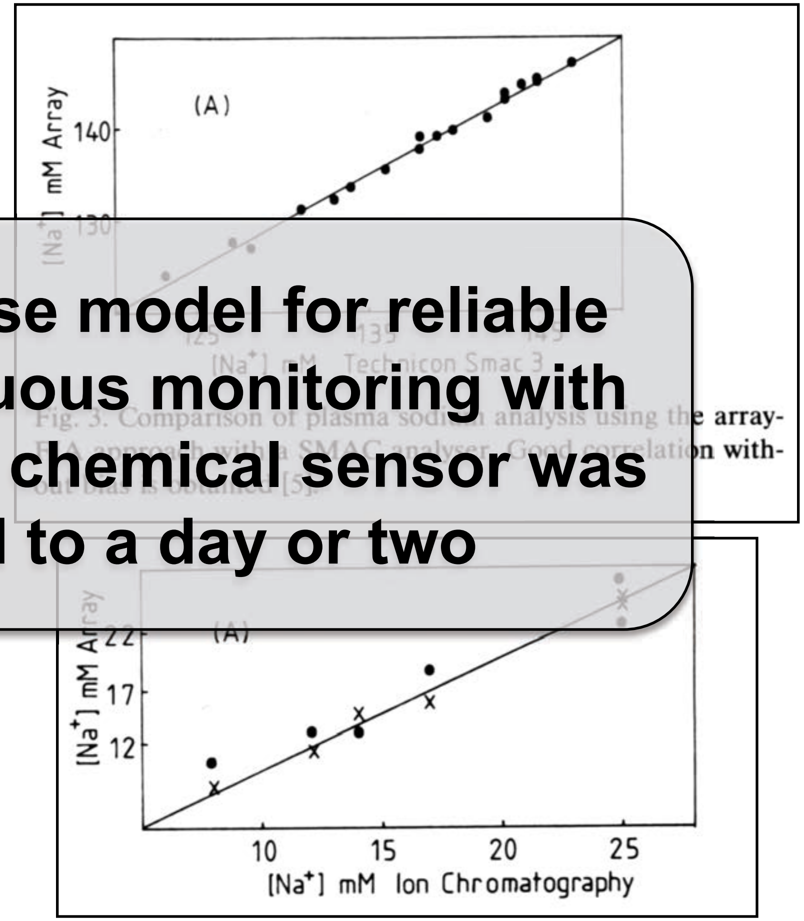
Blood Analysis; Implantible Sensors



In 1985, the use model for reliable in-vivo continuous monitoring with an implantable chemical sensor was restricted to a day or two

1985: Catheter Electrodes for intensive care – function for 24 hrs

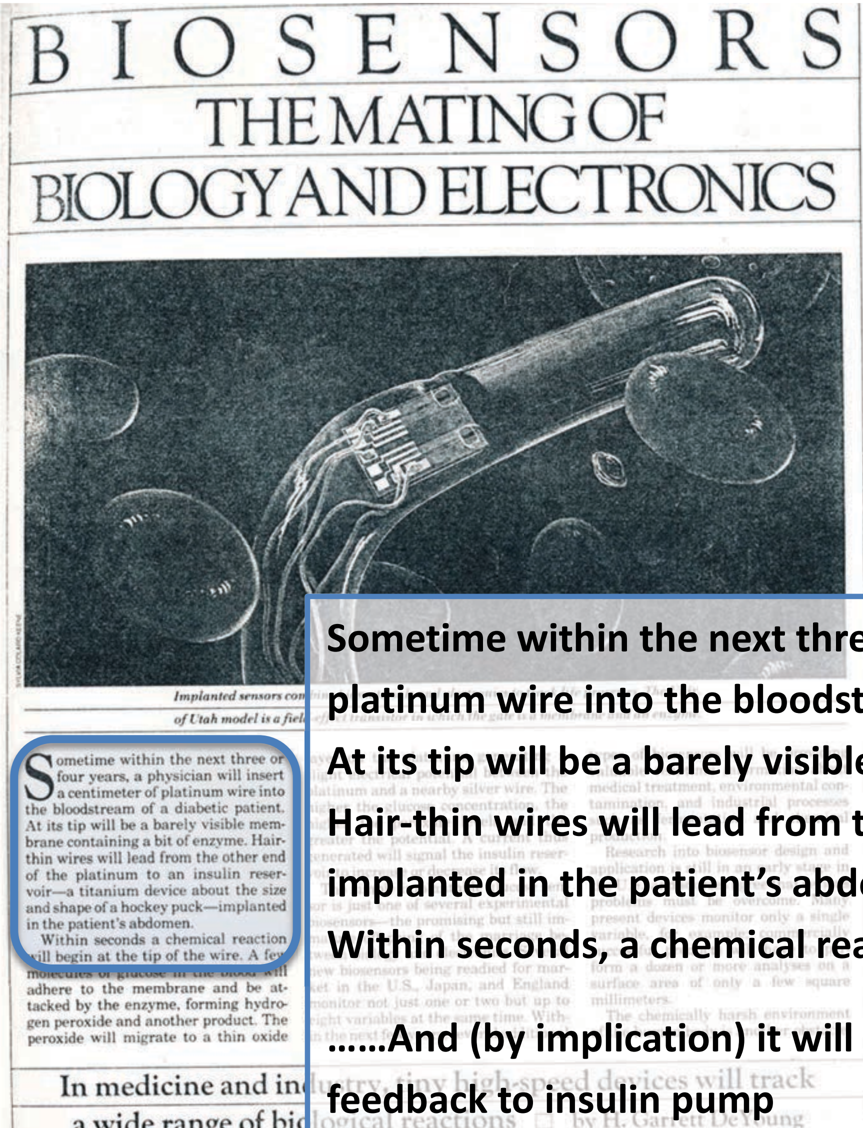
Dr. David Band, St Thomas's Hospital London



Anal. Chem., *64 (1992) 1721-1728.*

Ligand (and variations of) used in many clinical analysers for blood Na^+ profiling

The (broken) promise of biosensors…..



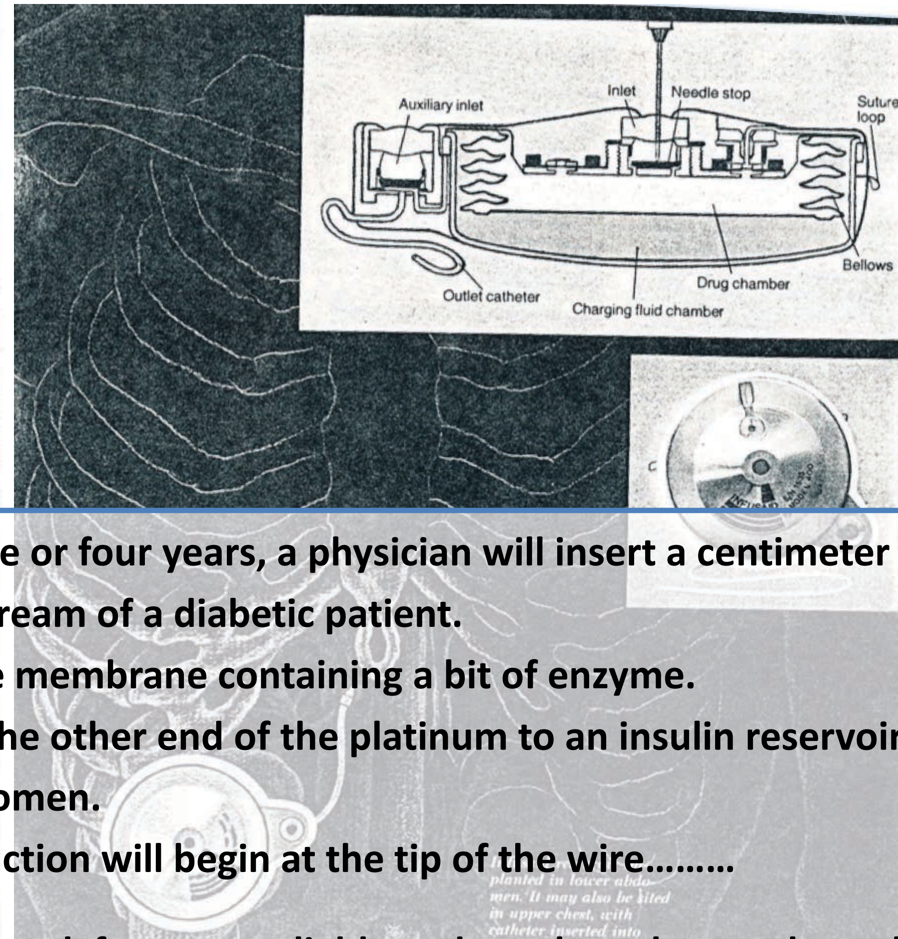
BIOSENSORS
THE MATING OF BIOLOGY AND ELECTRONICS

Sometime within the next three or four years, a physician will insert a centimeter of platinum wire into the bloodstream of a diabetic patient. At its tip will be a barely visible membrane containing a bit of enzyme. Hair-thin wires will lead from the other end of the platinum to an insulin reservoir—a titanium device about the size and shape of a hockey puck—implanted in the patient's abdomen.

Within seconds a chemical reaction will begin at the tip of the wire. A few molecules of glucose in the blood will adhere to the membrane and be attacked by the enzyme, forming hydrogen peroxide and another product. The peroxide will migrate to a thin oxide

In medicine and industry, tiny high-speed devices will track a wide range of biological reactions □ by H. Garrett DeYoung

High Technology, Nov. 1983, 41-49



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At its tip will be a barely visible membrane containing a bit of enzyme.
Hair-thin wires will lead from the other end of the platinum to an insulin reservoir implanted in the patient's abdomen.
Within seconds, a chemical reaction will begin at the tip of the wire………

……And (by implication) it will work for years reliably and regulate glucose through feedback to insulin pump

After Ca. 40 years – Dominant Use Model is Finger Prick Sampling

- e.g. Diabetes: ca. 7% of world population
- USA: population 300 million
- Ca. 20 million diabetics
- Personal control of condition using finger prick test => blood sample + glucose biosensor

- Say four measurements per day = 80 million/day
- Per year = ca. 30 Billion measurements/yr
- Each sensor used ONCE

Adam Heller

Subcutaneous sampling of interstitial fluid using microneedles to access the fluid through the skin without causing bleeding

San Francisco Business Times; Tuesday, April 6, 2004

'Abbott completes TheraSense acquisition'

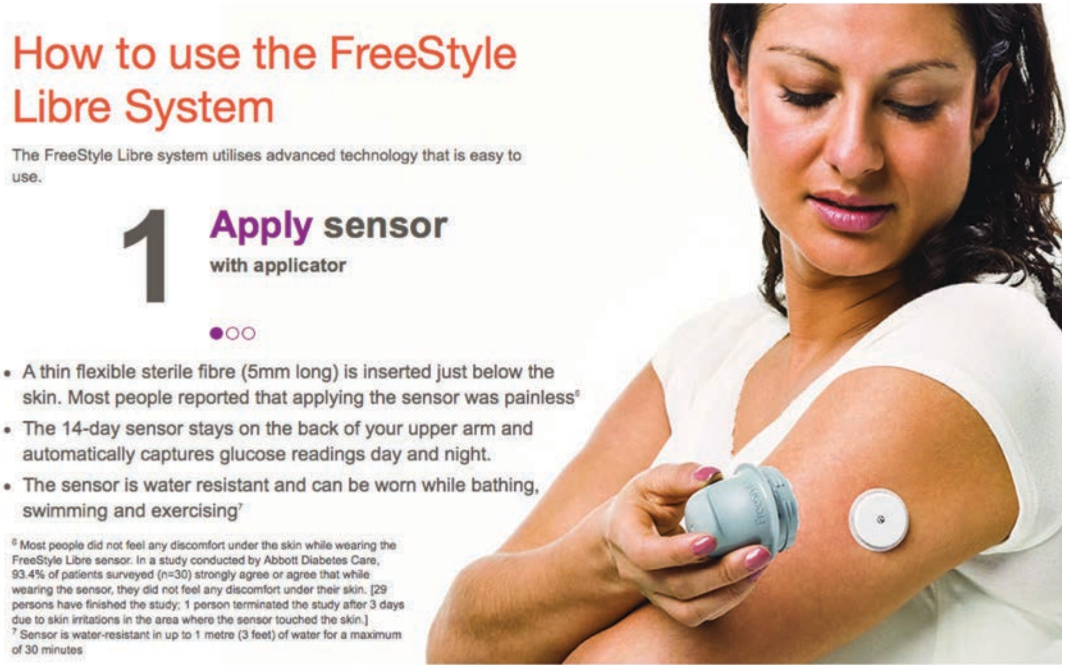
Abbott Laboratories said Tuesday it completed its $1.2 billion acquisition of Alameda-based TheraSense Inc. after a majority of shareholders approved the transaction a day earlier.

- **Abbott Press Release September 29, 2008**
- Abbott Park, Illinois — Adam Heller, Ph.D., a professor at the University of Texas in Austin who created the technology that led to the development of Abbott's FreeStyle Blood Glucose Monitoring Systems® and FreeStyle Navigator® Continuous Glucose Monitoring System, today received the 2007 National Medal of Technology and Innovation from President George W. Bush in an award ceremony at the White House.

Abbott Freestyle 'Libre'

The days of routine glucose testing with lancets, test strips and blood are over.[2]

Welcome to flash glucose monitoring!



How to use the FreeStyle Libre System

The FreeStyle Libre system utilises advanced technology that is easy to use.

1 Apply sensor
with applicator

- A thin flexible sterile fibre (5mm long) is inserted just below the skin. Most people reported that applying the sensor was painless[6]
- The 14-day sensor stays on the back of your upper arm and automatically captures glucose readings day and night.
- The sensor is water resistant and can be worn while bathing, swimming and exercising[7]

[6] Most people did not feel any discomfort under the skin while wearing the FreeStyle Libre sensor. In a study conducted by Abbott Diabetes Care, 93.4% of patients surveyed (n=30) strongly agree or agree that while wearing the sensor, they did not feel any discomfort under their skin. [29 persons have finished the study; 1 person terminated the study after 3 days due to skin irritations in the area where the sensor touched the skin.]
[7] Sensor is water-resistant in up to 1 metre (3 feet) of water for a maximum of 30 minutes

- 'Small fibre' used to access interstitial fluid
- Data downloaded at least once every 8 hr via 1s contactless scan (1-4 cm)
- Waterproof to 1 metre
- Replace every 2 weeks

Nightscout

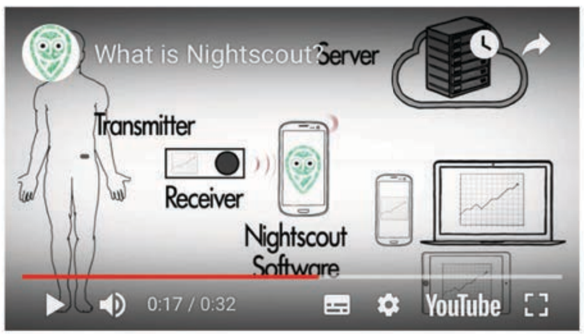
NIGHTSCOUT
#WeAreNotWaiting

http://www.nightscout.info https://www.dexcom.com

Search ...

Welcome to Nightscout

What is the Nightscout project?



Nightscout (CGM in the Cloud) is an open source, DIY project that allows real time access to a CGM data via personal website, smartwatch viewers, or apps and widgets available for smartphones.

Nightscout was developed by parents of children with Type 1 Diabetes and has continued to be developed, maintained, and supported by volunteers. When first implemented, Nightscout was a solution specifically for remote monitoring of Dexcom G4 CGM data. Today, there are Nightscout solutions available for Dexcom G4, Dexcom Share with Android, Dexcom Share/G5 with iOS, and Medtronic. Nightscout also provides browser-based visualization for #openAPS users and Loop users. The goal of the project is to allow remote monitoring of a T1D's glucose level using existing monitoring devices.

Disclaimer

All information, thought, and code described here is intended for informational and educational purposes only. Nightscout currently makes no attempt at HIPAA privacy compliance. Use of code from github.com is without warranty or support of any kind. Please review the LICENSE found within each repository for further details. **Use Nightscout at your own risk, and do not use the information or code to make medical decisions.**

Support Nightscout

Your contributions help the developers purchase test equipment, webspace, cables, and other tools that drive this project forward. Received donations are managed by The Nightscout Foundation. Click here to donate.

Please consult with your tax professional regarding deducting donations.

