From Molecules to Devices: Can we Create Disruptive Technologies based on 3D Functionality at Multiple Dimensions to Solve Global Challenges?

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Université de Bordeaux

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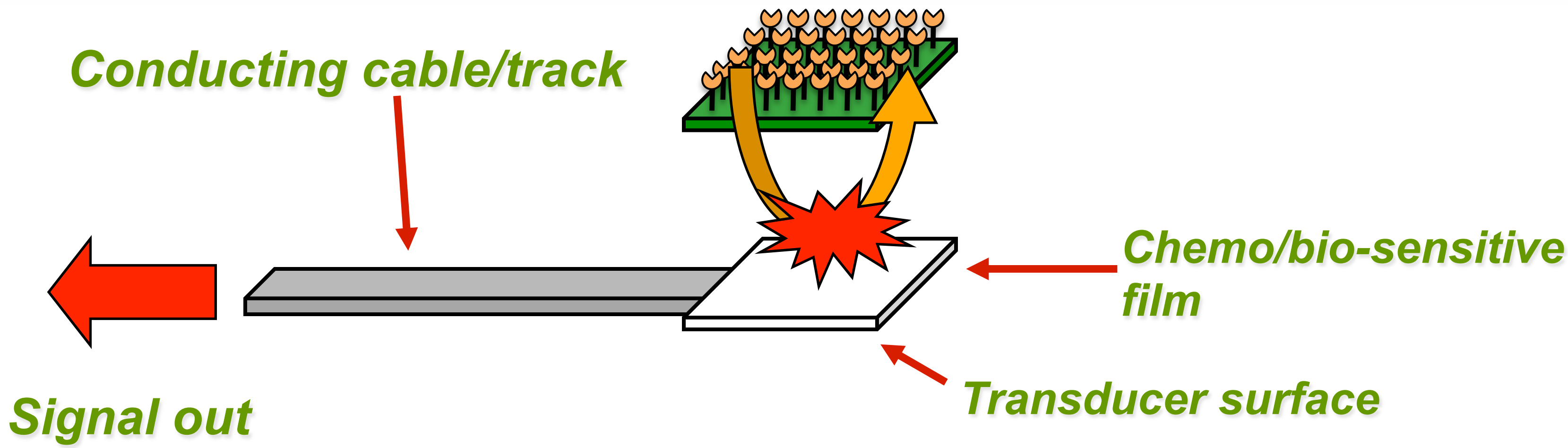
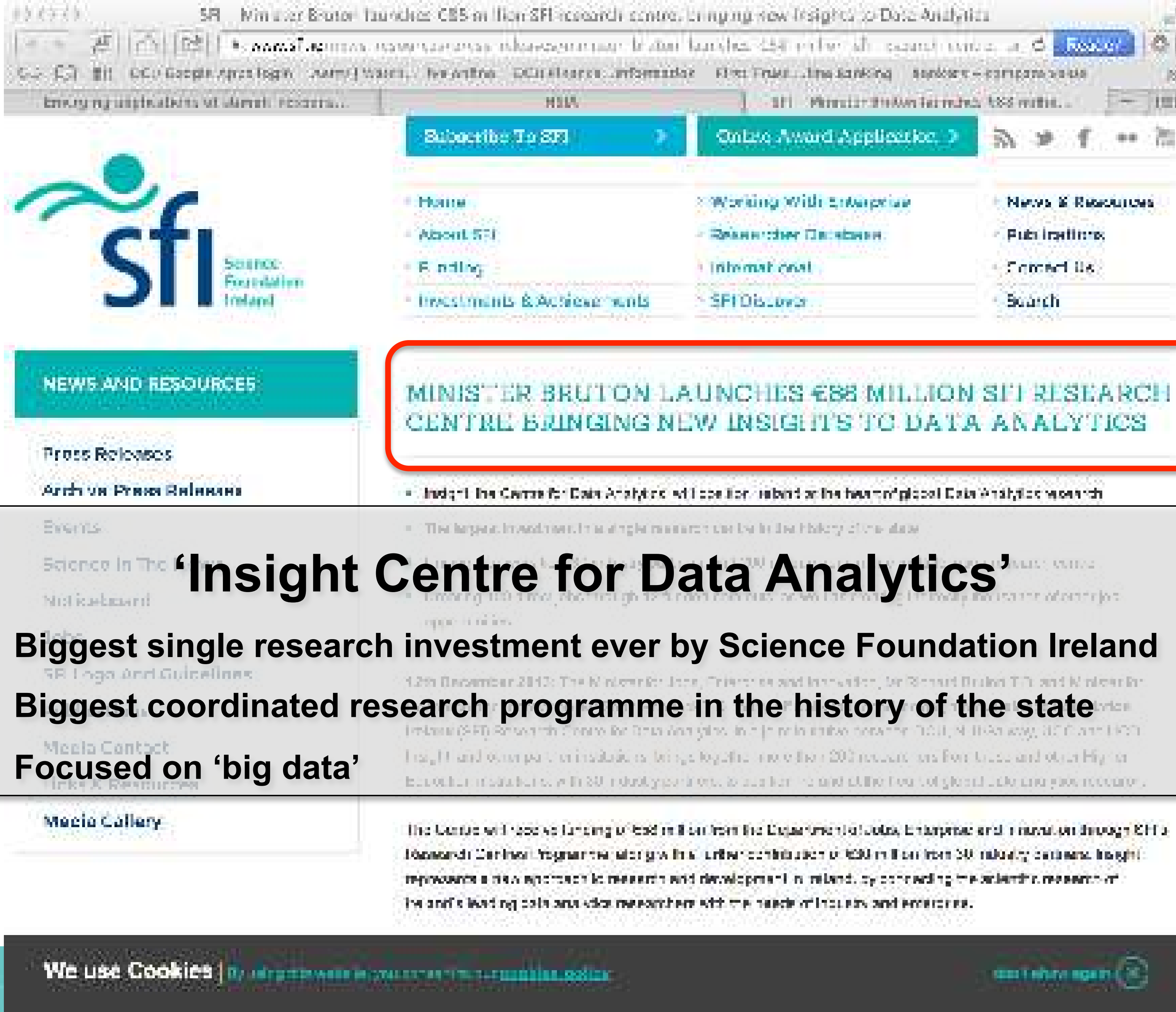
What is a Chemo/Bio-Sensor?

'a device, consisting of a transducer and a chemo/bio-sensitive film/membrane, that generates a signal related to the concentration of particular target analyte in a given sample'



Chemo/Bio-sensing involves selective **BINDING** & **TRANSDUCTION** on the device surface; this also implies the target analyte MUST meet the device surface (**LOCATION** & **MOVEMENT**). It provides a signal observable in the macroscopic world (**COMMUNICATION**)



‘Insight Centre for Data Analytics’

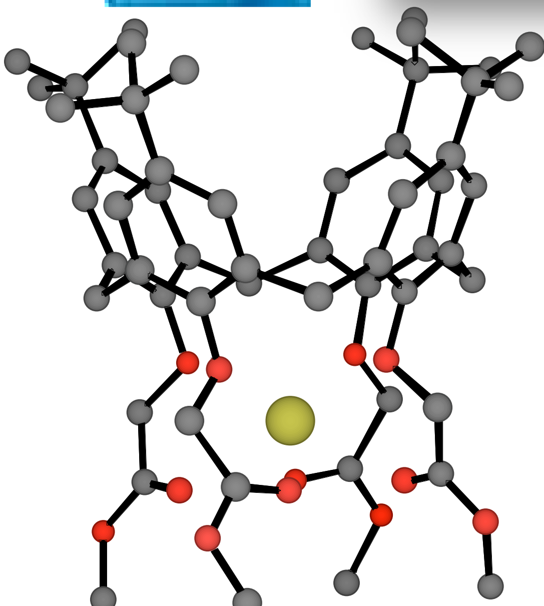
- Biggest single research investment ever by Science Foundation Ireland
- Biggest coordinated research programme in the history of the state
- Focused on ‘big data’

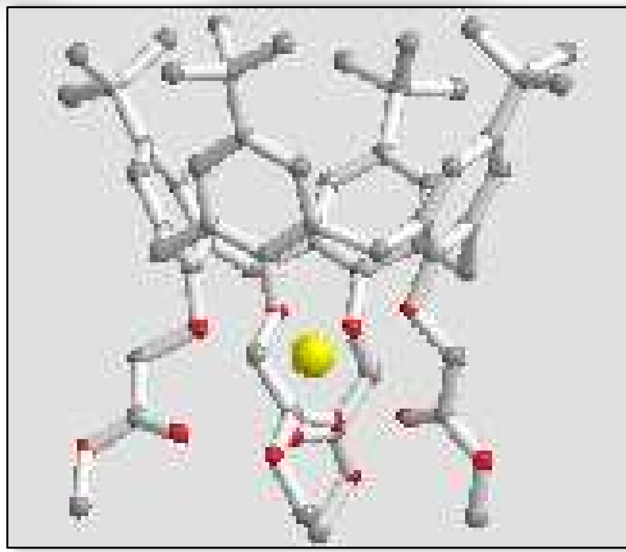
Keynote Article: August 2004, Analytical Chemistry (ACS)