Developed by coders & engineers within the T1 Diabetes Community & friends

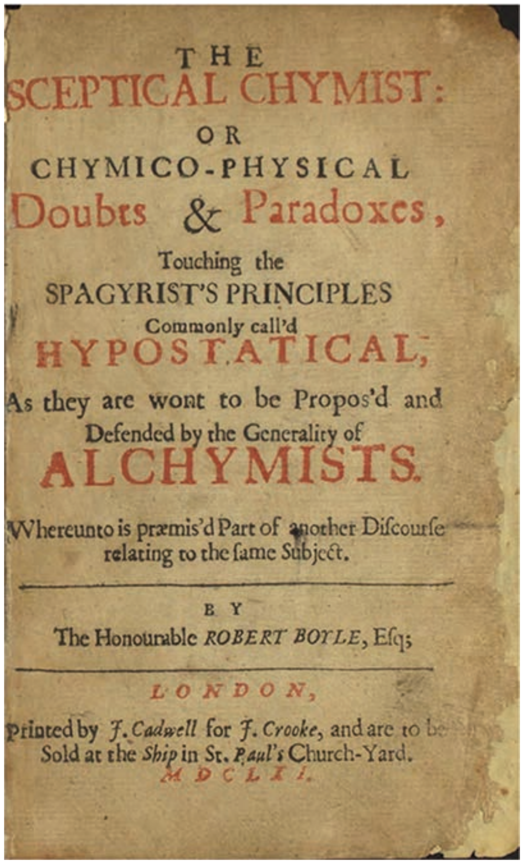
Developing APPs

Accessing real-time data from diabetes monitors (Dexcom, wearable glucose sensors)

User groups formed, self-funded

Use disclaimers, no warranty, not for making therapeutic decisions

‘The Sceptical Chemist’ (1661) ‘Chymico-Physical Paradoxes’

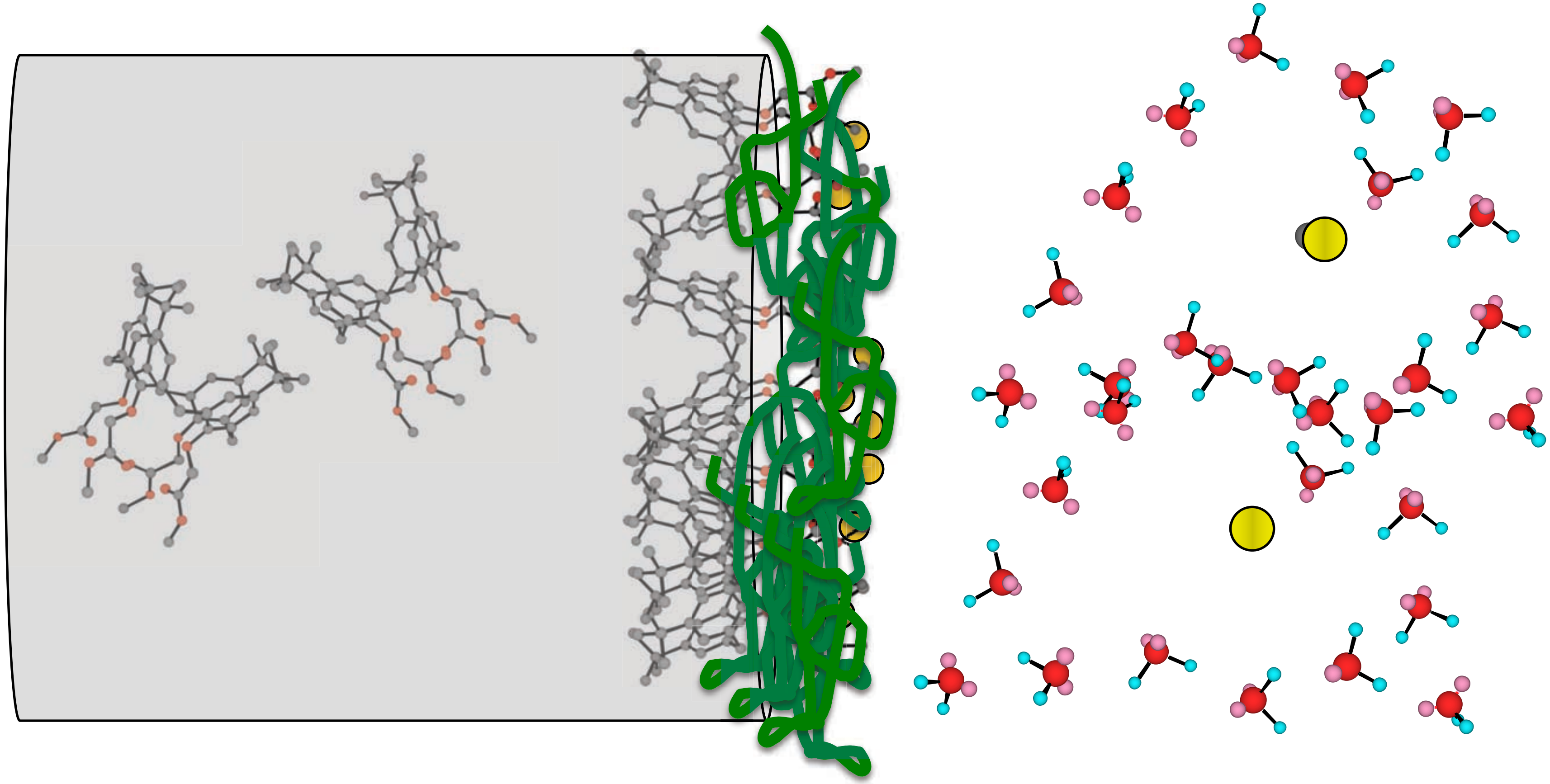

THE
SCEPTICAL CHYMIST:
OR
CHYMICO-PHYSICAL
Doubts & Paradoxes,
Touching the
SPAGYRIST'S PRINCIPLES
Commonly call'd
HYPOSTATICAL,
As they are wont to be Propos'd and
Defended by the Generality of
ALCHYMISTS.
Whereunto is præmis'd Part of another Discourse
relating to the same Subject.

BY
The Honourable *ROBERT BOYLE*, Esq;

LONDON,
Printed by *J. Cadwell* for *J. Crooke*, and are to be
Sold at the *Ship* in St. *Paul's* Church-Yard.
MDCLXI.

Robert Boyle: b. Lismore Castle, Waterford, 1621

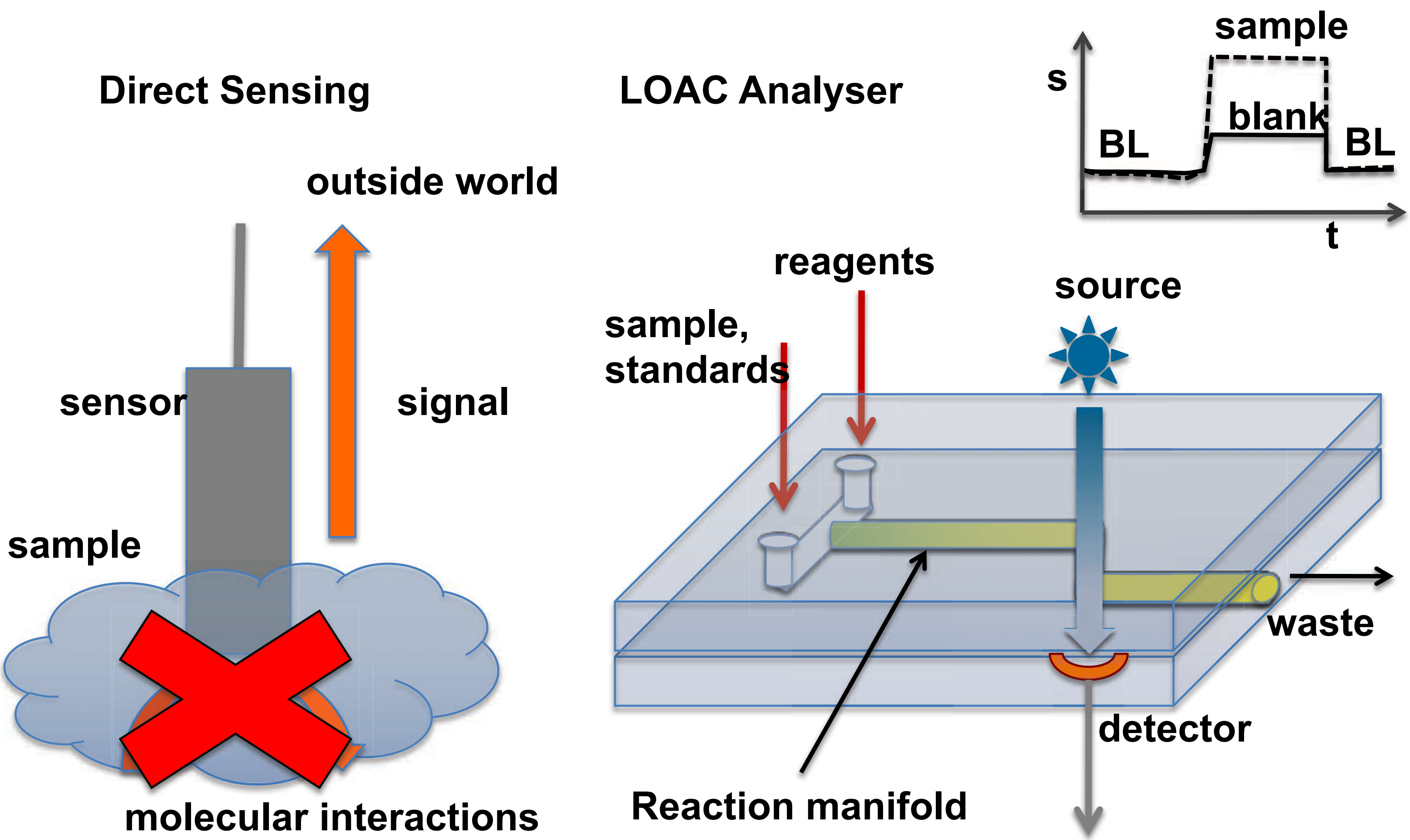
Control of membrane interfacial exchange & binding processes



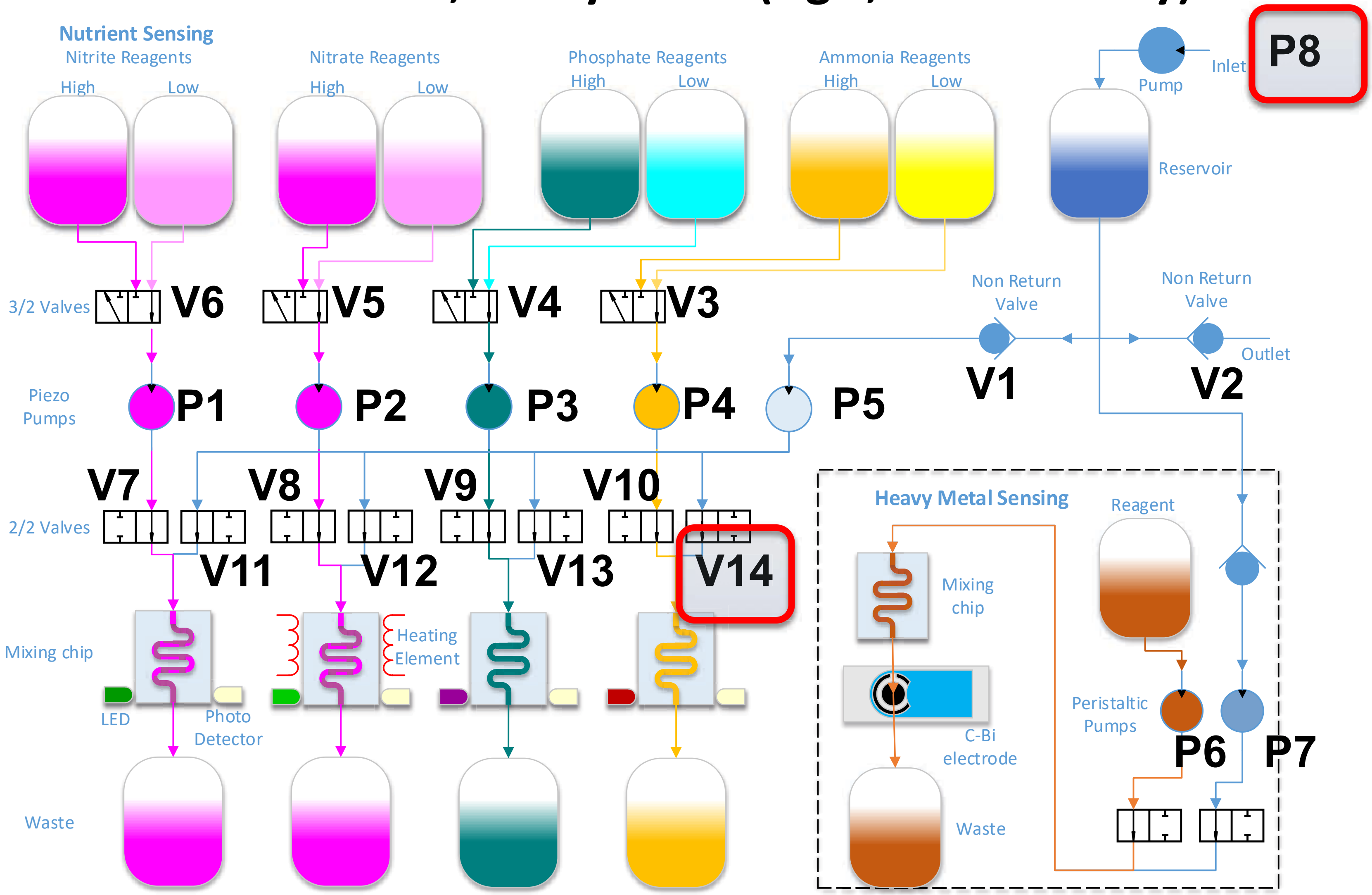
Remote, autonomous chemical sensing is a tricky business!

Osberstown – 3 week deployment

Direct Sensing vs. Reagent Based LOAC/ufluidics

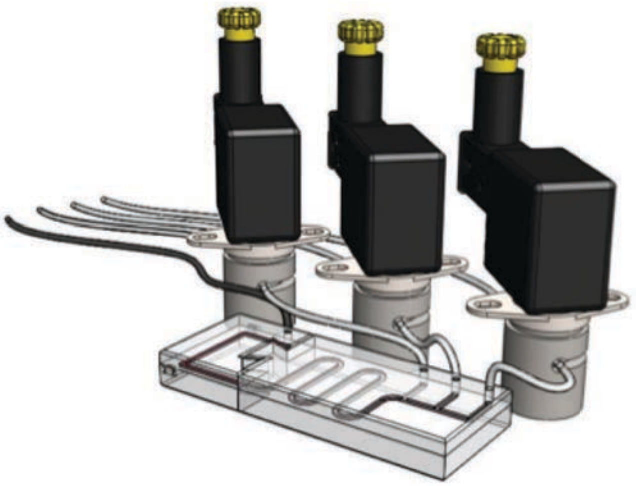


Fluidic Schematic: Multi-Analyte - Nitrite, nitrate, phosphate, ammonia, heavy metal (Hg^{2+}, voltammetry)



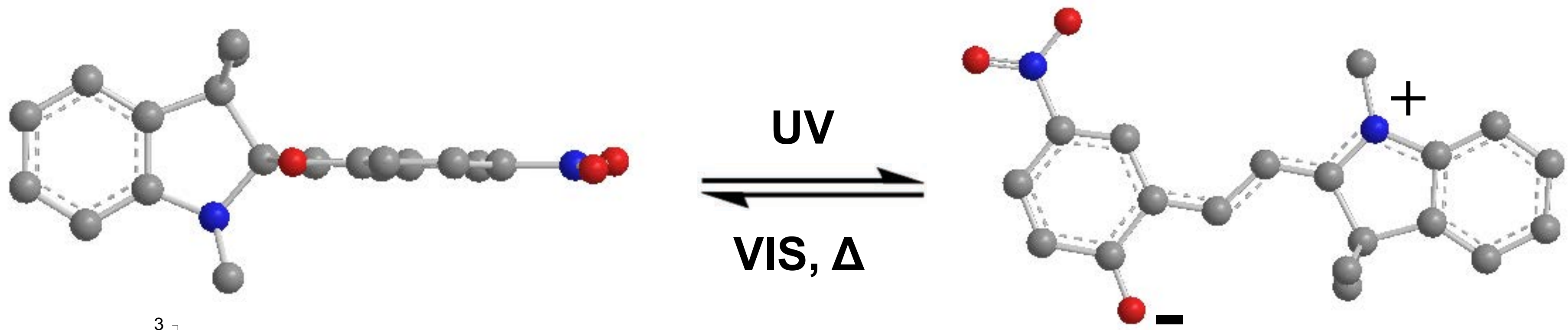
How to advance fluid handling in LOC platforms: re-invent valves (and pumps)!

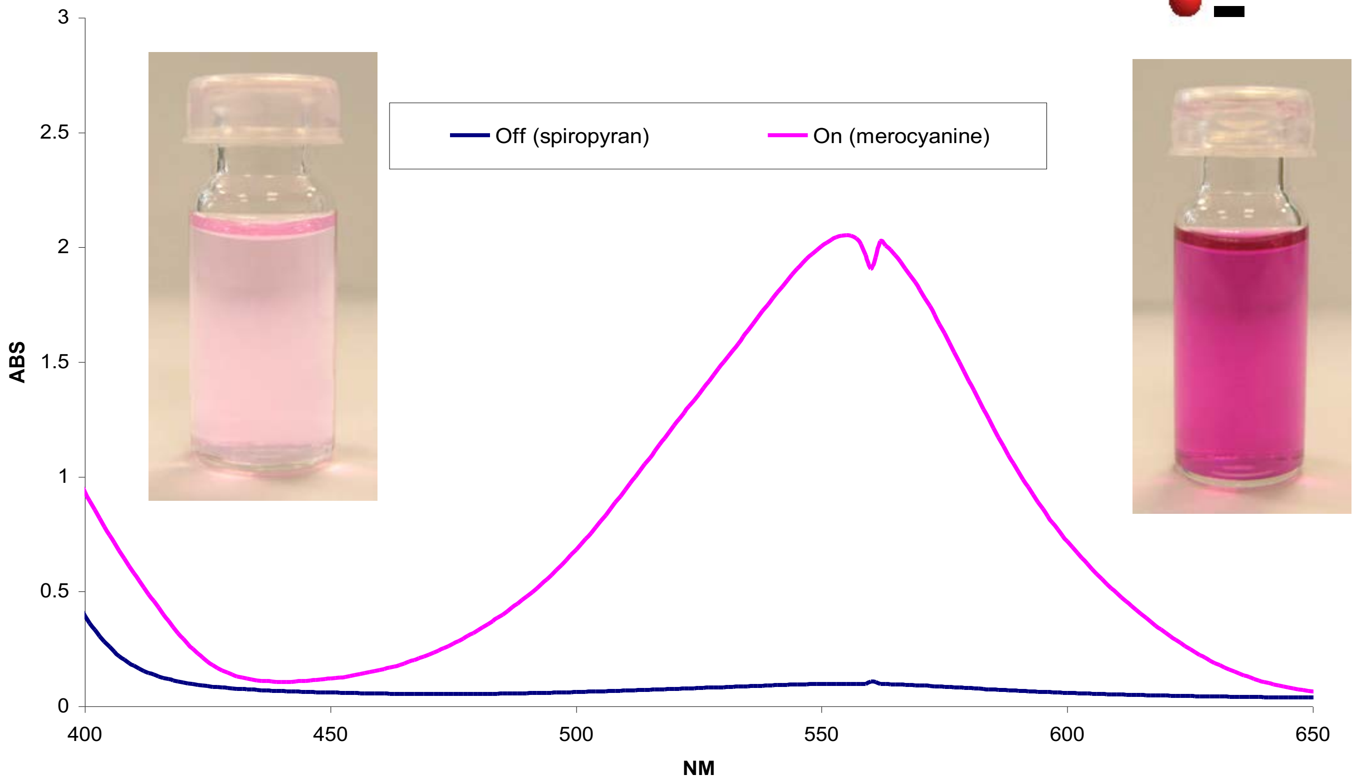
- **Conventional valves cannot be easily scaled down - Located off chip: fluidic interconnects required**
  - Complex fabrication
  - Increased dead volume
  - Mixing effects
- **Based on solenoid action**
  - Large power demand
  - Expensive



Solution: soft-polymer (biomimetic) valves fully integrated into the fluidic system

Photoswitchable Soft Actuators





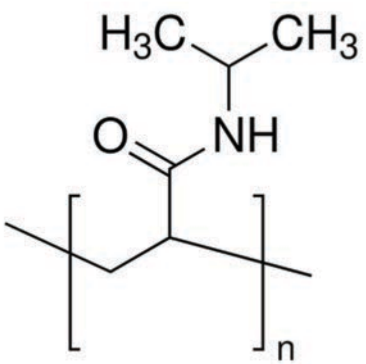
Famous Molecule….