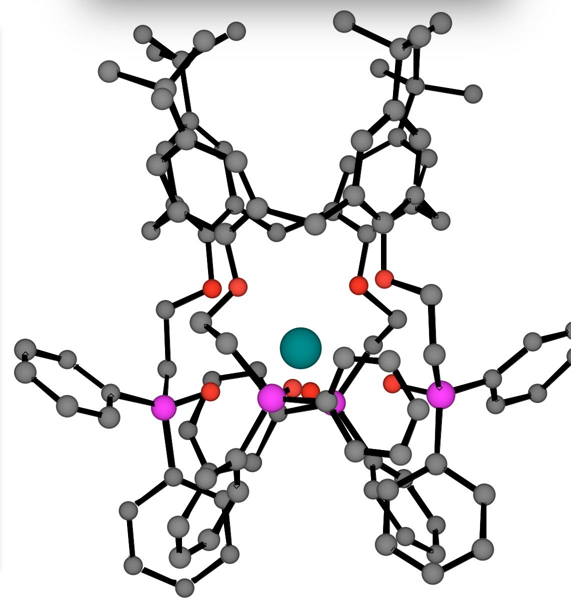
Dermot Diamond, Anal. Chem., 76 (2004) 278A-286A
(Ron Ambrosio & Alex Morrow, IBM TJ Watson)

Scalability depends fundamentally of the availability of **affordable** Chem/Bio-sensing devices that can function **autonomously** for **years** in inaccessible/remote locations?

History: Calixarenes, 1983/5

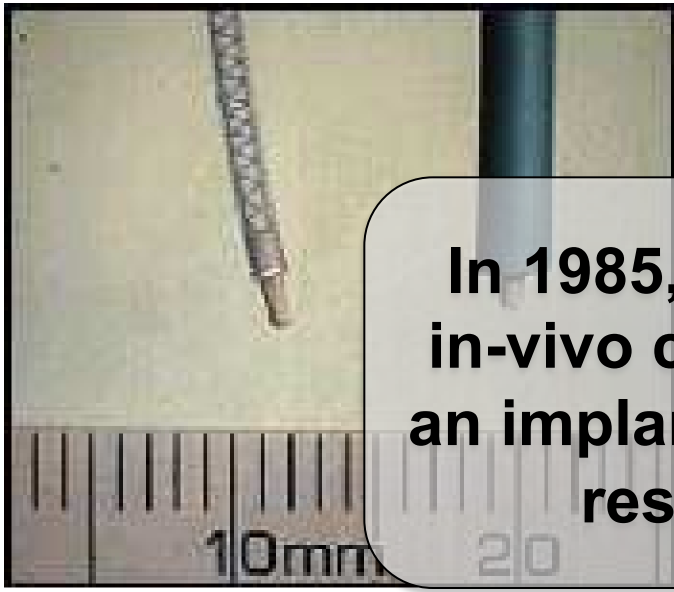






Neutral Carrier Based Ion-Selective Electrodes, D.Diamond, Anal. Chem. Symp. Ser., 25 (1986) 155.
A sodium Ion-Selective Electrode based on Methyl p-t-Butyl Calix[4]aryl Acetate as the Ionophore, D.Diamond, G.Svehla, E.Seward,and M.A.McKervey, Anal. Chim. Acta., 204 (1988) 223-231.
Sodium Selective Polymeric Membrane Electrodes based on Calix[4]arene Ionophores, A.Cadogan, D.Diamond, M.R.Smyth, M.Deasy, M.A.McKervey and S.J.Harris, Analyst 114 (1989) 1551.

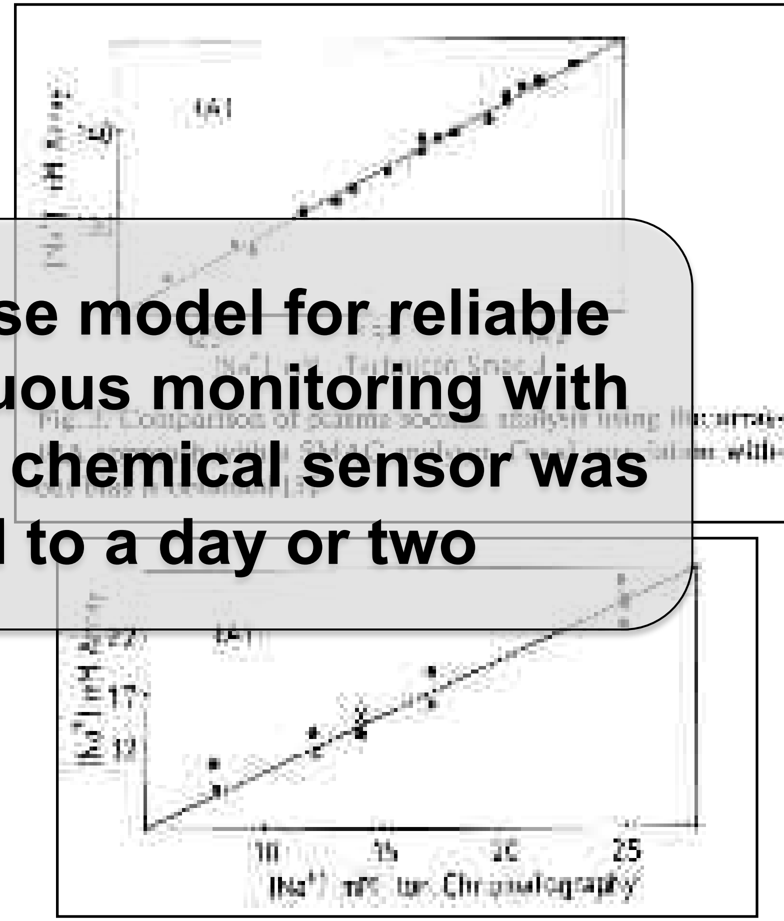
Blood Analysis; Implantible Sensors



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

Dr. David Band, St Thomas's Hospital London

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



Anal. Chem., *<u>64</u> (1992) 1721-1728.*

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

Abbott Freestyle 'Libre'

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

Welcome to flash glucose monitoring!

- '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

ACS Nano Cover and Editorial

‘Grand Plans for Nano’, (9) 12 December 2015

Grand Plans for Nano

This year, nanoscience and nanotechnology have been called front and center to help address the grand challenges that the world faces. Our community has been asked to suggest future challenges, and the first such crowd-sourced grand challenge has been announced by the White House Office of Science and Technology Policy.[1−5] As we have said on these pages, we believe that nanoscientists and nanotechnologists around the world have special roles to play in bringing together expertise from diverse fields in order to tackle important tasks both large and small.[2] Indeed, our higher perspectives and communication across fields have great value globally in key areas such as devices, energy, health, and safety.[6−10]

What about the environment – water quality monitoring!

Remote (Continuous) Sensing Challenges: Platform and Deployment Hierarchies

Physical Transducers –low cost, reliable, low power demand, long life-time

Thermistors (temperature), movement, location, power,, light level, conductivity, flow, sound/audio, !!

Chemical Sensors – more complicated, need regular calibration, more costly to implement

Electrochemical, Optical, .. For metal ions, pH, organics!

Biosensors – the most challenging, very difficult to work with, die quickly, single shot (disposable) mode dominant use model

Due to the delicate nature of biomaterials enzymes, antibodies!.

Increasing difficulty & cost

Increasing scalability

Gas/Air Sensing – easiest to realise

Reliable sensors available, relatively low cost

Integrate into platforms, develop IT infrastructure, GIS tools, Cloud Computing

On-land Water/ Monitoring

More accessible locations

Target concentrations tend to be higher

Infrastructure available

Marine Water

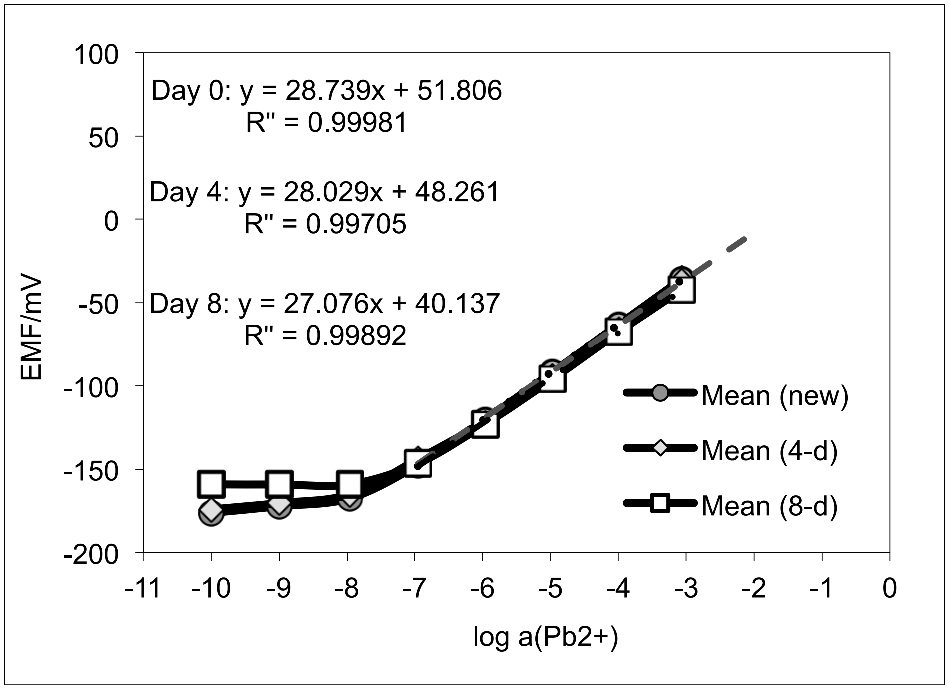
Challenging conditions

Remote locations & Limited infrastructure

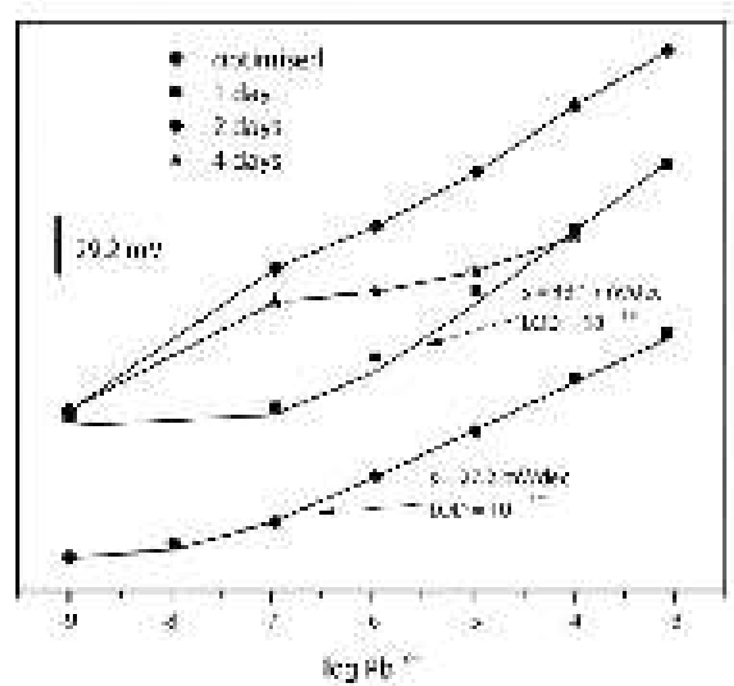
Concentrations tend to be lower and tighter in range

Change in Electrode Function over Time

See Electrochimica Acta 73 (2012) 93–97



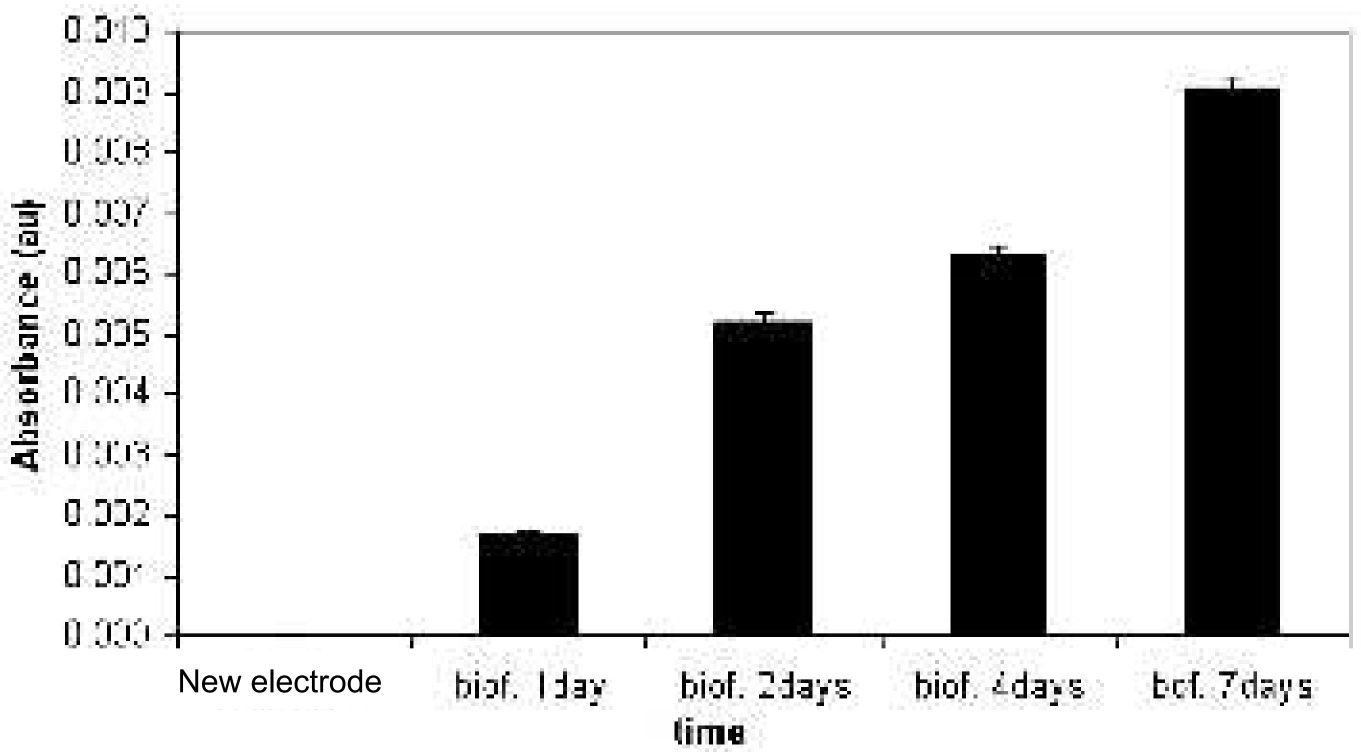
stored in 10^{-9}M Pb^{2+}, pH=4



Continuous contact with river water

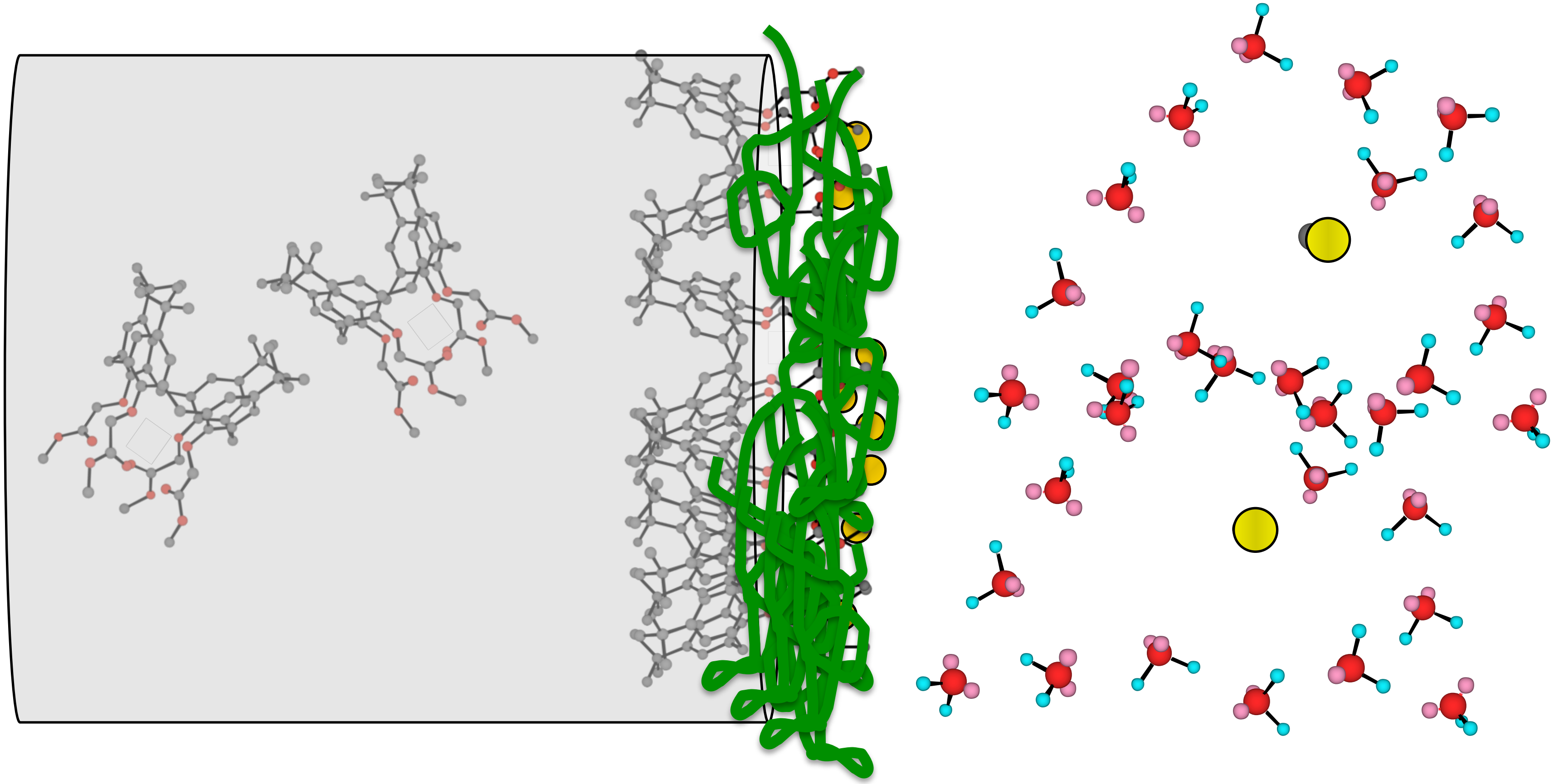
Conventional PVC-membrane based ISEs

Biofilm Formation on Sensors



- **Electrodes exposed to local river water (Tolka)**
- **‘Slime test’ shows biofilm formation happens almost immediately and grows rapidly**