From Prof. Thorfinnur Gunnlaugsson, TCD School of Chemistry
Spotted on Nickelodeon Cartoons February 2015

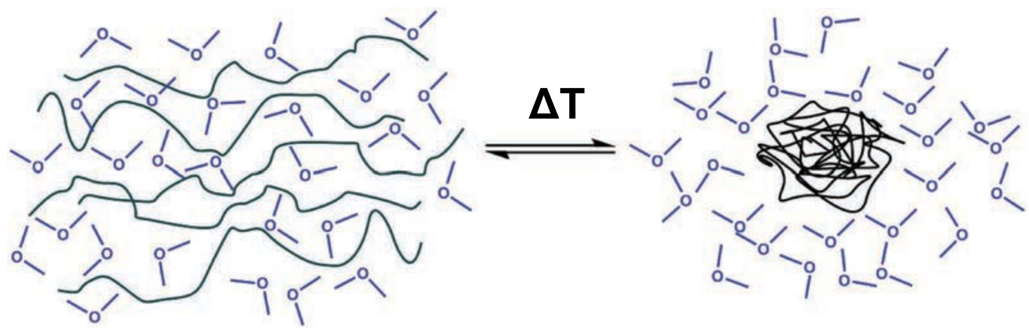
Poly(*N*-isopropylacrylamide)

- **pNIPAAM exhibits inverse solubility upon heating**
- **This is referred to as the LCST (Lower Critical Solution Temperature)**
- **Typically this temperature lies between 30-35^{o}C, but the exact temperature is a function of the (macro)molecular microstructure**
- **Upon reaching the LCST the polymer undergoes a dramatic volume change, as the hydrated polymer chains collapse to a globular structure, expelling the bound water in the process**

pNIPAAM



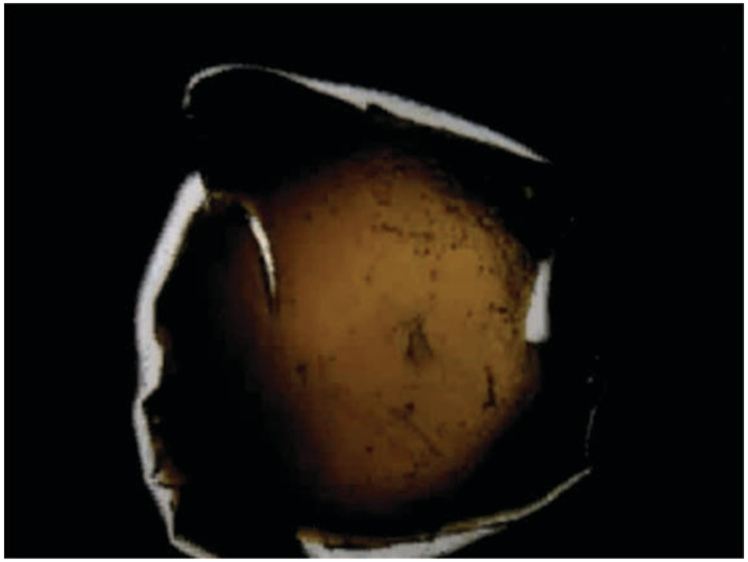
Hydrophilic **Hydrophobic**

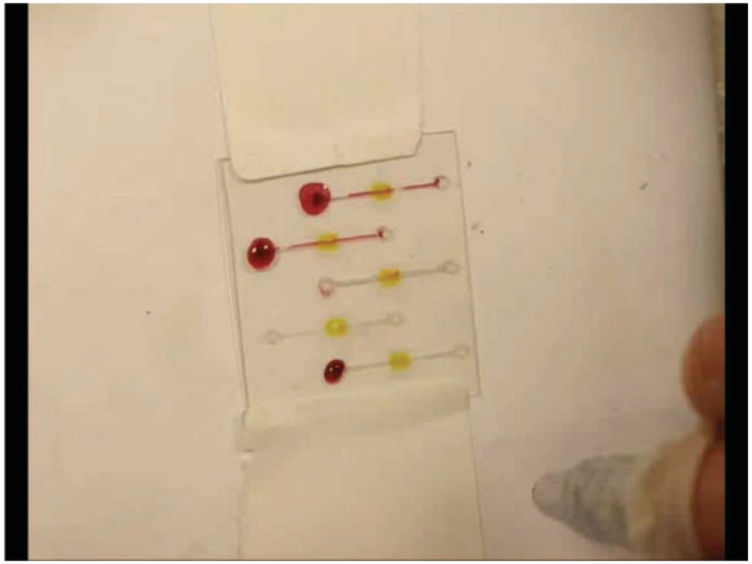


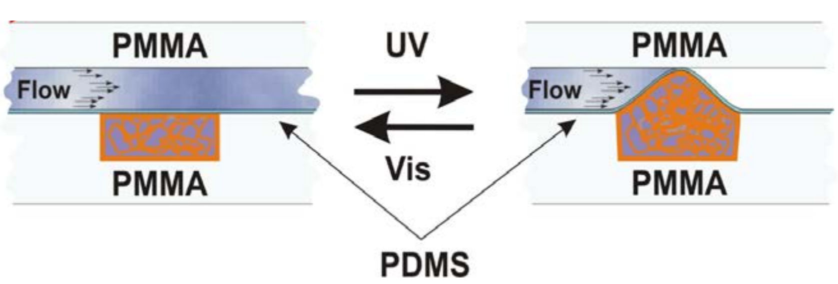
Hydrated Polymer Chains

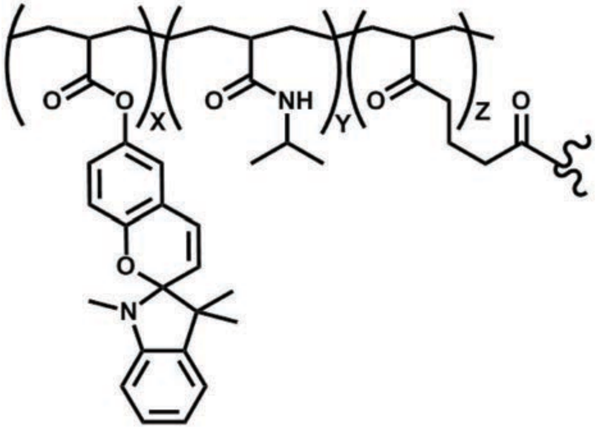
Loss of bound water -> polymer collapse

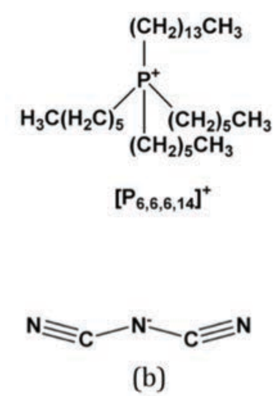
Photo-actuator polymers as microvalves in microfluidic systems











trihexyltetradecylphosphonium dicyanoamide $[P_{6,6,6,14}]^+[dca]^-$

Ionogel-based light-actuated valves for controlling liquid flow in micro-fluidic manifolds, Fernando Benito-Lopez, Robert Byrne, Ana Maria Raduta, Nihal Engin Vrana, Garrett McGuinness, Dermot Diamond, Lab Chip, 10 (2010) 195-201.

Experimental set up for PID Control

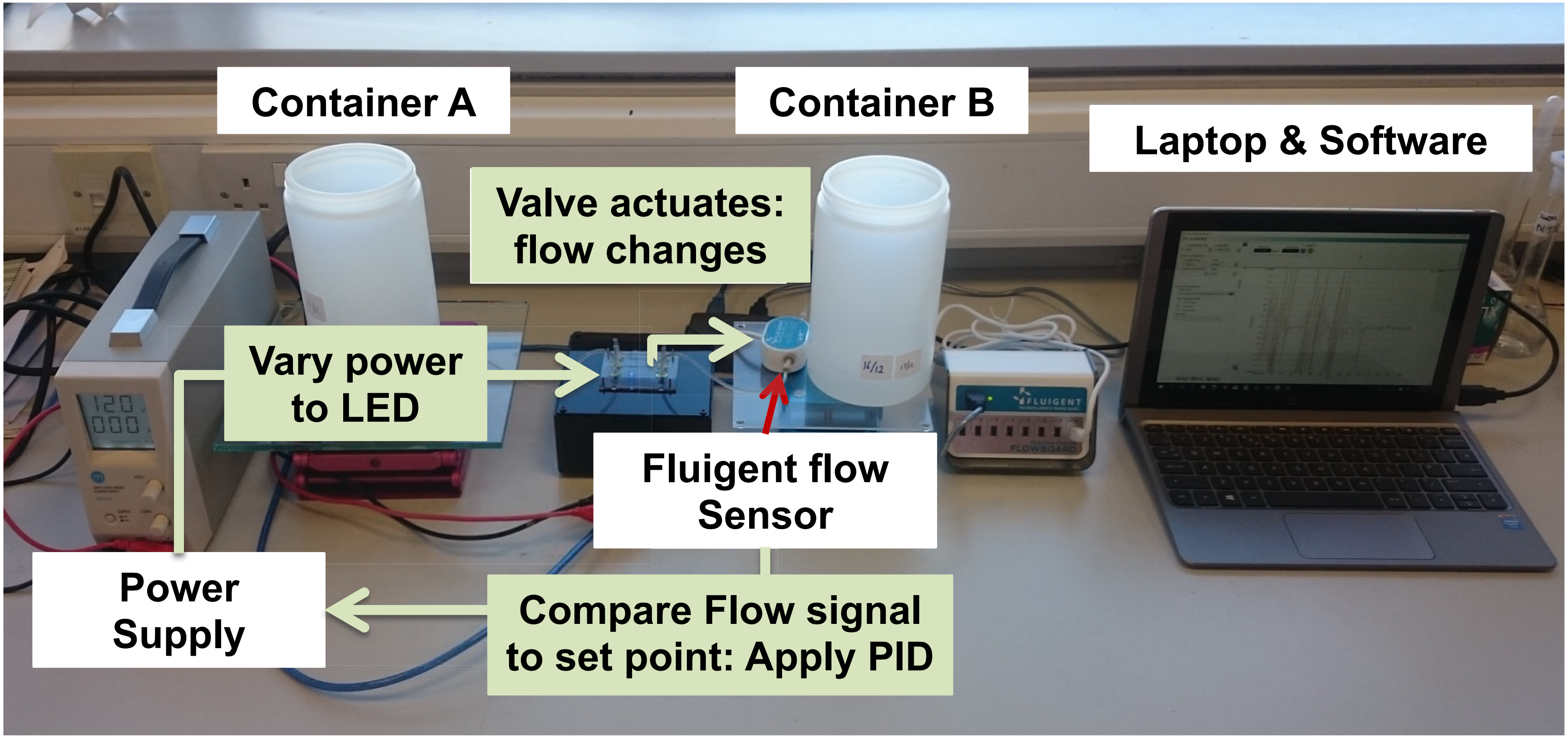
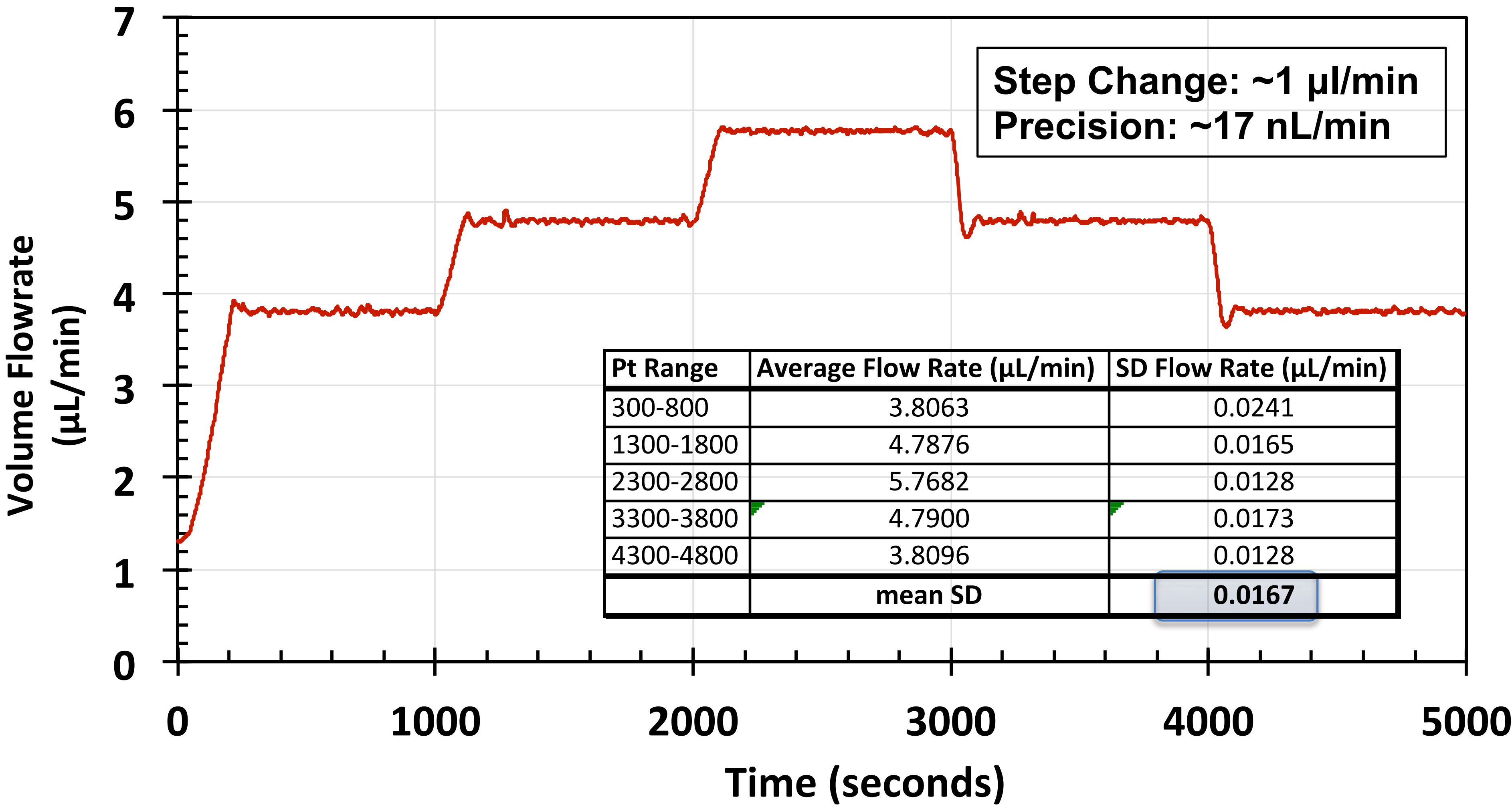


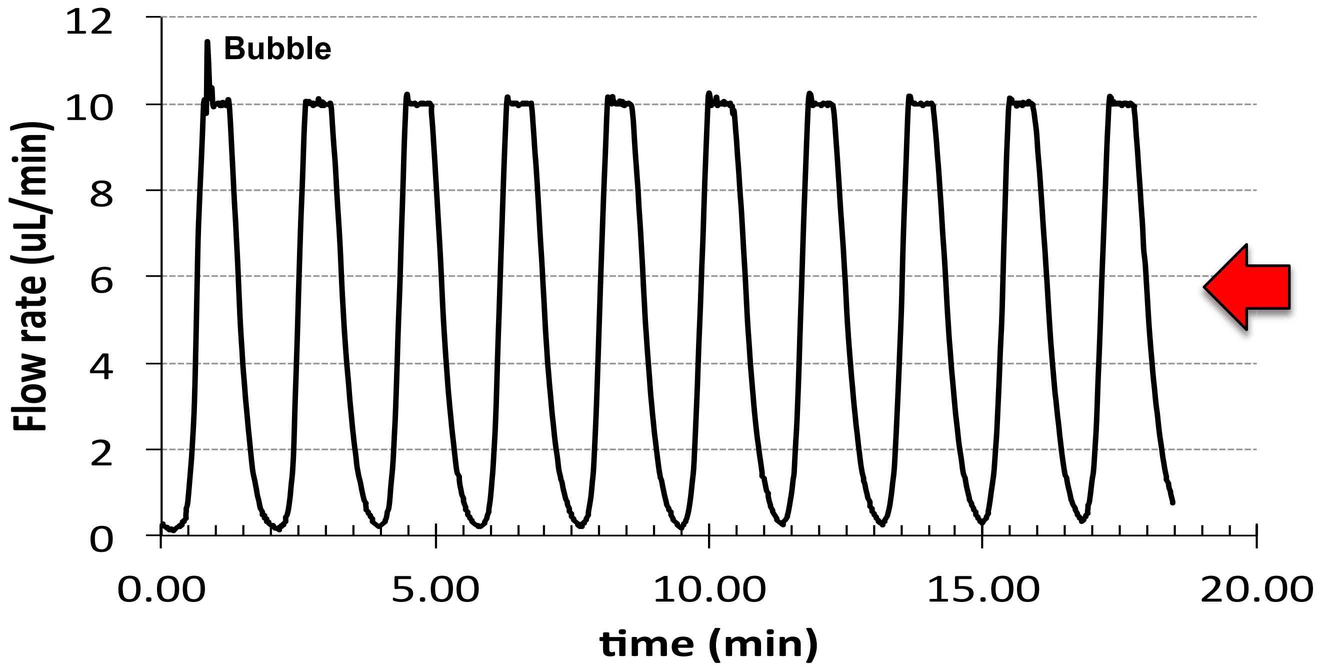
Photo-Controlled Flow Rate



Pt Range	Average Flow Rate (µL/min)	SD Flow Rate (µL/min)
300-800	3.8063	0.0241
1300-1800	4.7876	0.0165
2300-2800	5.7682	0.0128
3300-3800	4.7900	0.0173
4300-4800	3.8096	0.0128
	mean SD	**0.0167**

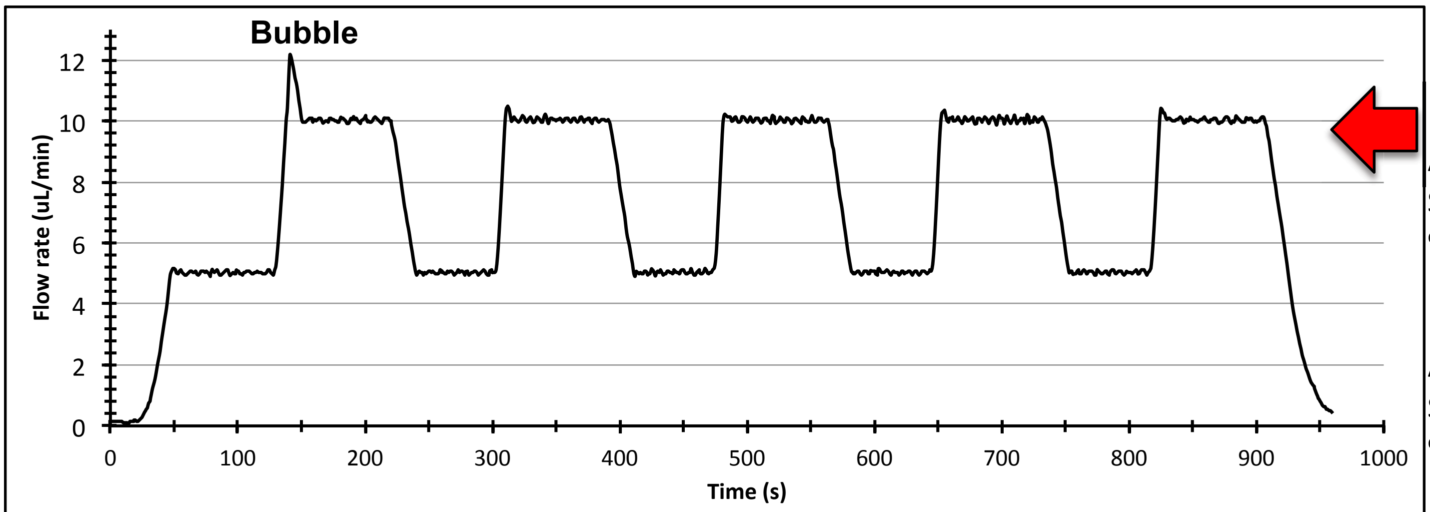
C. Delaney, P. McCluskey, S. Coleman, J. Whyte, N. Kent, D. Diamond, Precision control of flow rate in microfluidic channels using photoresponsive soft polymer actuators, LAB ON A CHIP. 17 (2017) 2013–2021. doi:[10.1039/c7lc00368d](10.1039/c7lc00368d).