Control of membrane interfacial exchange & binding processes

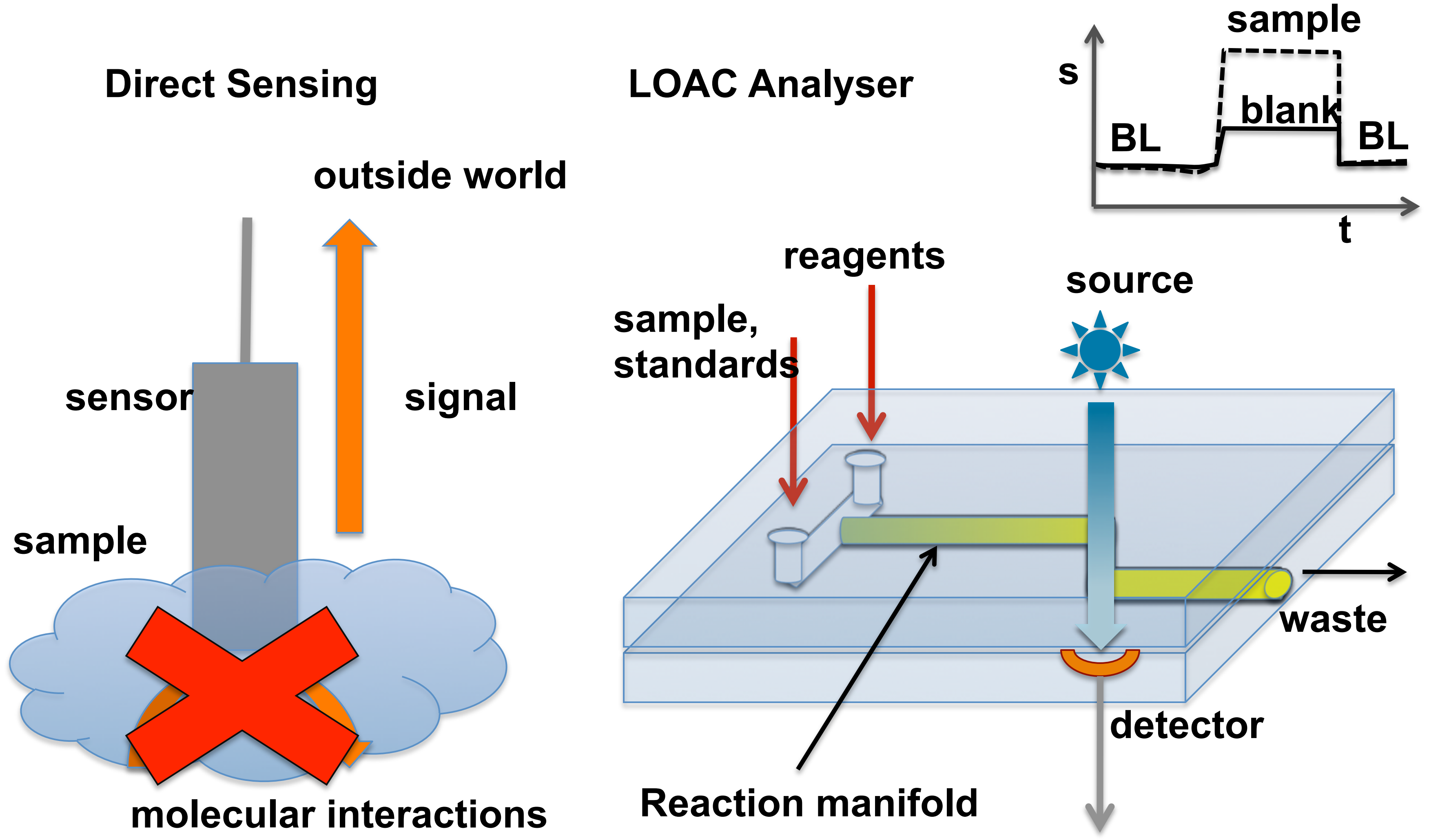


Remote, autonomous chemical sensing is a tricky business!

What is the core issue??

- Simple, bare chem/biosensors do not function reliably EXCEPT as single shot or short-term use devices – regular recalibration required (if they manage to keep functioning)
- Sensor surfaces change as soon as they are exposed to the real world – biofouling, interferents, leaching of components!.
- Current systems work for days (after decades of research)
- Implants must work for 10 years!
- Environmental Sensors are far too expensive

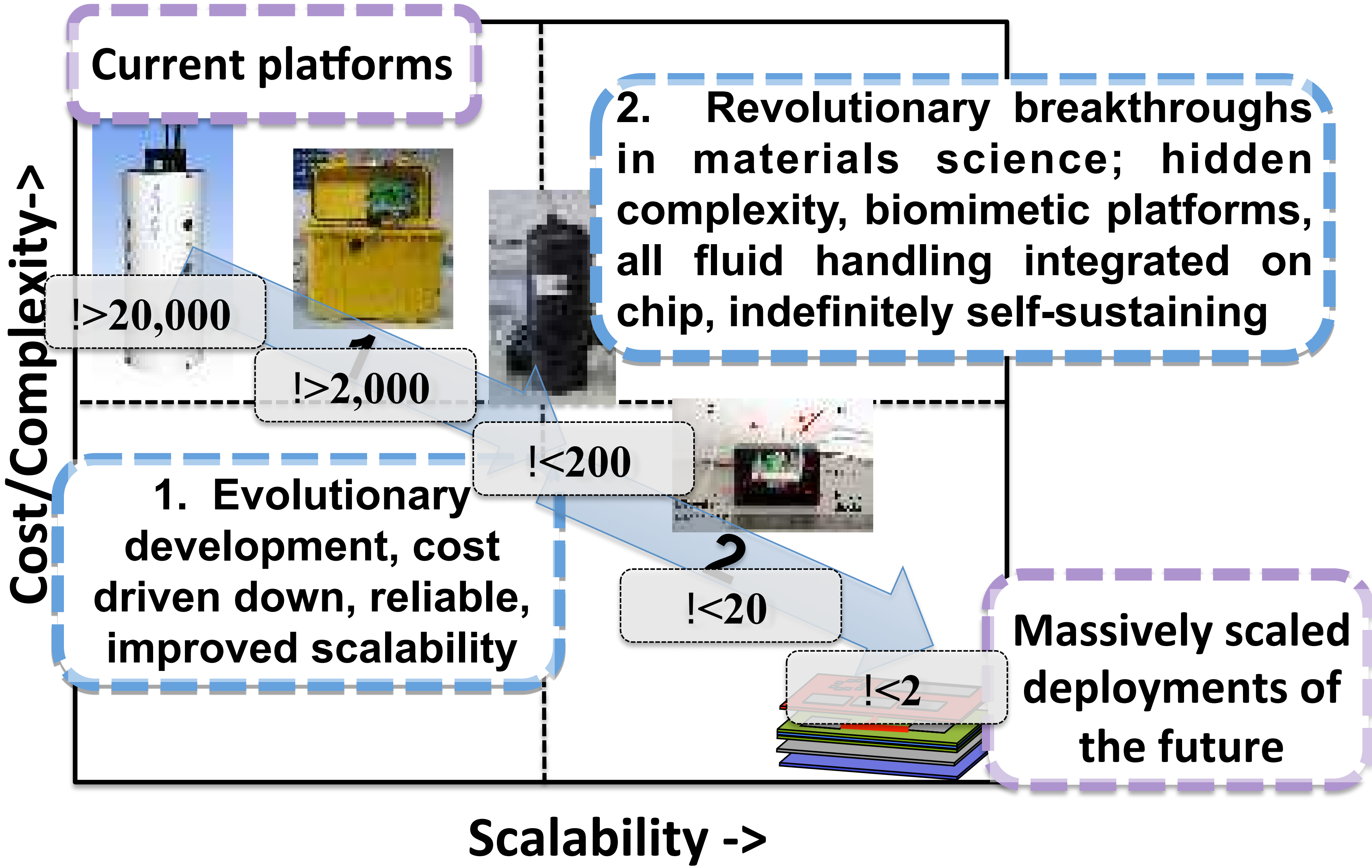
Direct Sensing vs. Reagent Based LOAC/ufluidics



Microfluidics, to date, has been largely focused on the development of science and technology, and on scientific papers, <u>rather than on the solution of problems</u>

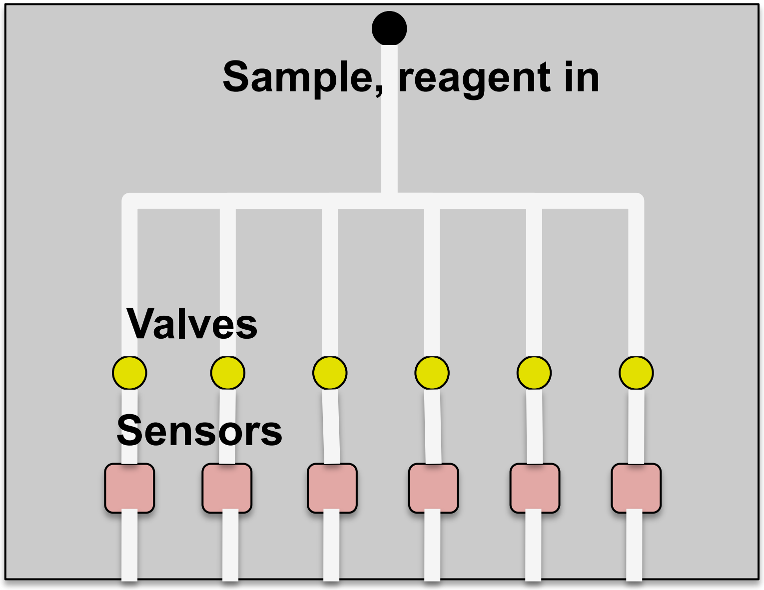
Editorial 'Solving Problems', George Whitesides, Lab Chip 10 (2010) 2317-2318

Achieving Scale-up



Lets Make a Start: Extend Period of Use via Multiple short-use Sensors!.?

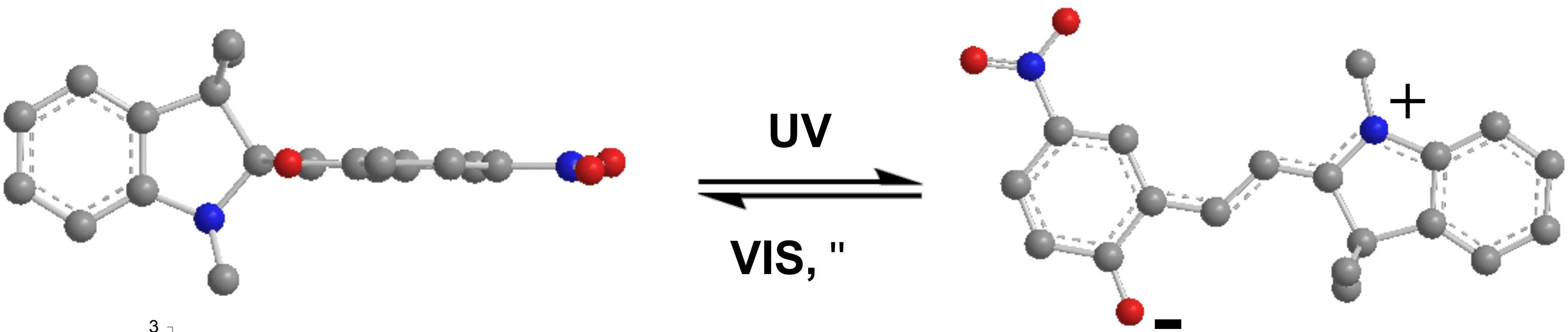
- If each sensor has a functional lifetime of 1 week!.
- And these sensors are very reproducible!.
- And they are very stable in storage (up to several years)

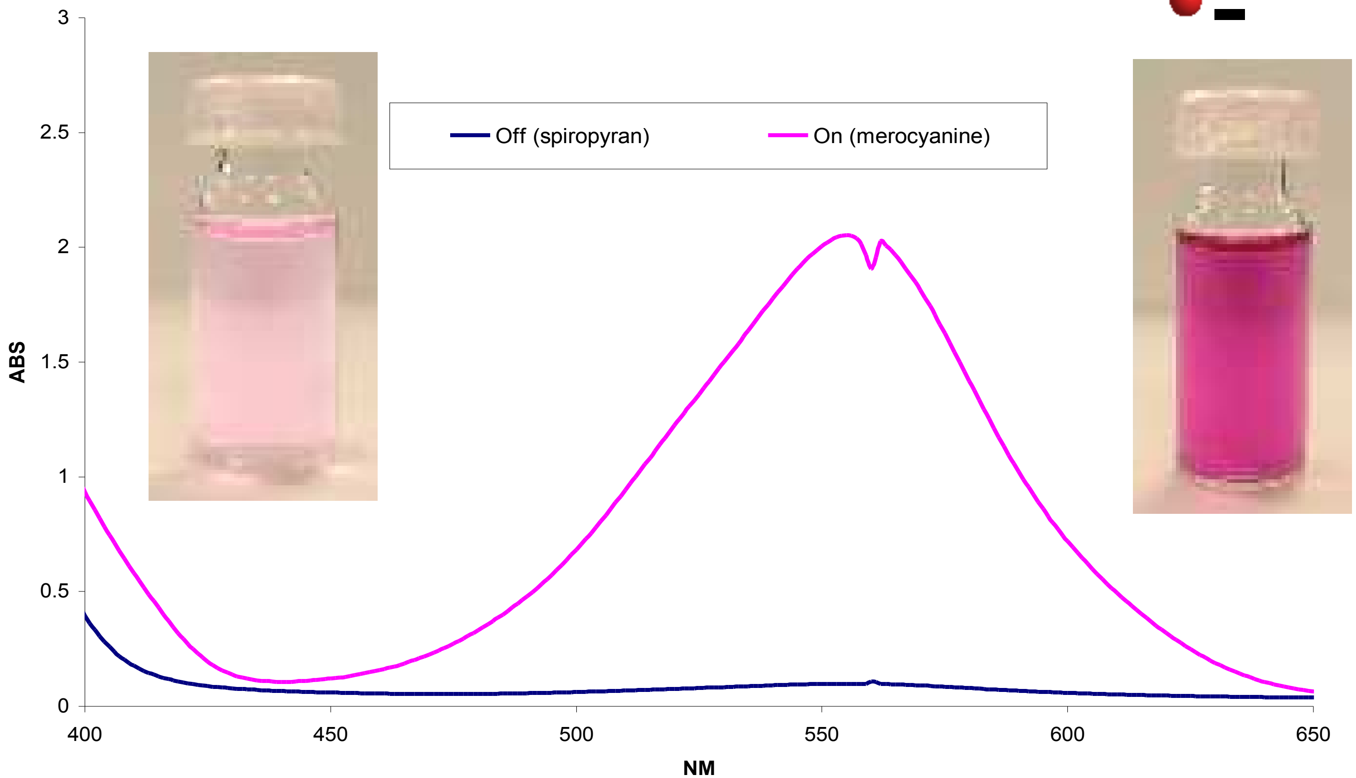


Then 50 sensors when used sequentially could provide an aggregated in-use lifetime of around 1 year

But now we need multiple valves integrated into a fluidic platform to select each sensor in turn

Photoswitchable Soft Actuators

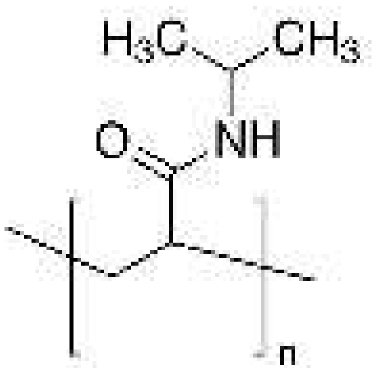




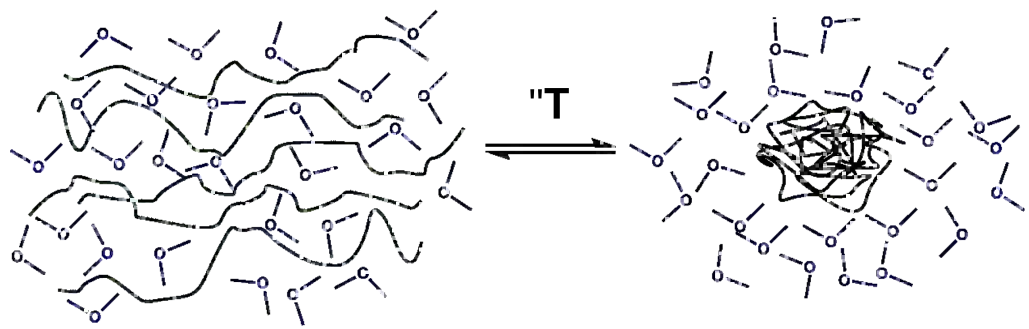
Poly(*N*-isopropylacrylamide)