Some figures of merit



Switching 0.0-10.0 µL/min
n= 15 points sampled behind the initial small overshoot

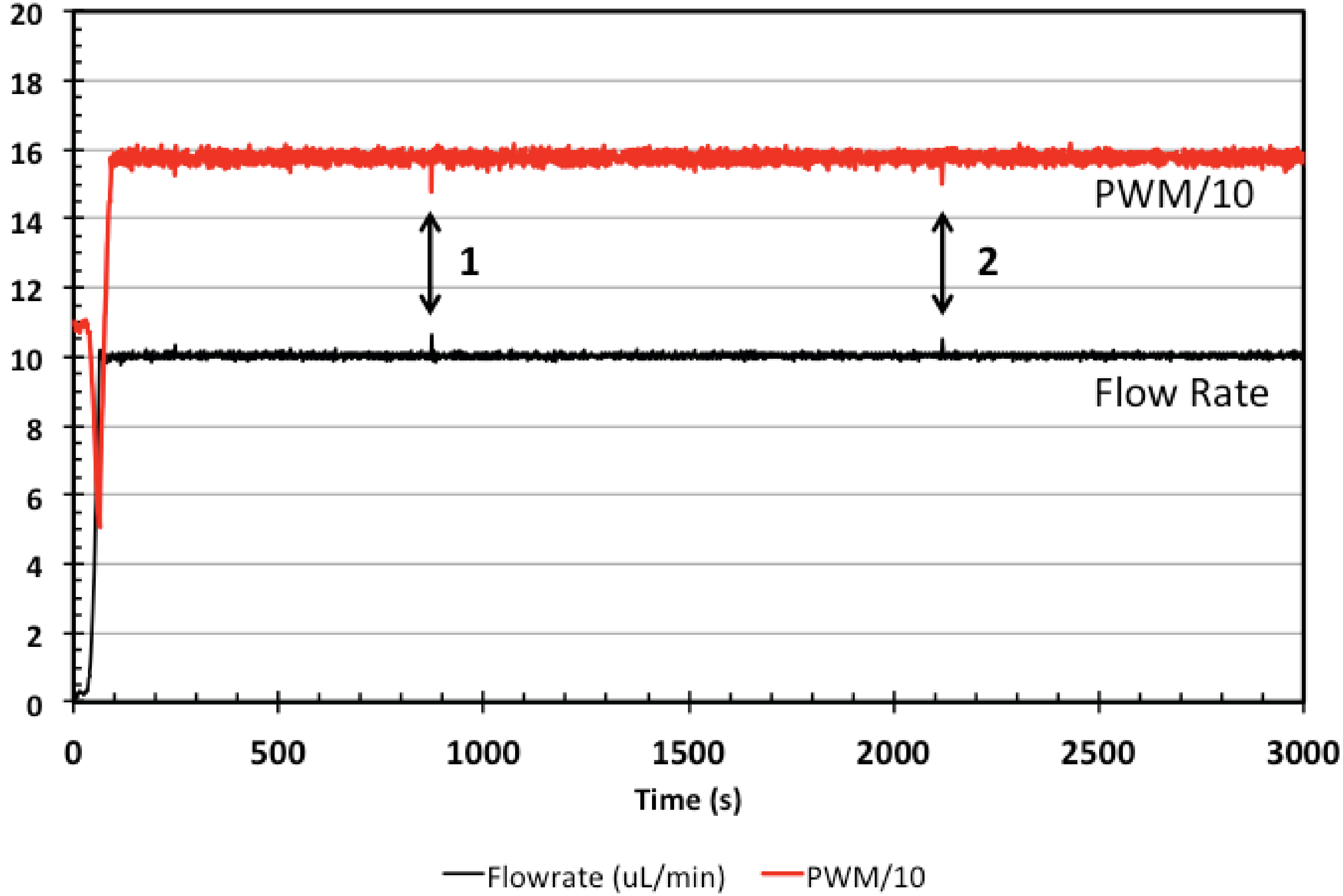
Averages (n=10)	
mean	10.0028
Mean SD	0.0323
Error Mean	0.0028
%RSD	0.3235
%RE mean	0.0279



Switching 5.0-10.0 µL/min
n= 30 points sampled

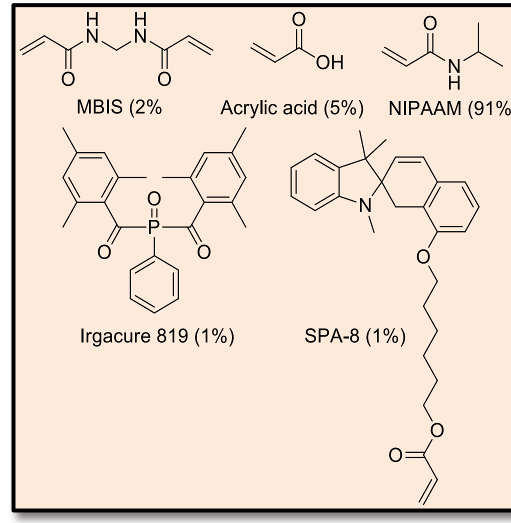
Mean %RE (5=true)	0.780
Mean %RE (5.039=true)	0.098
Average of mean	5.039
SD Mean	0.006
%RSD	0.120
Mean %RE (10=true)	0.372
Mean %RE (10.037=true)	0.102
Average of mean	10.037
SD Mean	0.012
%RSD	0.124

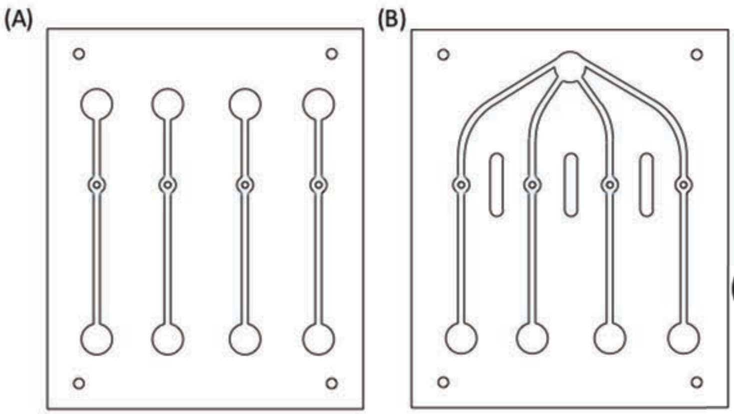
Power Supply to LED

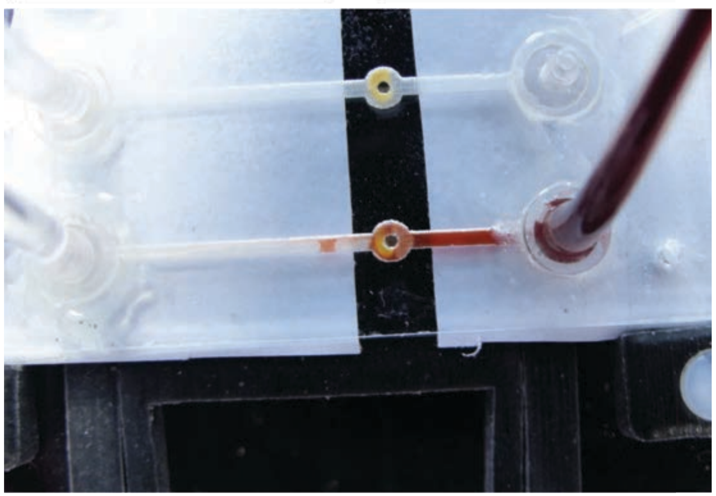


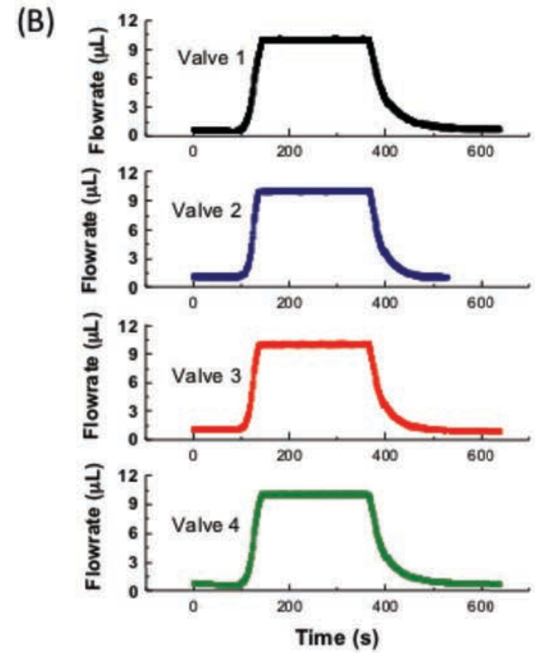
Over a period of 50 min constant maintenance of 10 µL/min flow rate there is no discernable change in LED power ➔ diagnostic information

Multiplexing: Valve Arrays









Impact of 3d Printing

Minimum thickness

- Assembled chip 4.25 mm
- 3D Printed Chip 1.58 mm

Assembled Chip **Printed Chip**

Advantages:

- No Assembly
- No Bonding necessary
- Integrated barbs (1/16”)
- Chip thickness reduced by 63%
- Automated manufacturing

Rendered Chip

Printed Chip

Holifab H2020 Project; Laurent Malaquin, LAAS-CNRS, Margaret McCaul (DCU)

From Multi-Part to Single Part Fluidic Chips

7 Parts : 3 days
~€50/chip

3 Parts : 1 day

1 Part : 1 hour
~€1/chip

Margaret McCaul (DCU) and Laurent Malaquin (LAAS-CNRS)

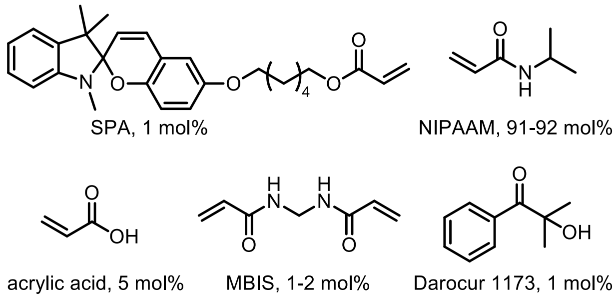
Photocontrol of Assembly and Subsequent Switching of Surface Features

ACS APPLIED MATERIALS & INTERFACES
Research Article
www.acsami.org

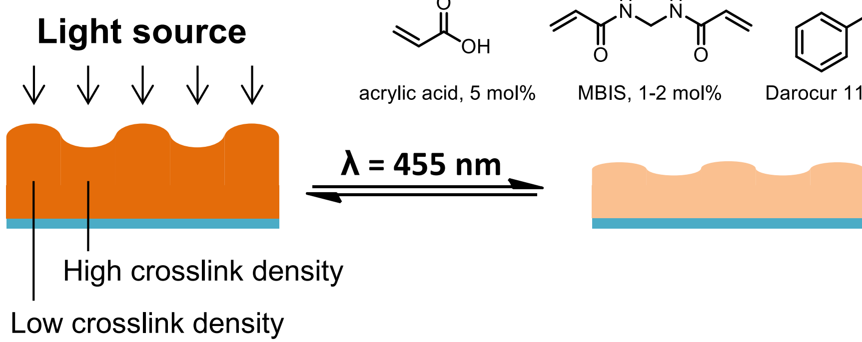
ACS applied materials & interfaces, 6 (2014) 7268-7274

Photoswitchable Ratchet Surface Topographies Based on Self-Protonating Spiropyran–NIPAAM Hydrogels

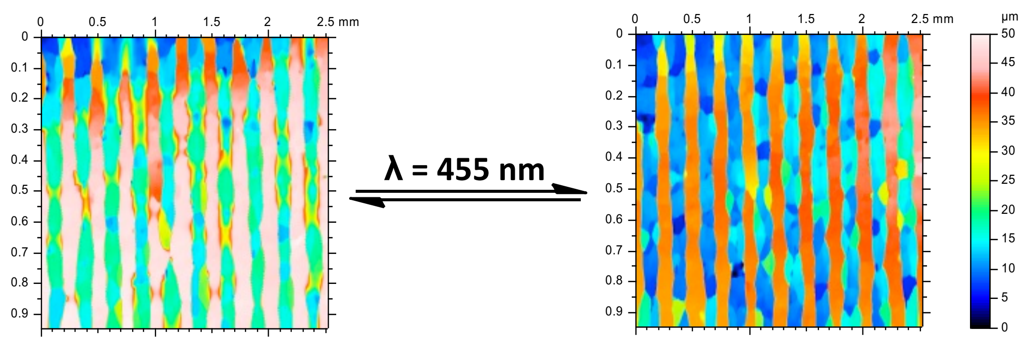
Jelle E. Stumpel,[†] Bartosz Ziółkowski,[‡] Larisa Florea,[‡] Dermot Diamond,[‡] Dirk J. Broer,[*,†,§] and Albertus P. H. J. Schenning[*,†,§]

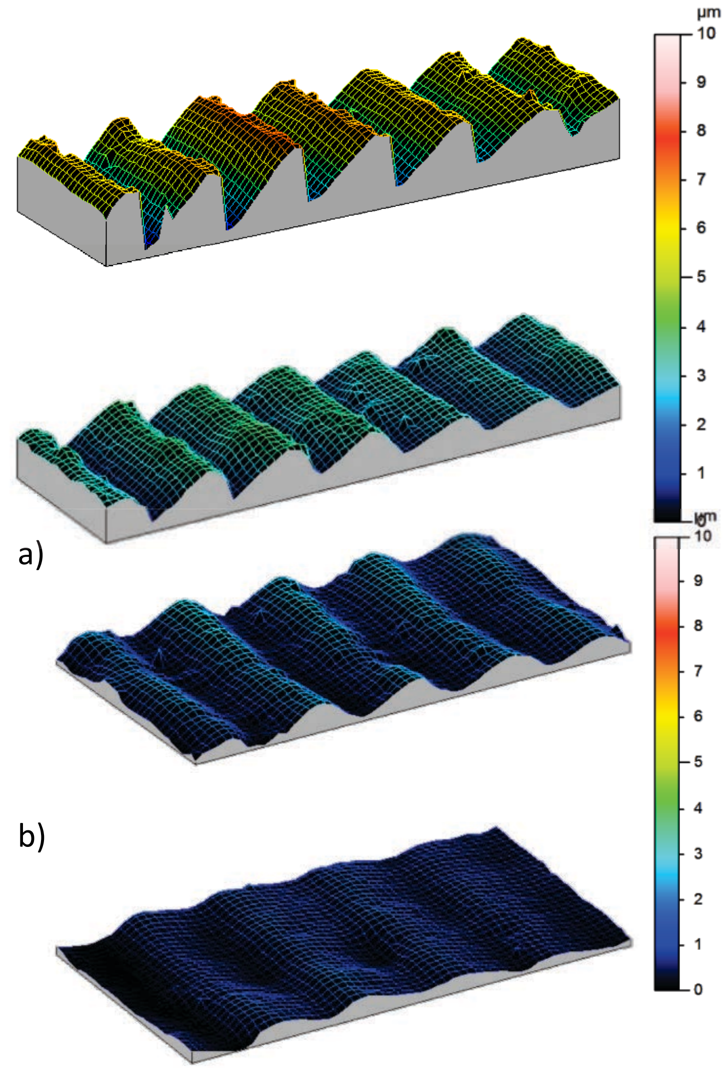


a)