- 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**

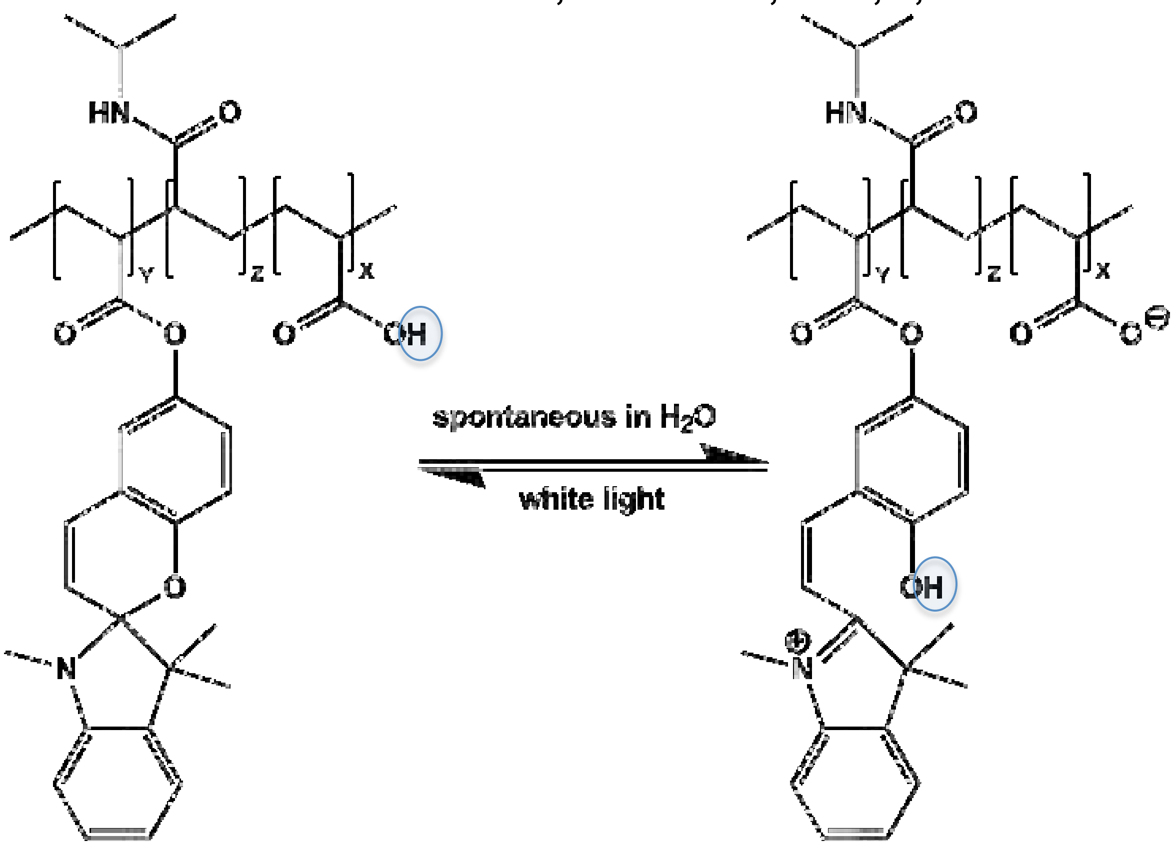


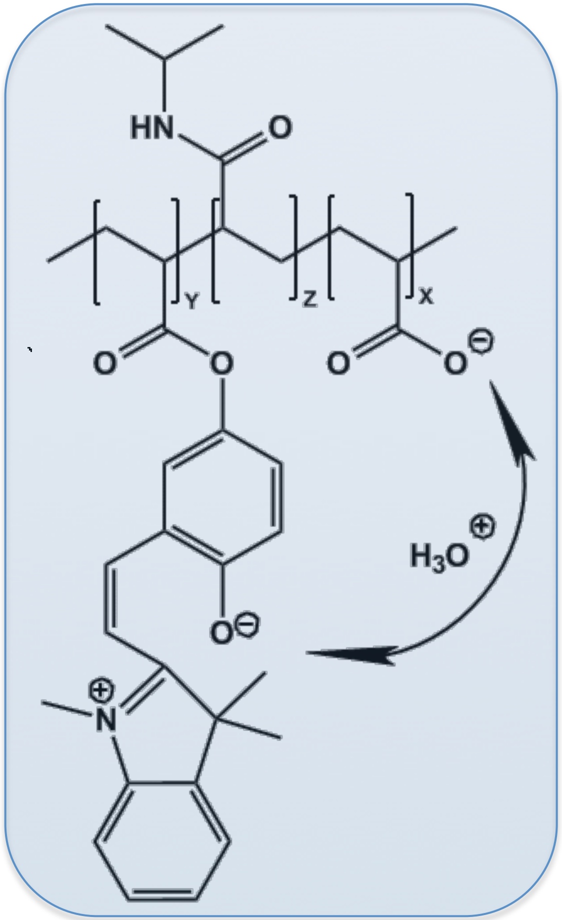
Hydrated Polymer Chains

Loss of bound water
-> polymer collapse

Self protonating photoresponsive gel

Ziolkowski *et al.*, Soft Matter, 2013, 9, 8754–8760





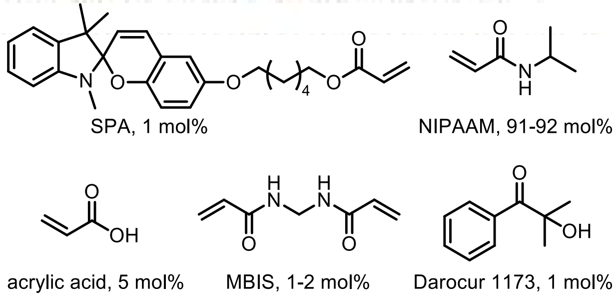
Previously proton source was external (acidic soln. required)
Protons, counter ions & solvent diffuse into/out of the gel

Now the proton exchange is 'internalised'
The proton population is essentially conserved

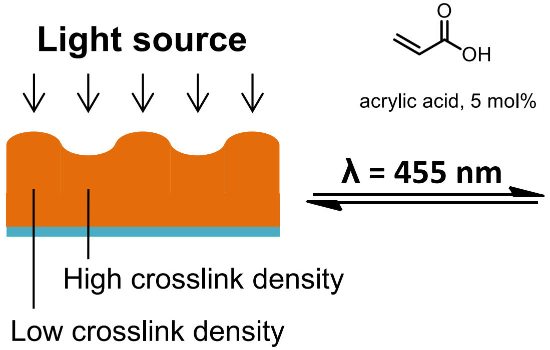
Photocontrol of Surface Features – Channel Surfaces Become 'Active'

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

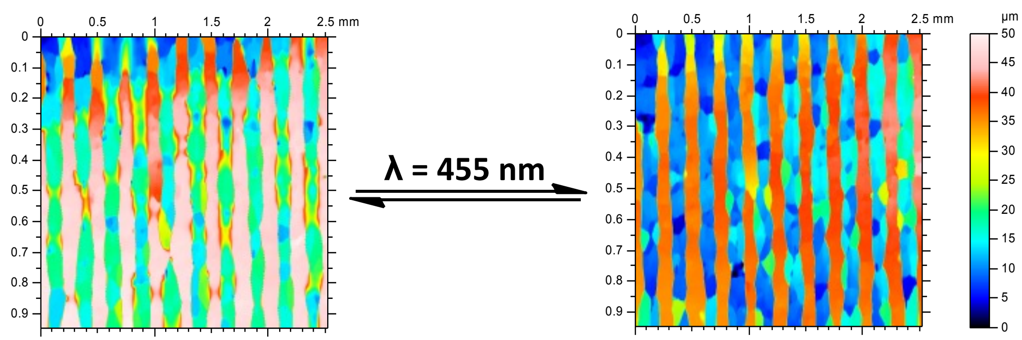
Photoswitchable Ratchet Surface Topographies Based on Self-Protonating Spiropyran–NIPAAM Hydrogels

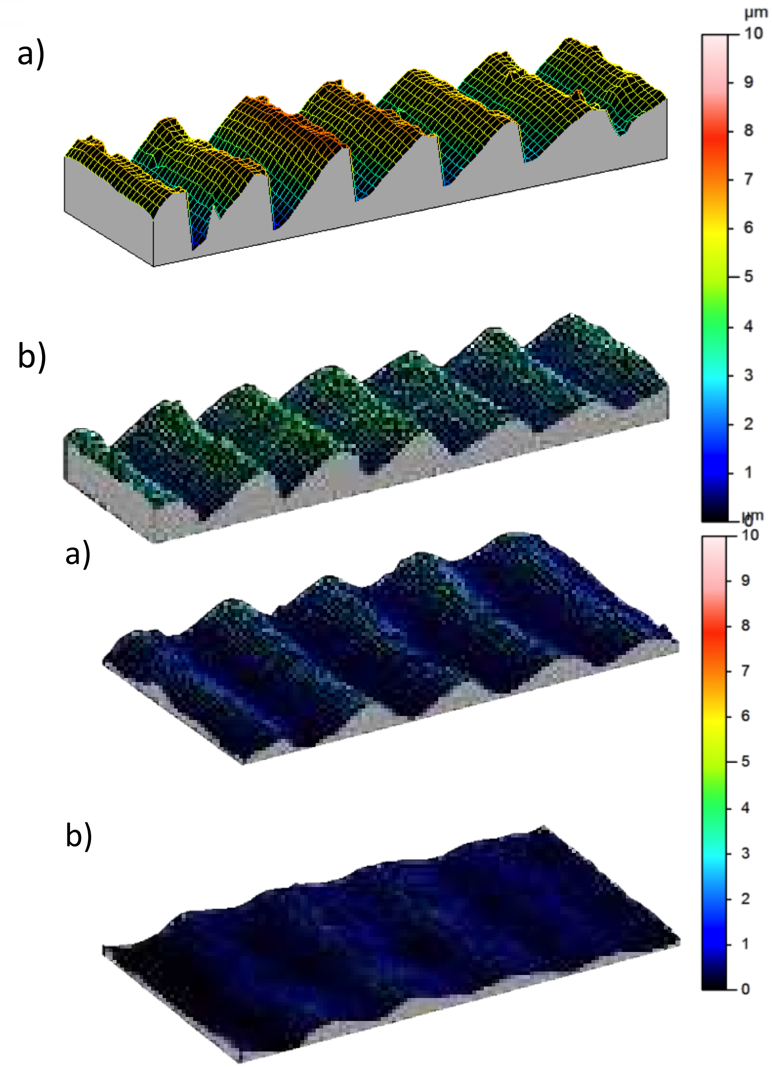


a)