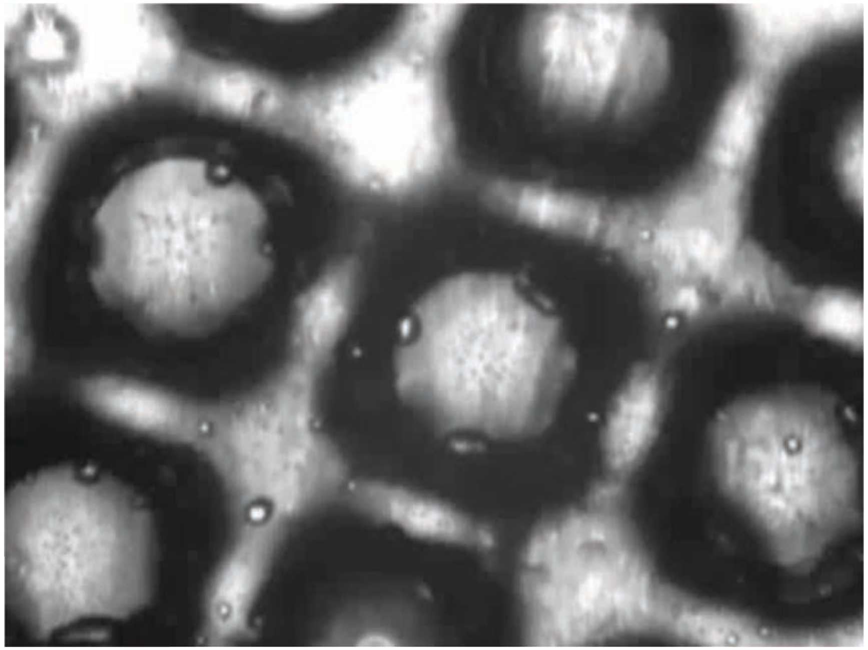


b)

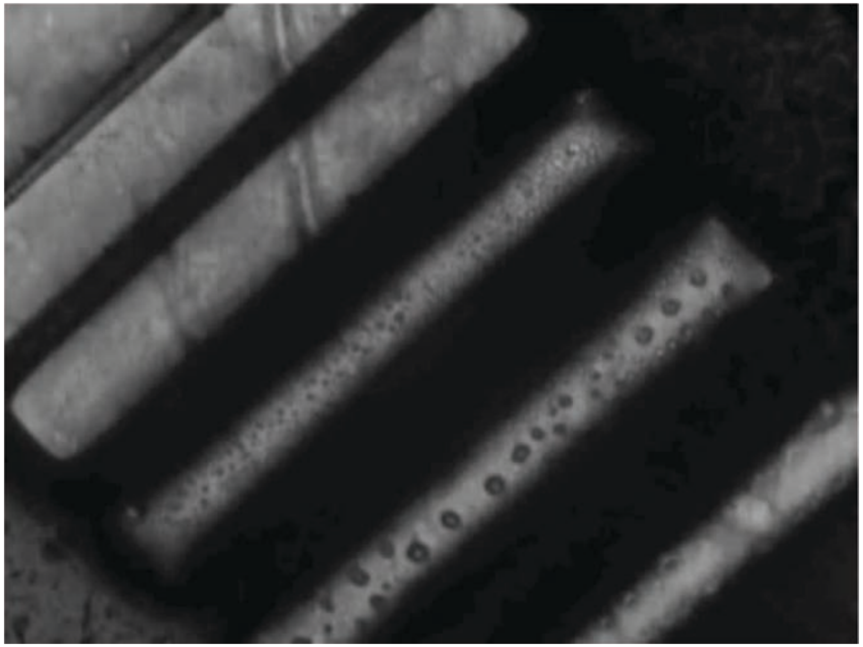




Flexible creation of μ-dimensioned features in flow channels using in-situ photo-polymerisation



Ntf2 pillars speed x3

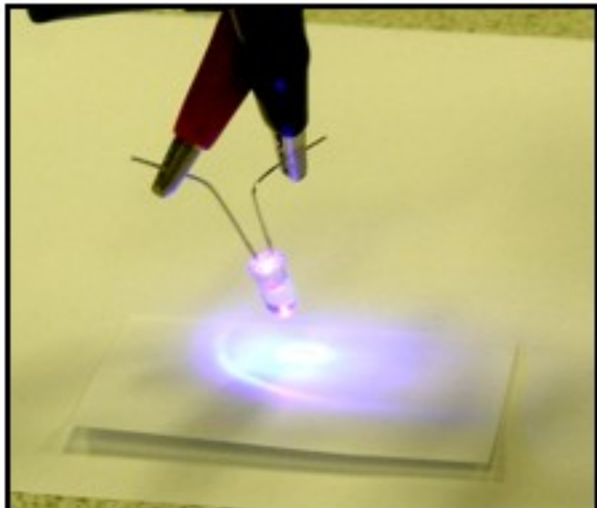


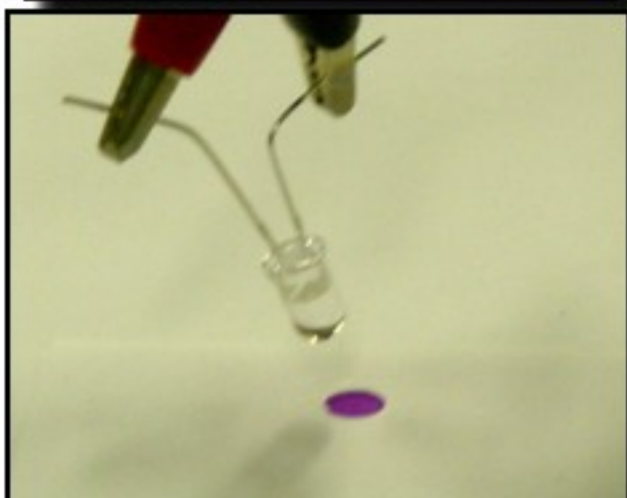
DCA lines speed x4

With Dr Peer Fischer, Fraunhofer-Institut für Physikalische Messtechnik (IPM), Freiburg

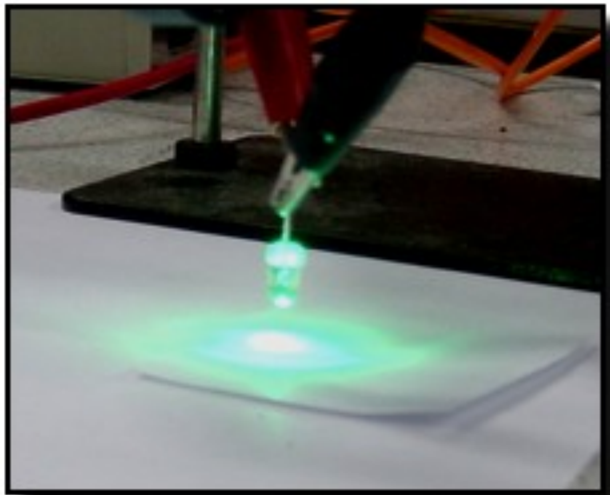
Switching SP-Doped Films

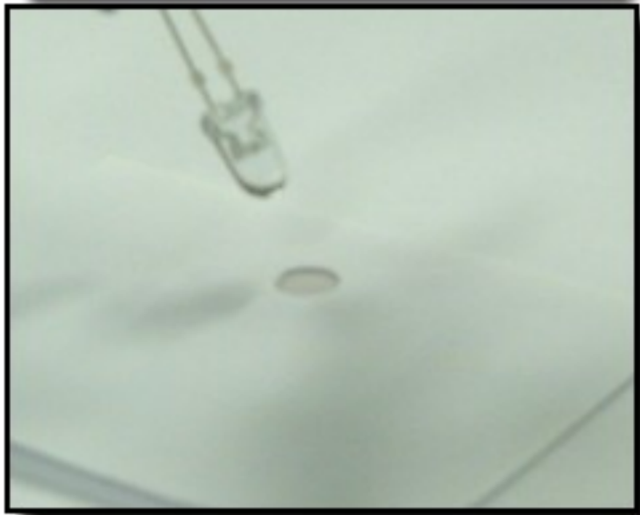
UV LED 380 nm



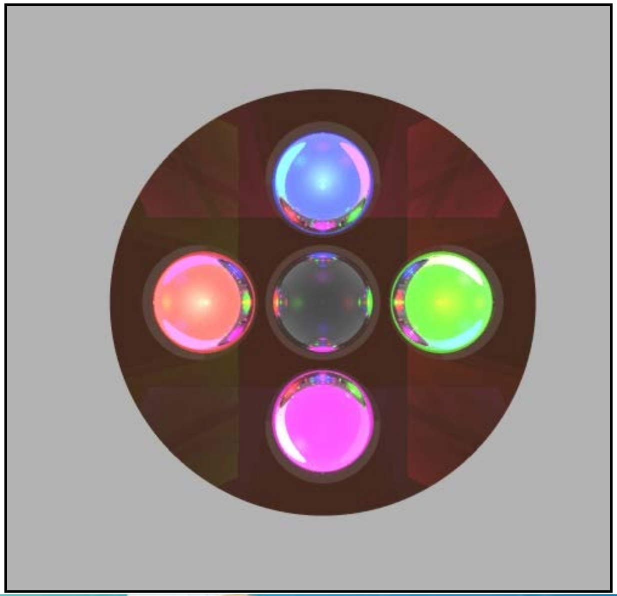


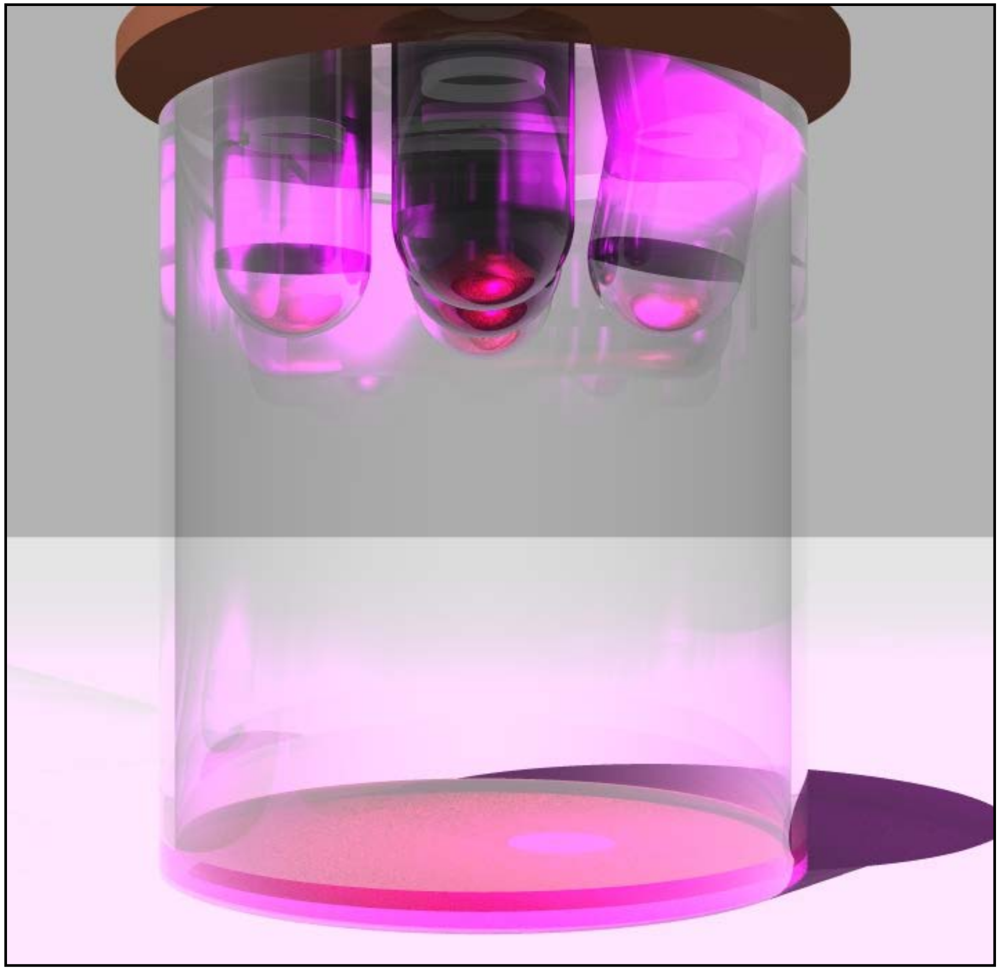
Green LED 523 nm



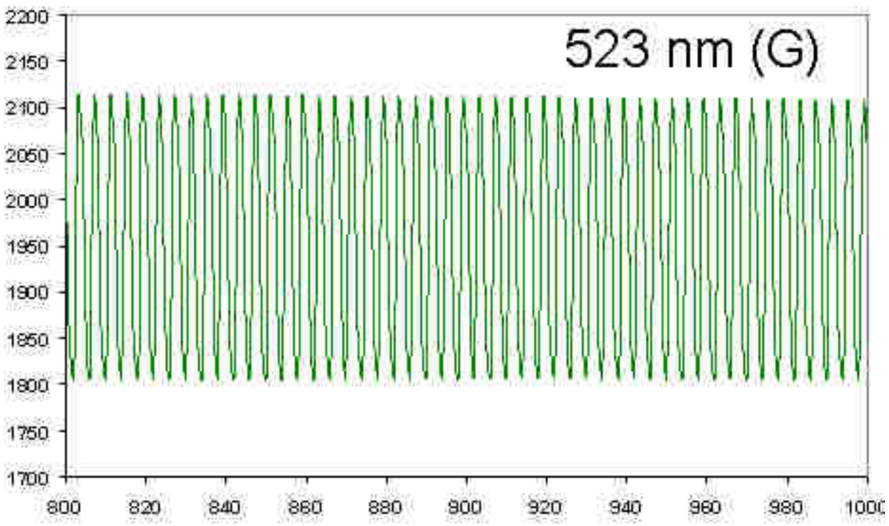


LED-Based Device for Switching and Monitoring SP-MC: The Discophotometer

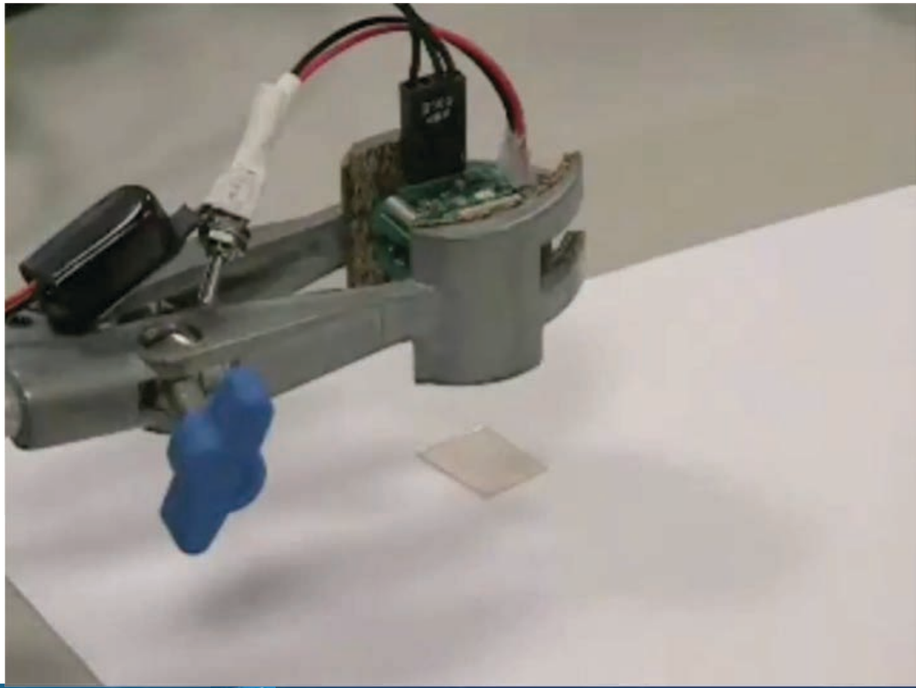




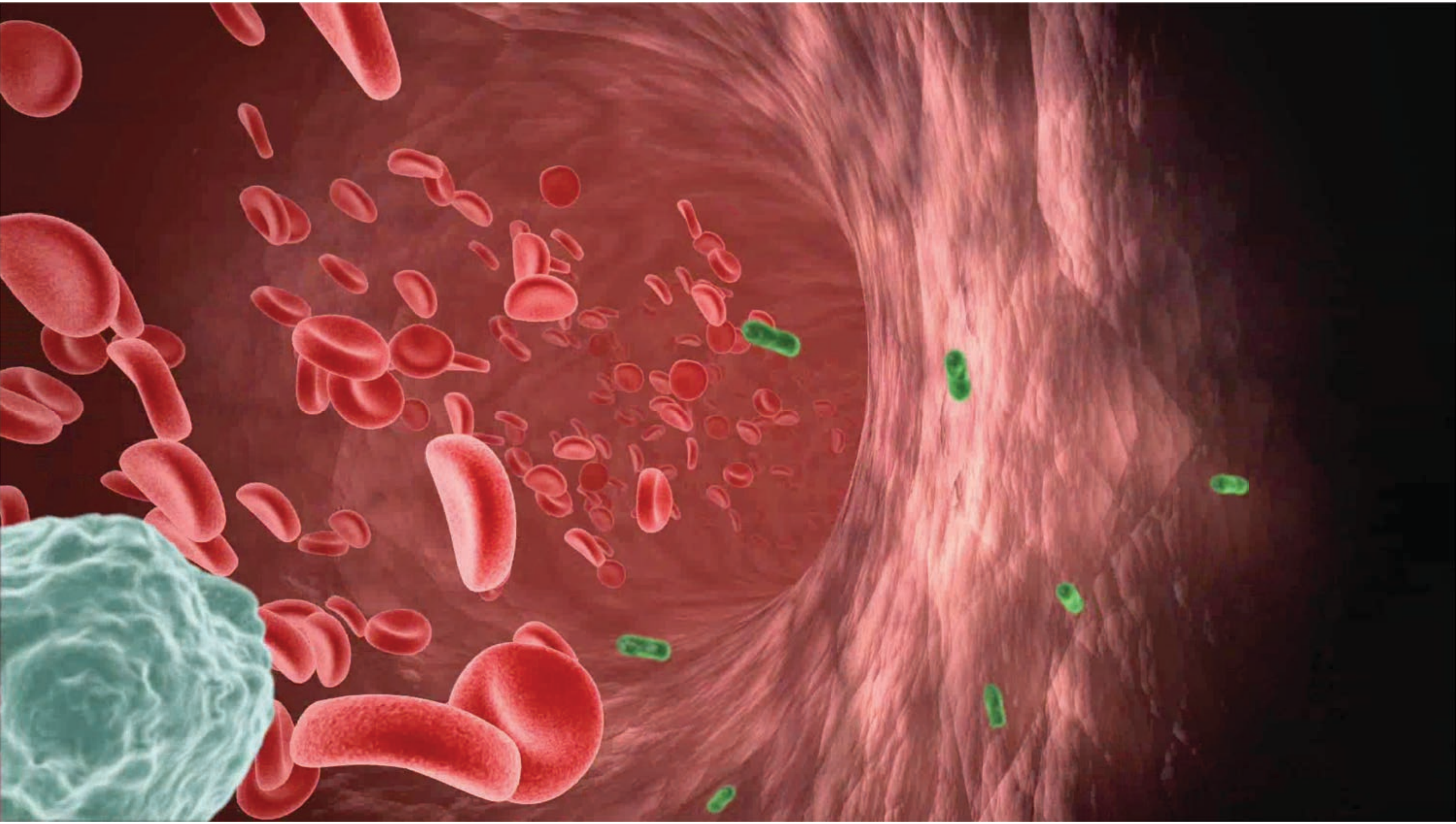
Multiple Switching of SP-MC using LEDs



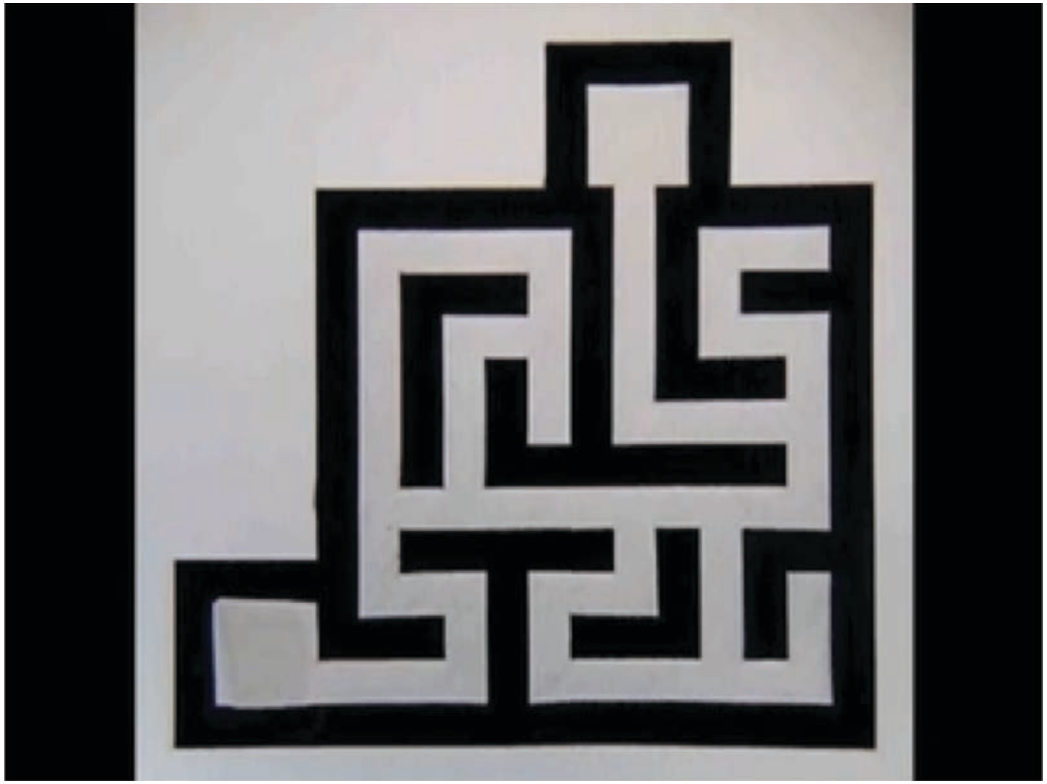
- Take measurements R,G,B (flash <1s)
- UV LED ‘on’ 10 s; wait 10 s; repeat measurements
- Green LED ‘on’ 10 s; wait 10 s; repeat measurements
- Green channel more sensitive as expected
- >2,000 repeat switches performed on a single surface

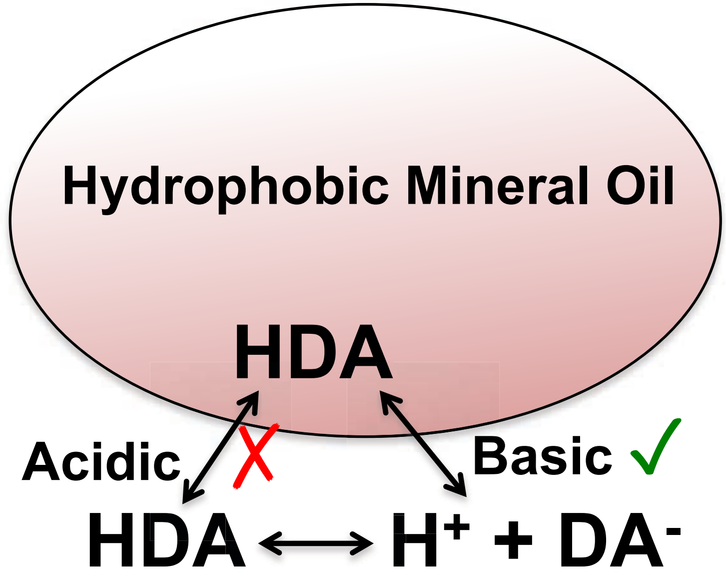


The Immune System



Chemotactic Systems





In a pH gradient, DA^- is preferentially transferred to the aqueous phase at the more basic side of the drop.

Published on Web 11/01/2010 (speed ~x4): channels filled with KOH (pH 12.0-12.3 + surfactant; agarose gel soaked in HCl (pH 1.2) sets up the pH gradient; droplets of mineral oil or DCM containing 20-60% 2-hexyldecanoic acid + dye. Droplet speed ca. 1-10 mm/s; movement caused by convective flows arising from concentration gradient of HDA at droplet-air interface (greater concentration of DA^- towards higher pH side); **HDA <-> H^+ + DA^-**

Maze Solving by Chemotactic Droplets; Istvan Lagzi, Siowling Soh, Paul J. Wesson, Kevin P. Browne, and Bartosz A. Grzybowski; **J. AM. CHEM. SOC. 2010,** ***132, 1198–1199***
Fuerstman, M. J.; Deschatelets, P.; Kane, R.; Schwartz, A.; Kenis, P. J. A.;Deutch, J. M.; Whitesides, G. M. *Langmuir 2003, 19, 4714.*

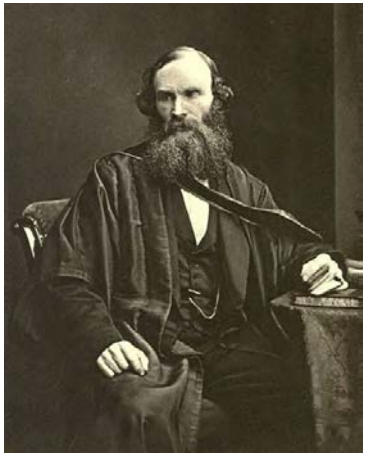
Marangoni Effect; ‘Tears of wine’

The mass transfer along an interface between two fluids due to a gradient of the surface tension.

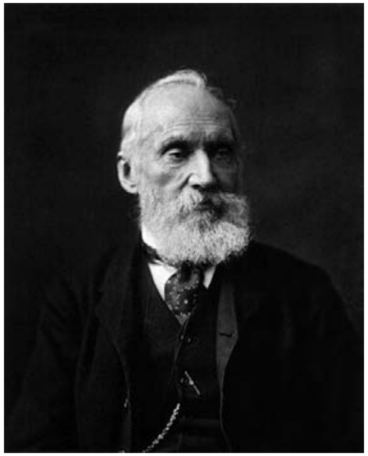
The general effect is named after Italian physicist **Carlo Marangoni** (1840-1925), who studied it for his doctoral dissertation at the **University of Pavia** and published his results in **1865.**

Carlo Marangoni

Enrnestina Marangoni (1876-1972)



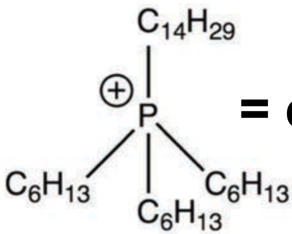
James Thompson



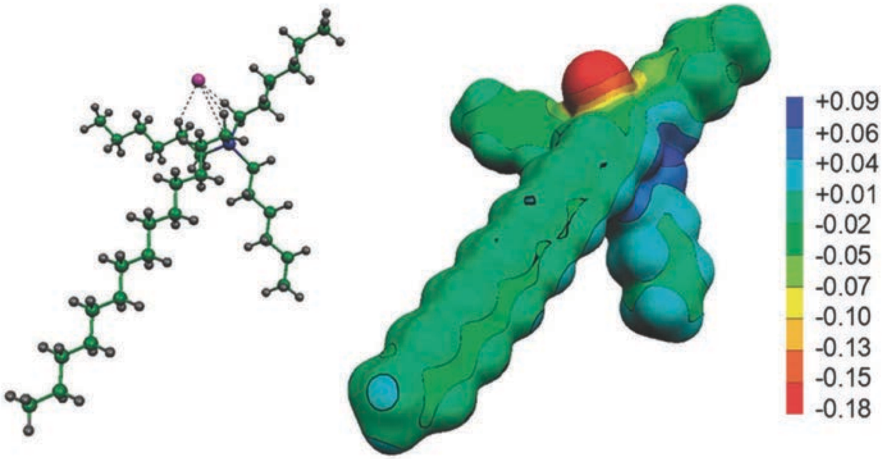
William Thompson

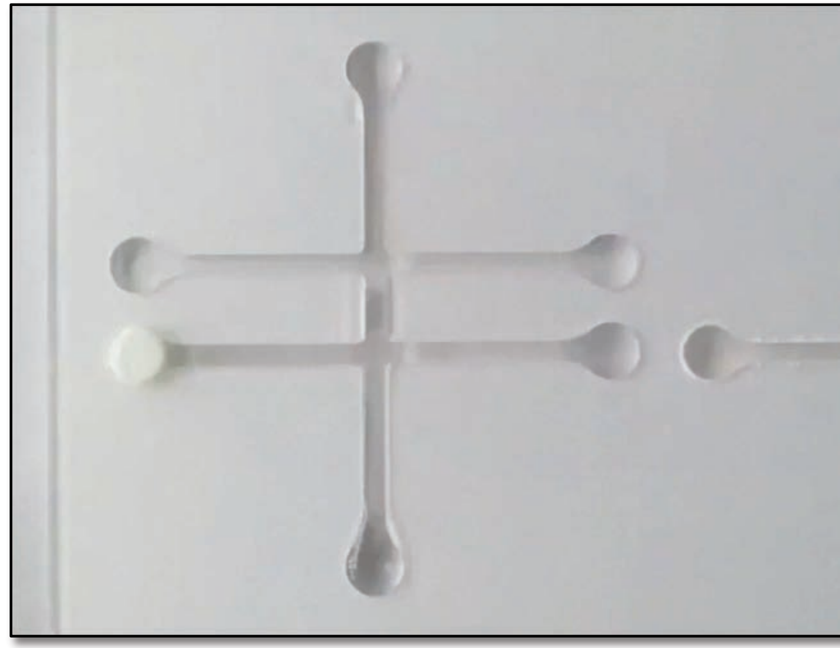
See http://web.mit.edu/1.63/www/Lec-notes/Surfacetension/Lecture4.pdf

Chemotactic IL Droplets



= cationic surfactant



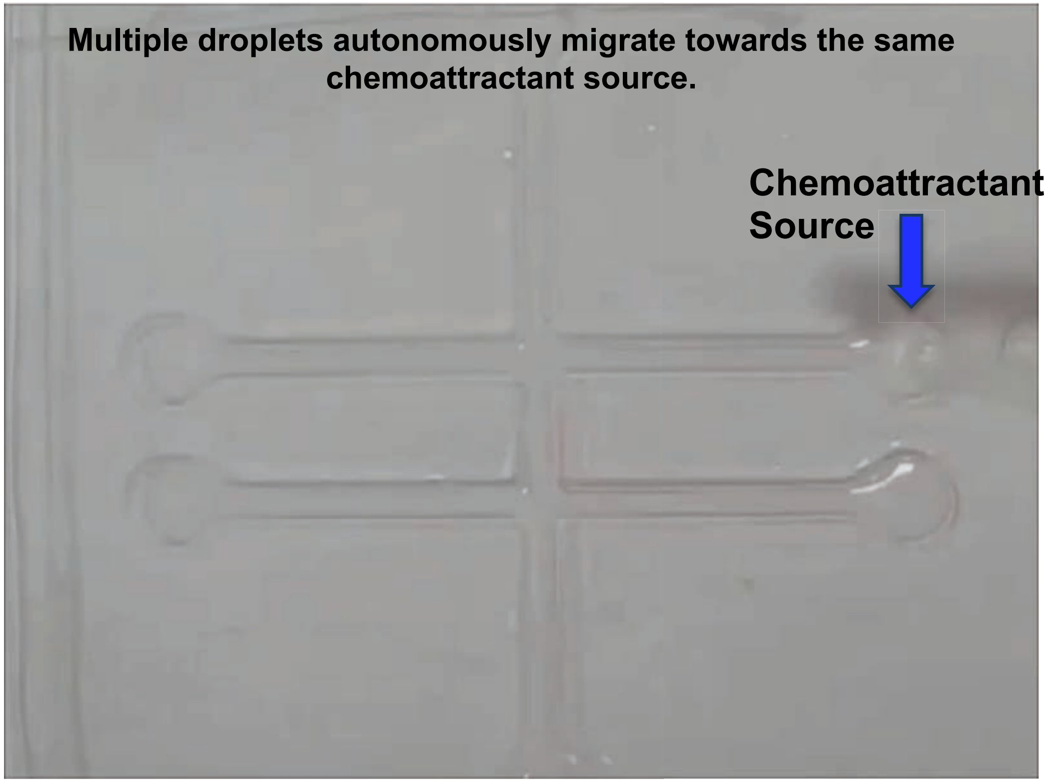


Trihexyl(tetradecyl)phosphonium chloride ([$P_{6,6,6,14}$][Cl]) droplets with a small amount of 1-(methylamino)anthraquinone red dye for visualization. The droplets spontaneously follow the gradient of the Cl^- ion which is created using a polyacrylamide gel pad soaked in 10^{-2} M HCl; A small amount of NaCl crystals can also be used to drive droplet movement.

***Electronic structure calculations and physicochemical experiments quantify the competitive liquid ion association and probe stabilisation effects for nitrobenzospiropyran in phosphonium-based ionic liquids*, D. Thompson et al., *Physical Chemistry Chemical Physics*, 2011, 13, 6156-6168.**

From 2D to 3D Movement

2D Movement



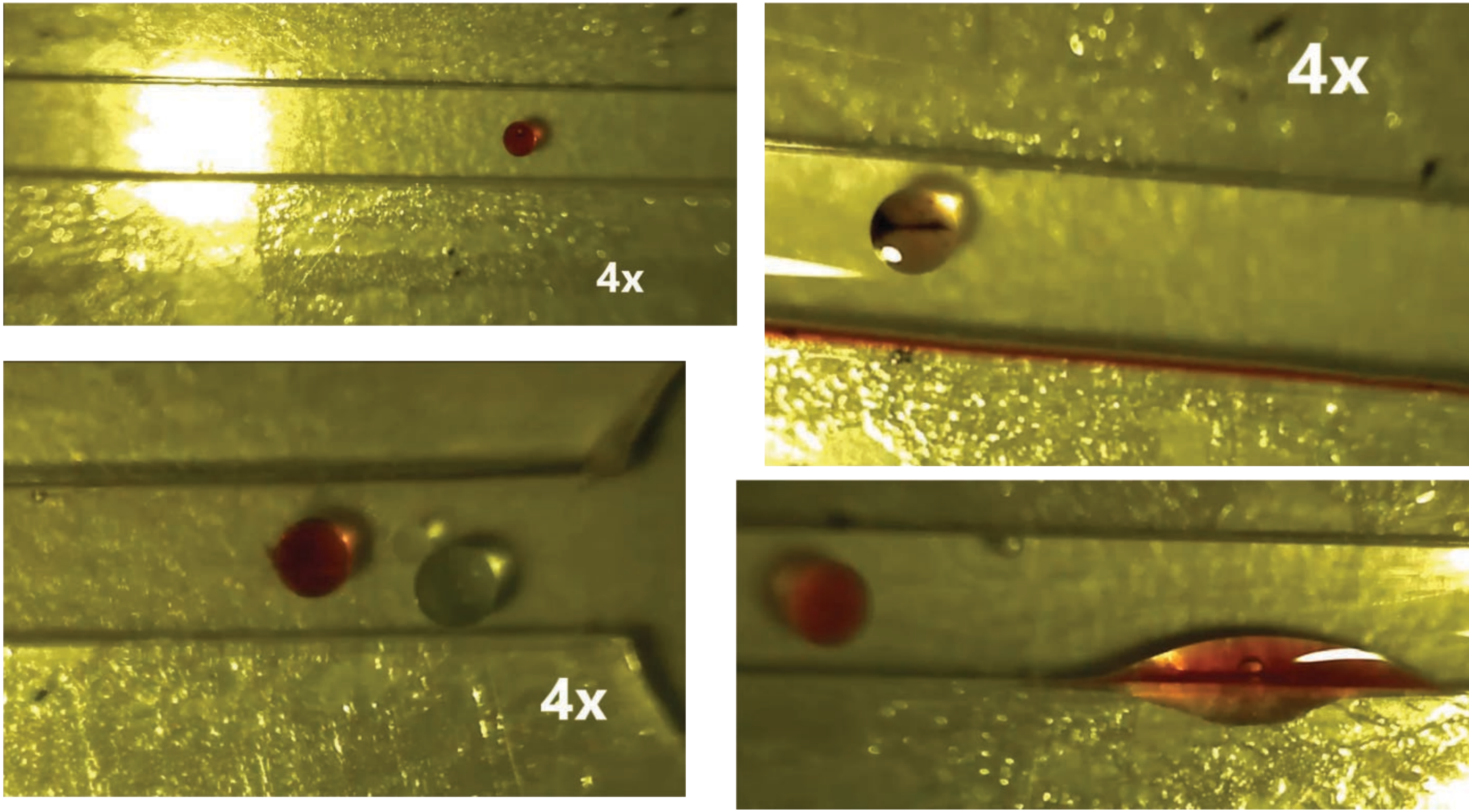
L. Florea et al. Chem. Comm. 51 (2015) 2342.