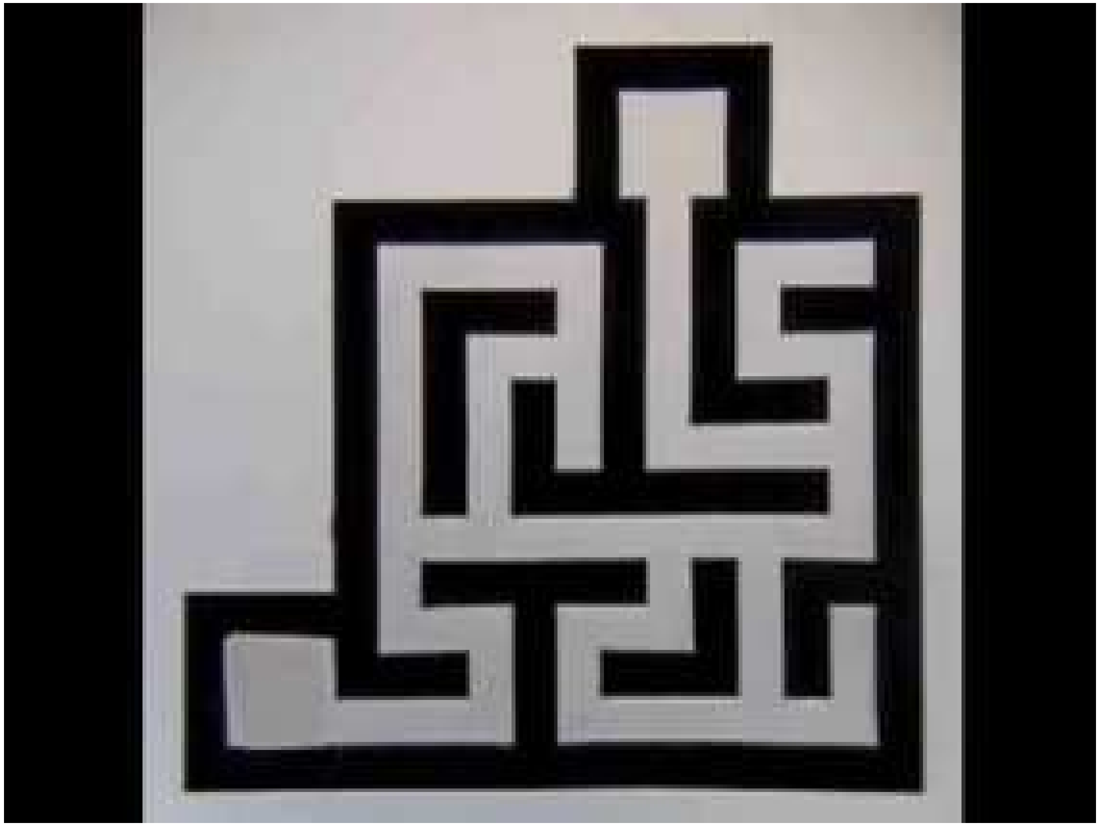


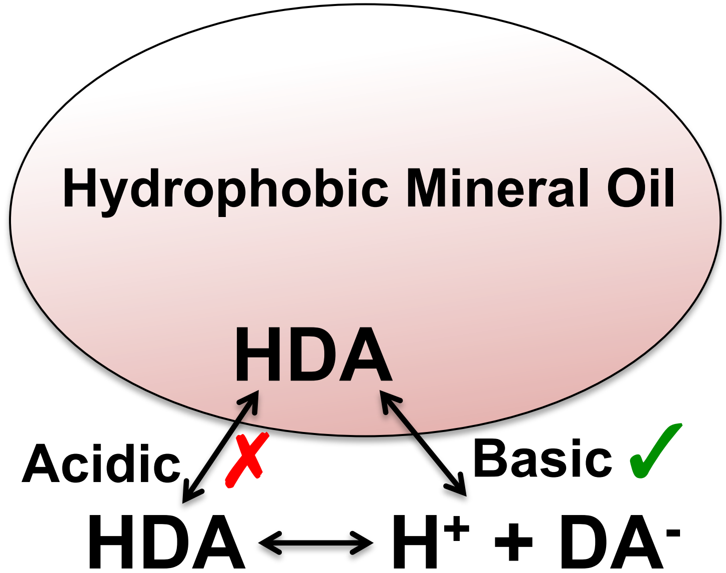
b)





Chemotactic Systems



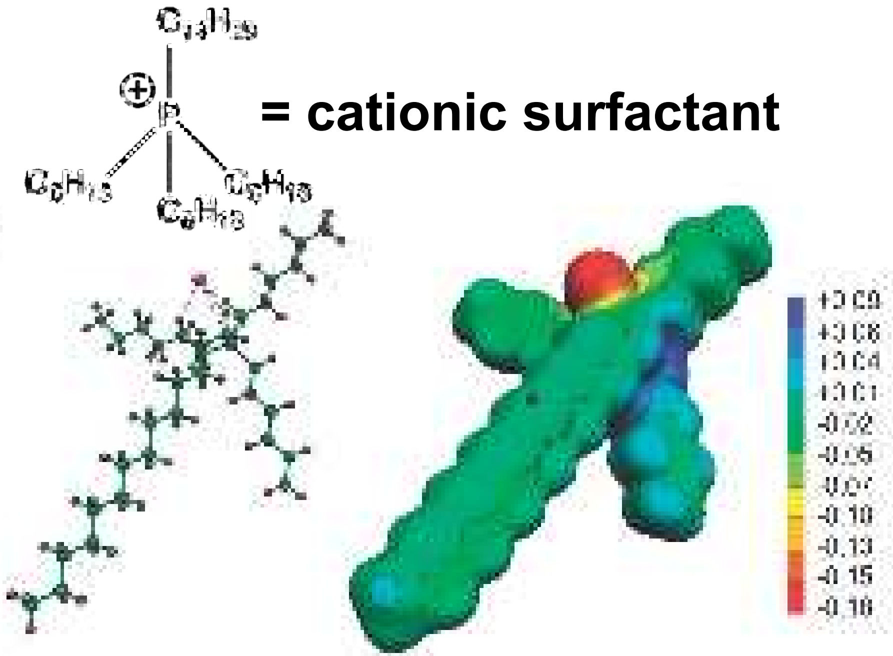


In a pH gradient, DA⁻ is preferentially transferred to the aqueous phase at the more basic side of the drop.

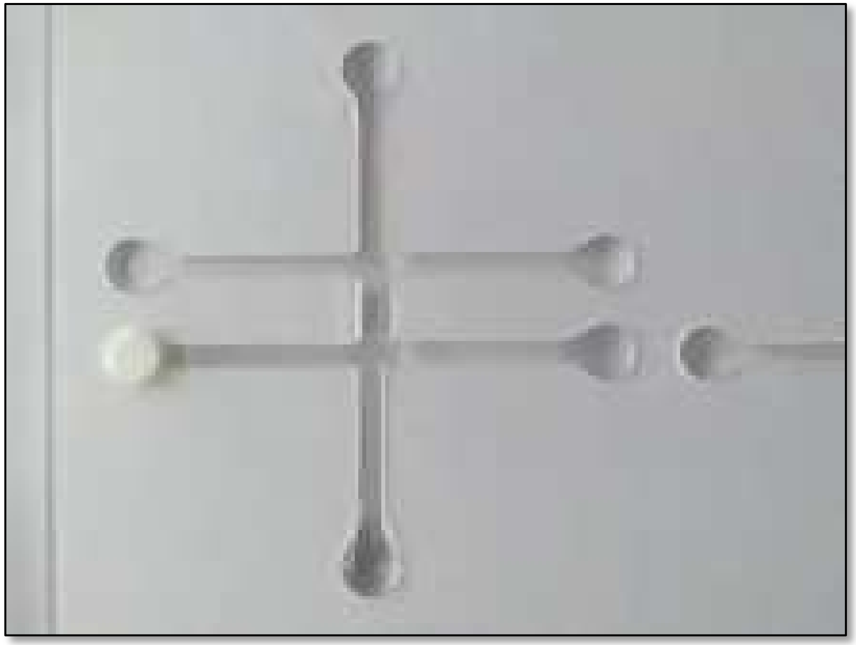
Published on Web 11/01/2010 (speed ~x4): channels filled with KOH (pH 12.0-12.3 + surfactant; agarose gel soaked in HCl (pH 1.2) sets up the pH gradient; droplets of mineral oil or DCM containing 20-60% 2-hexyldecanoic acid + dye. Droplet speed ca. 1-10 mm/s; movement caused by convective flows arising 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.*

We can do the same with IL Droplets



= cationic surfactant



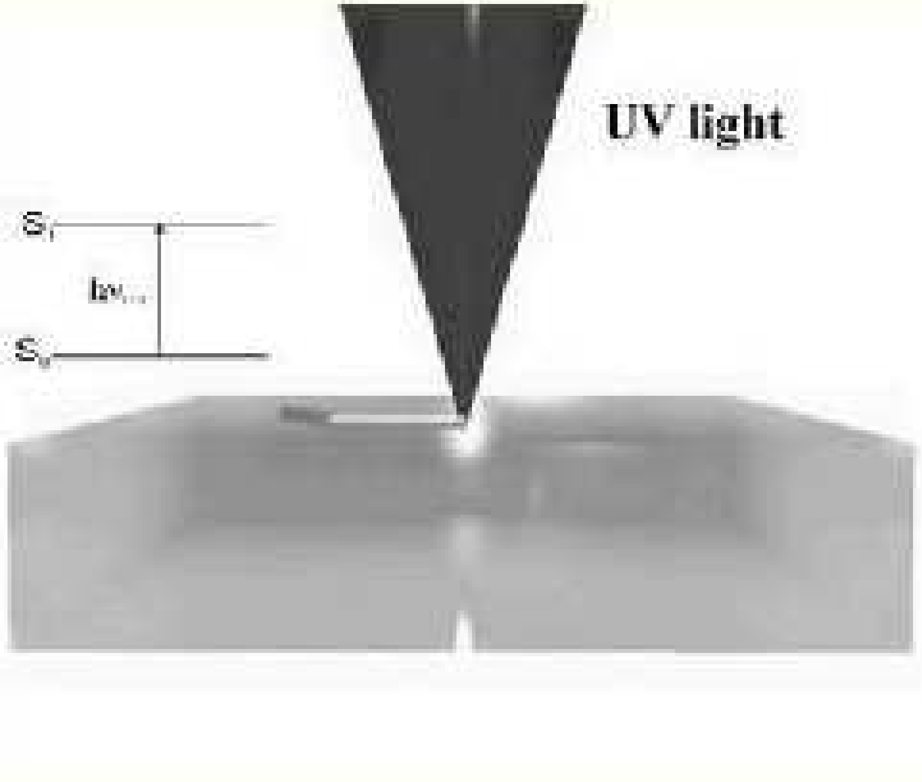
Trihexyl(tetradecyl)phosphonium chloride ($[P_{6,6,6,14}][Cl]$) droplets with a small amount of 1-(methylamino)anthraquinone red dye for visualization. The droplets spontaneously follow the gradient of the Cl^- ion which is created using a polyacrylamide gel pad soaked in 10^{-2} M HCl; A small amount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

Self-propelled chemotactic ionic liquid droplets, W. Francis, C. Fay, L. Florea, D. Diamond, Chemical Communications, 51 (2015) 2342-2344.

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.

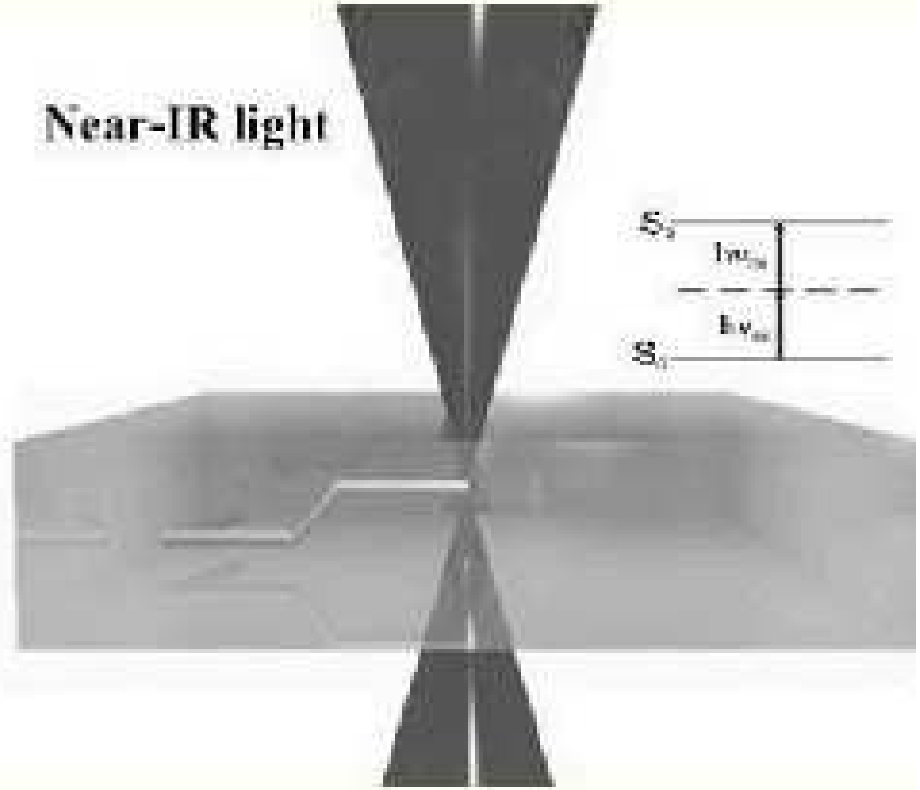
2-Photon Polymerisation

Stereolithography



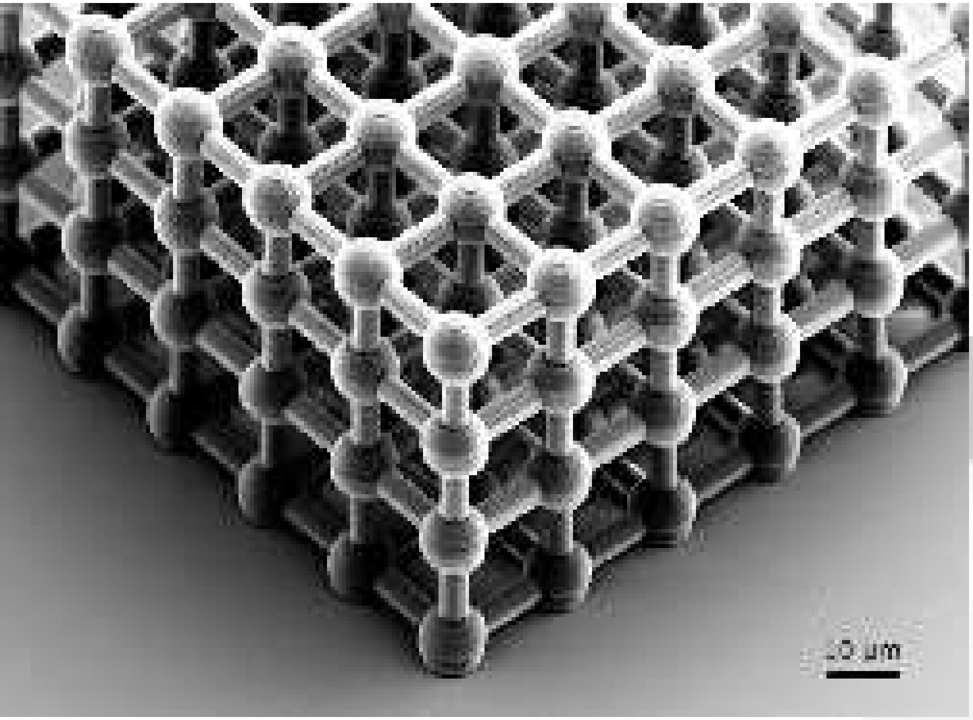
- Single photon absorption
- 2D patterns

Two-photon polymerisation



- Two photon absorption
- 3D structures

2-Photon Polymerisation



http://www.nanoscribe.de/

Near Term Goals (5Years)

Data and Information; IOT

Outside: On-Body

- Smart Bandages
- Sensorised Contact Lens
- platforms patches/watches
- Sensorised Splints/ dentures
- Smart Textiles/ Clothing

Inside: Implants/In-vivo

- Smart Stents
- Self-Aware Transplant
- Platforms and Implants
- Post-Operative IC (days)
- Medium term Convalescence (weeks)

Devices and Platforms

MATERIALS

Physics Chemistry Biology Engineering (photonics, electronics, fluidics, 4D materials)

Time of EXCITING OPPORTUNITY!

- **New materials with exciting characteristics and unsurpassed potential!**
- **Combine with emerging technologies and techniques for exquisite control of 3D morphology**
- **And greatly improved methods for characterisation of structure and activity**
- **Learn from nature – e.g. more sophisticated circulation systems for ‘self-aware’ sensing devices!**

HAVE FUN!

Thanks to!..

- Members of my research group
- NCSR, DCU
- Science Foundation Ireland & INSIGHT Centre
- Enterprise Ireland
- Research Partners – academic and industry
- EU Projects: NAPES, CommonSense, Aquawarn, MASK-IRSES, OrgBio

Thanks for the invite!

NAPES

COMMON SENSE
MARINE SENSORS - MARINE MONITORING

aquawarn

sfi DCU UCC