L. Florea et al. Sens. Actuators B 239 (2017) 1069.

3D Movement

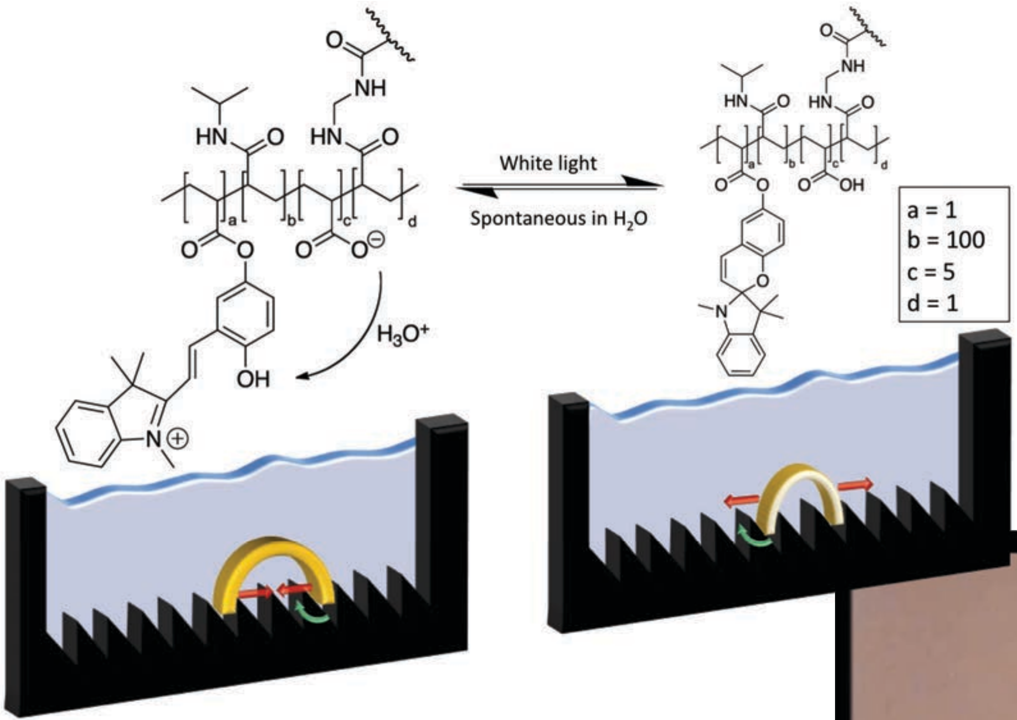
With David Officer, Adv Mater. 2018
doi: 10.1002/adma.201801821

Fun with Droplets and Dynamic Electro-Ionic Gradients



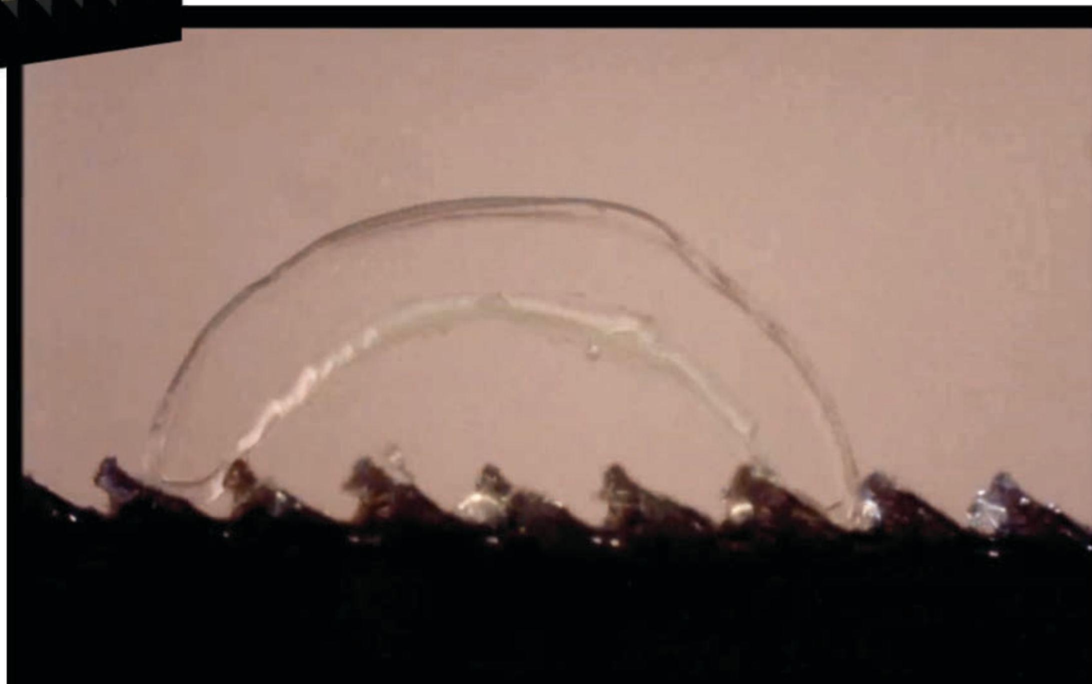
Joan Cabot, Brett Paull (UTAS), Larisa Florea

Photo-Responsive Soft Hydrogels



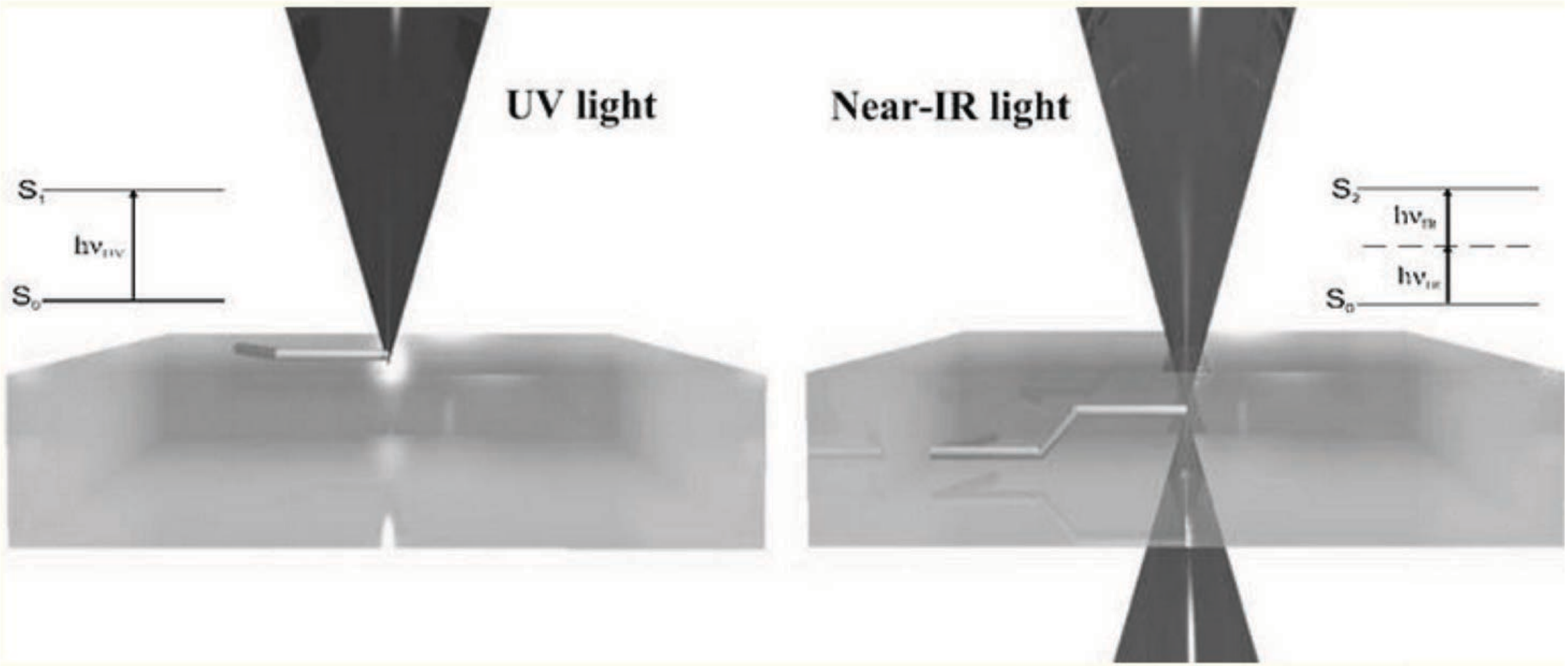
'Walking towards the light'

W. Francis et al. / Sensors and Actuators B 250 (2017) 608–616



Background

Stereolithography | **Two-photon polymerisation**



Stereolithography:

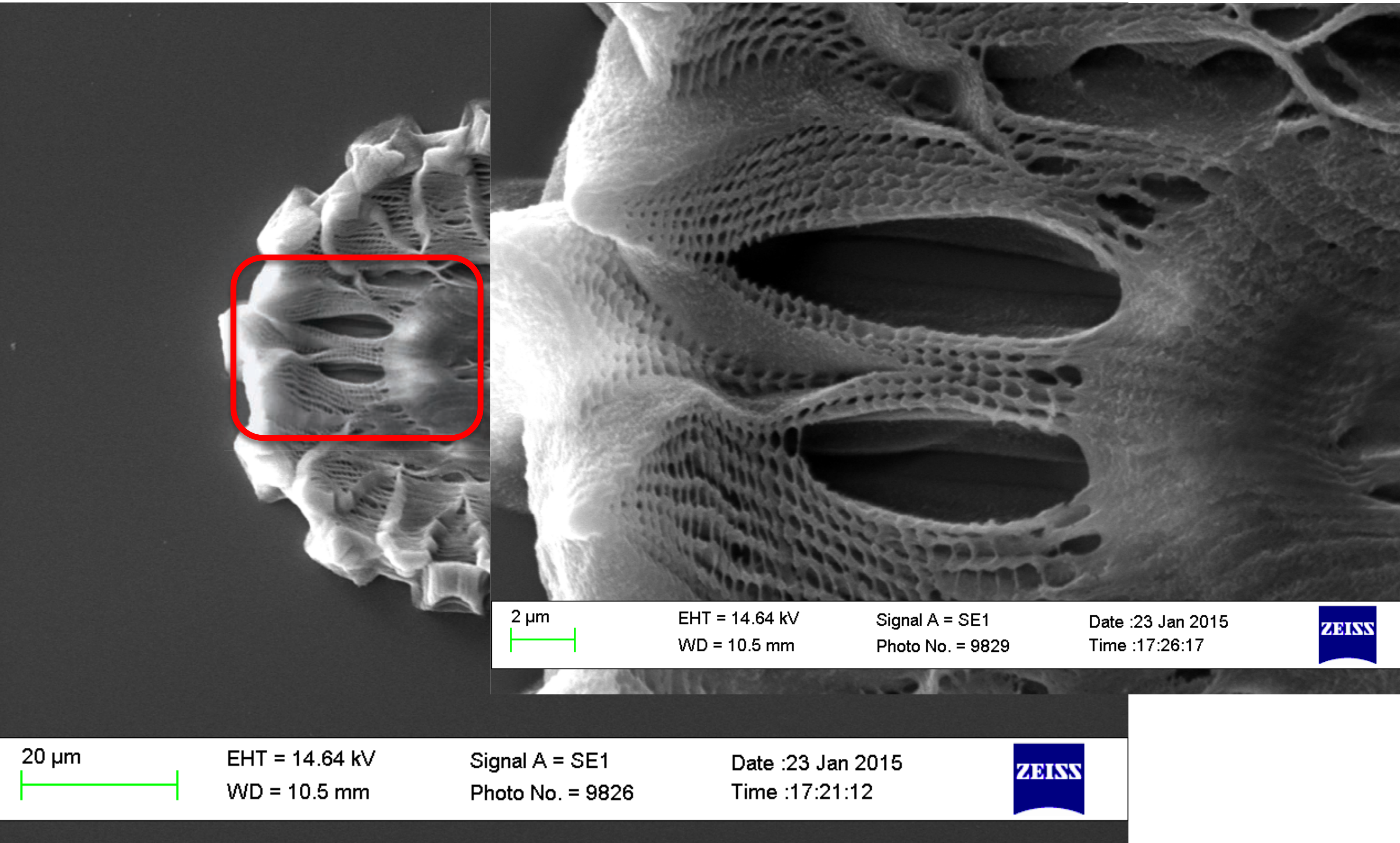
- Single photon absorption
- 2D patterns

Two-photon polymerisation:

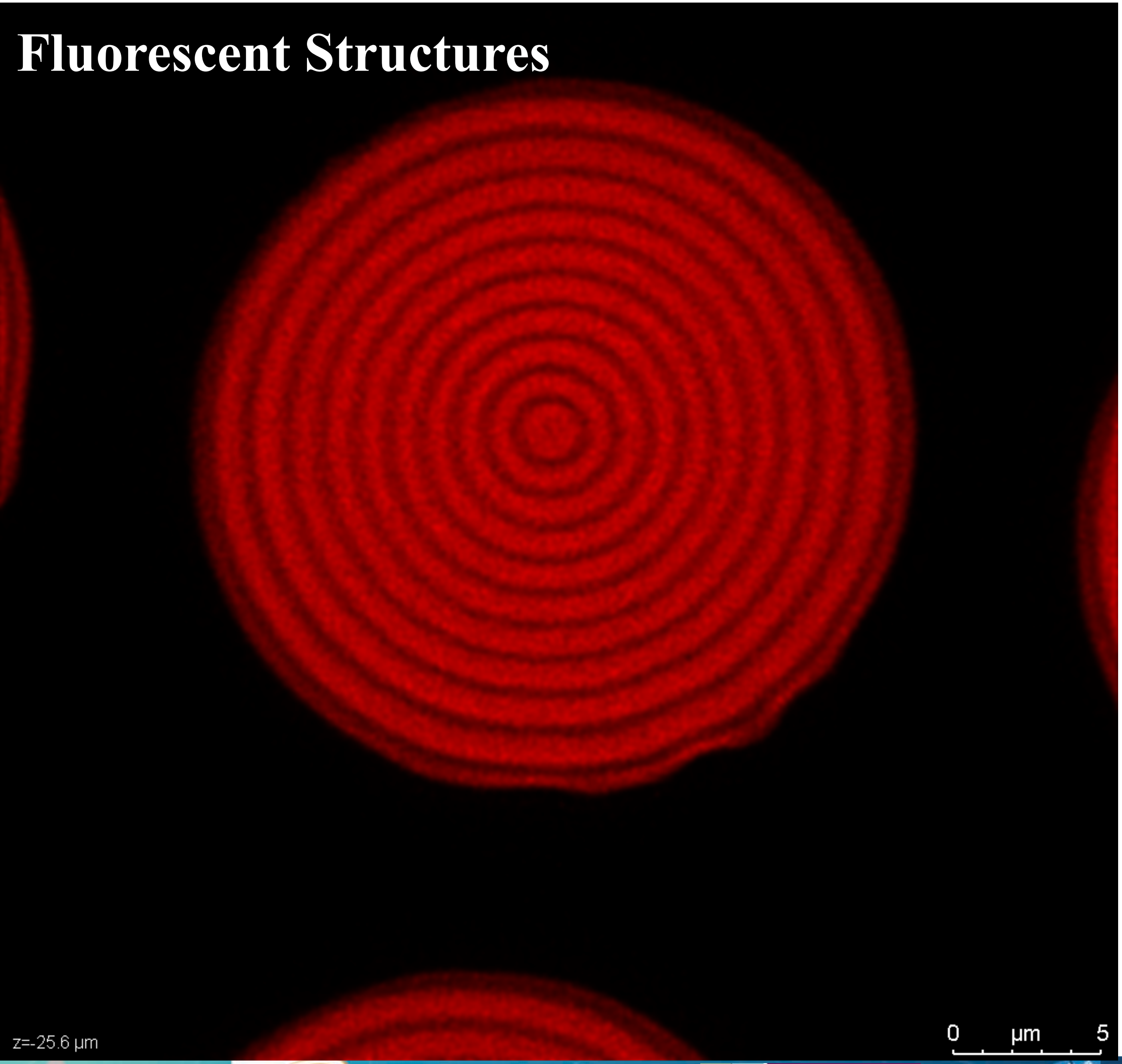
- Two photon absorption
- 3D structures

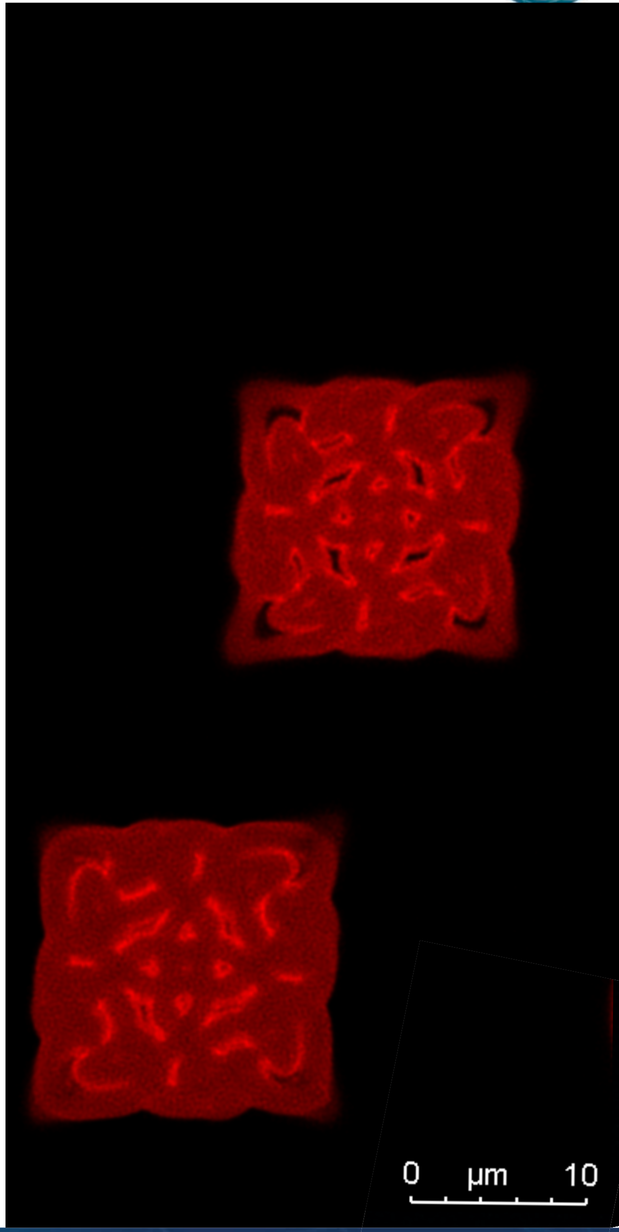
‘Daisy’ – Micro/Nano Scaled Porous Structure

(with Guang Zhong Yang, Imperial College London)



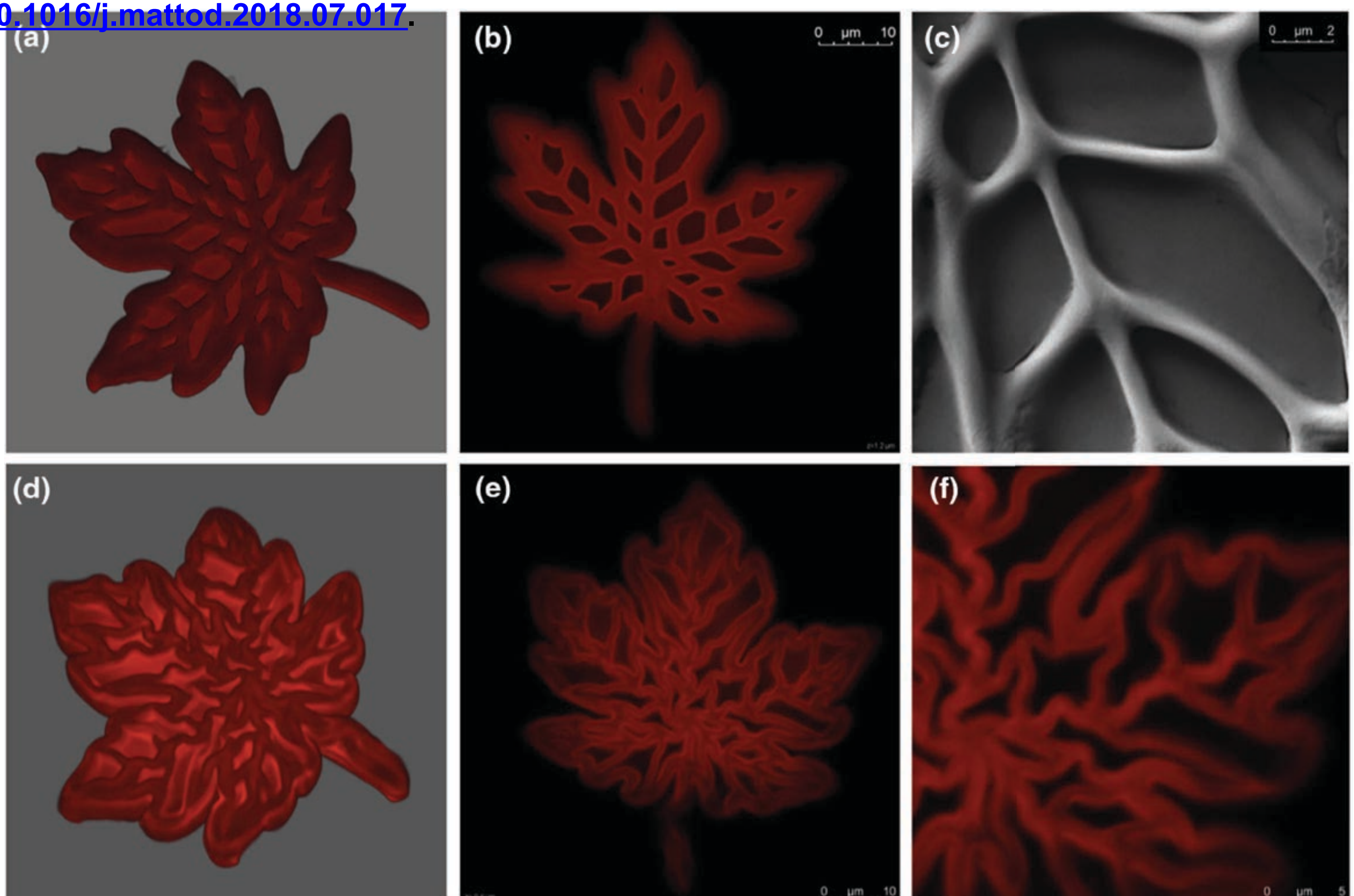
Rhodamine labeled gels (STED Microscopy)



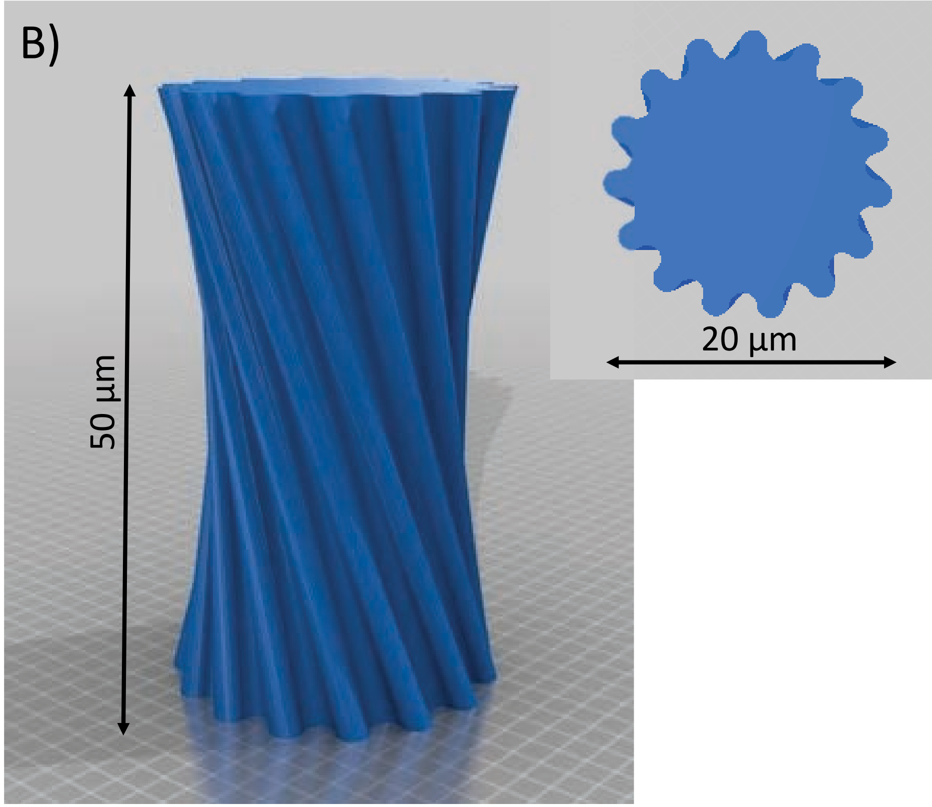


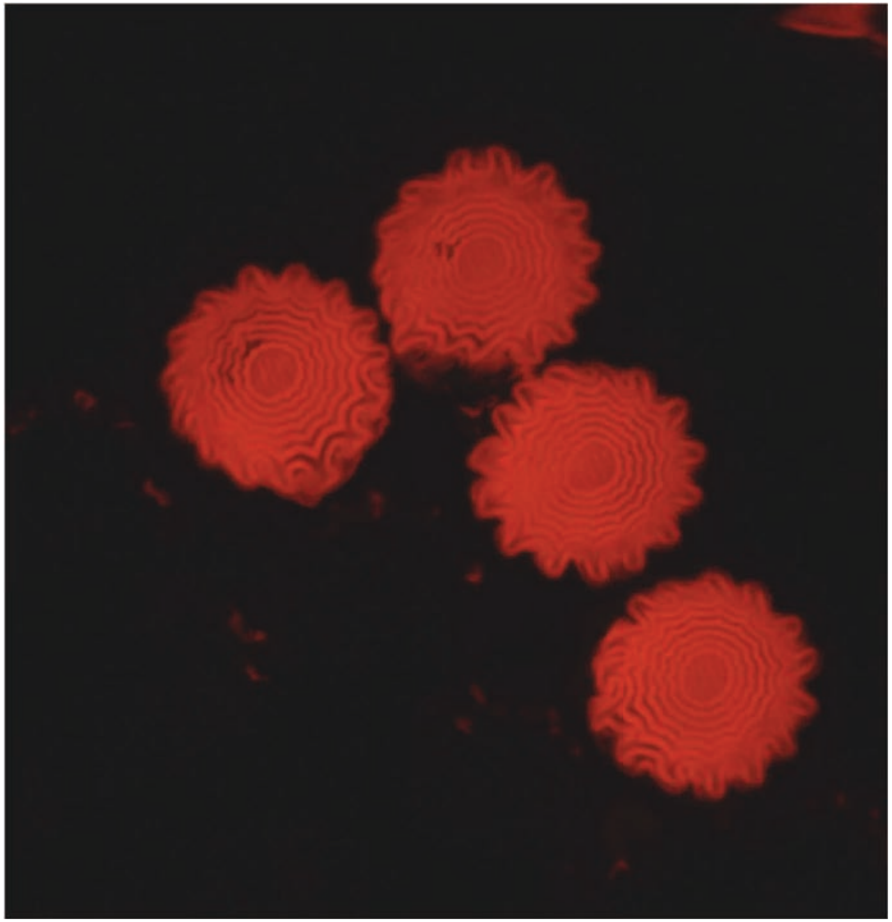
Thermally Responsive Maple Leaf PIL Structure

A. Tudor, C. Delaney, H. Zhang, A.J. Thompson, V.F. Curto, G.-Z. Yang, M.J. Higgins, D. Diamond, L. Florea, Fabrication of soft, stimulus-responsive structures with sub-micron resolution via two-photon polymerization of poly(ionic liquid)s, Materials Today. 21 (2018) 807–816. doi:10.1016/j.mattod.2018.07.017.



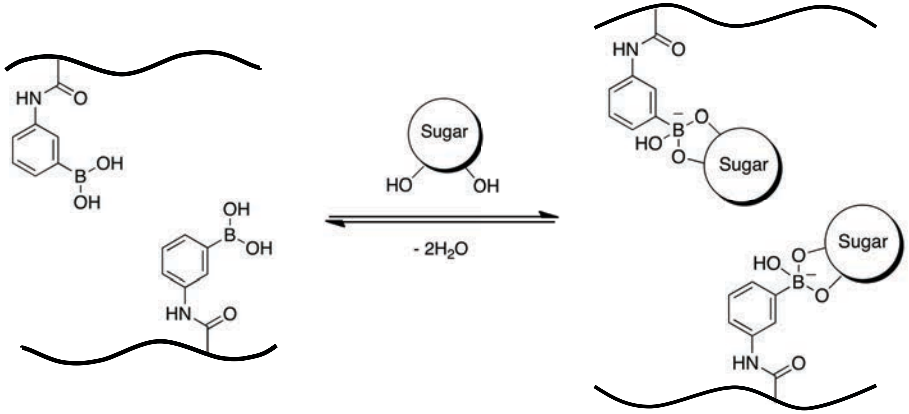
Twisting Motion from Spiral Ratchet Structure

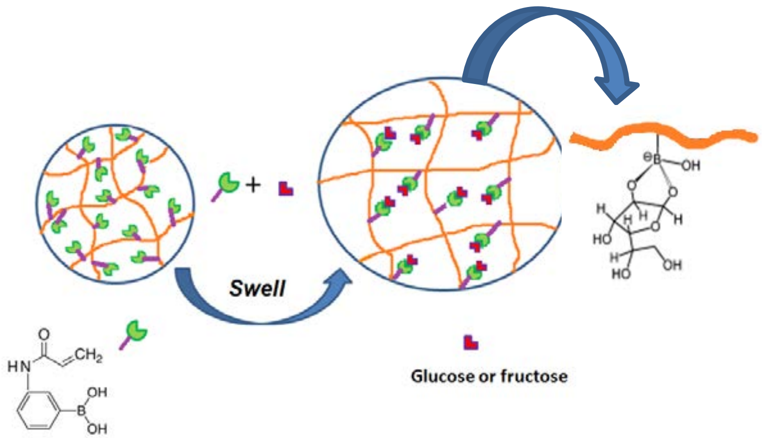




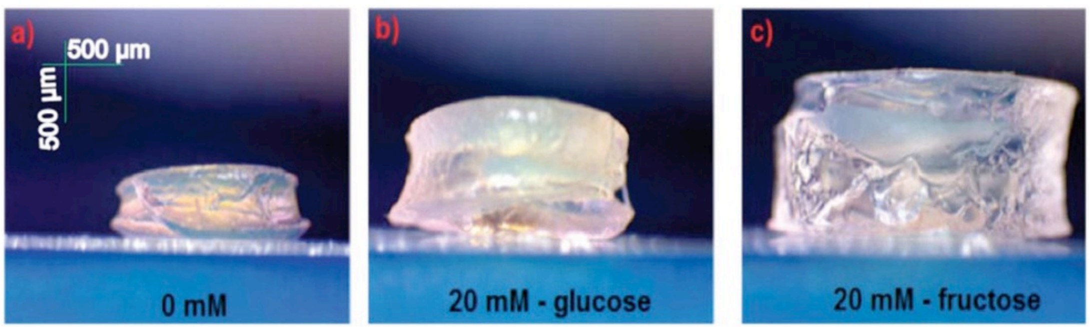
Materials Today. 21 (2018) 807–816. doi:10.1016/j.mattod.2018.07.017.

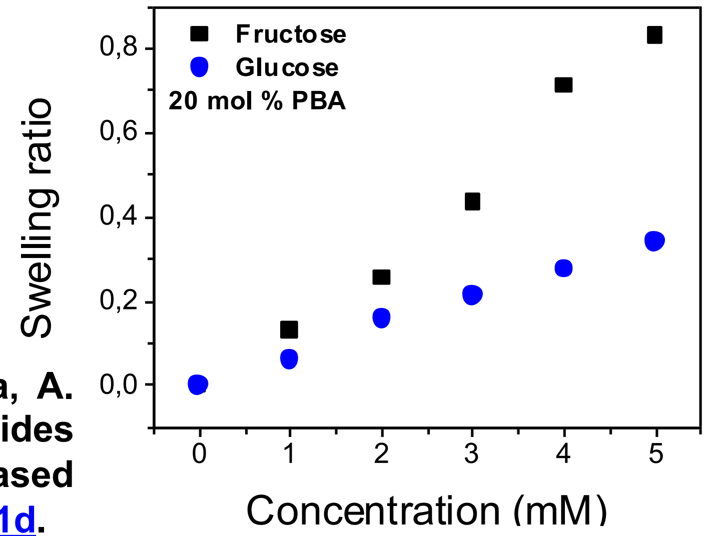
Sugar-Responsive Soft Hydrogels





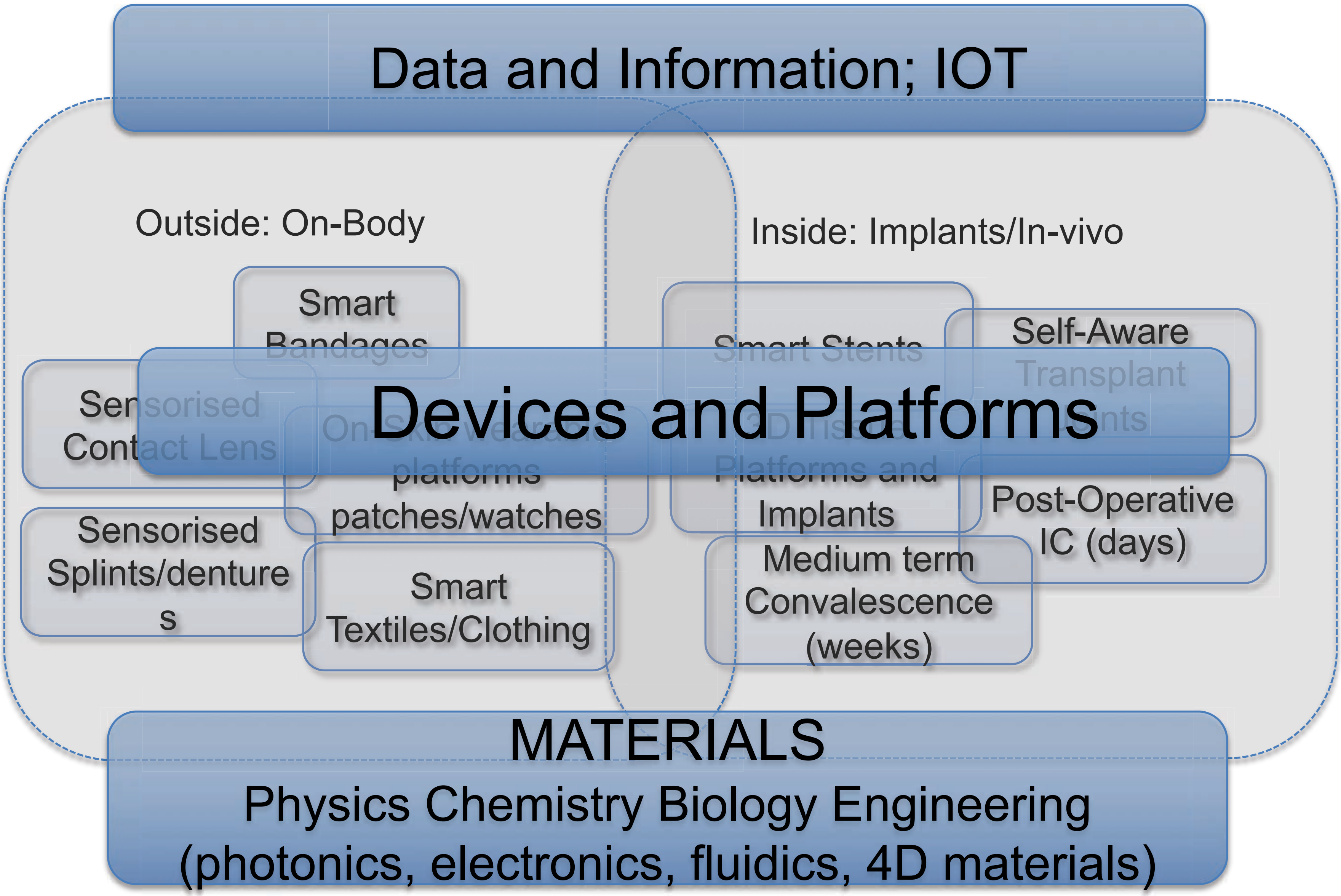
Acrylamide-*co*-PBA Polymer





C.M. Daikuzono, C. Delaney, H. Tesfay, L. Florea, O.N. Oliveira, A. Morrin, D. Diamond, Impedance spectroscopy for monosaccharides detection using responsive hydrogel modified paper-based electrodes, Analyst. 142 (2017) 1133–1139. doi:10.1039/c6an02571d.

Merging of Materials, Devices and Data



Thanks to…..

- NCSR, SCS, DCU
- Science Foundation Ireland & INSIGHT Centre
- Enterprise Ireland
- Research Partners – academic and industry
- H2020: Holifab Project

Jean Louis Viovy (Fluigent) , Mark Bowkett (TE Laboratories), Laurent Malaquin (LAAS)

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020

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