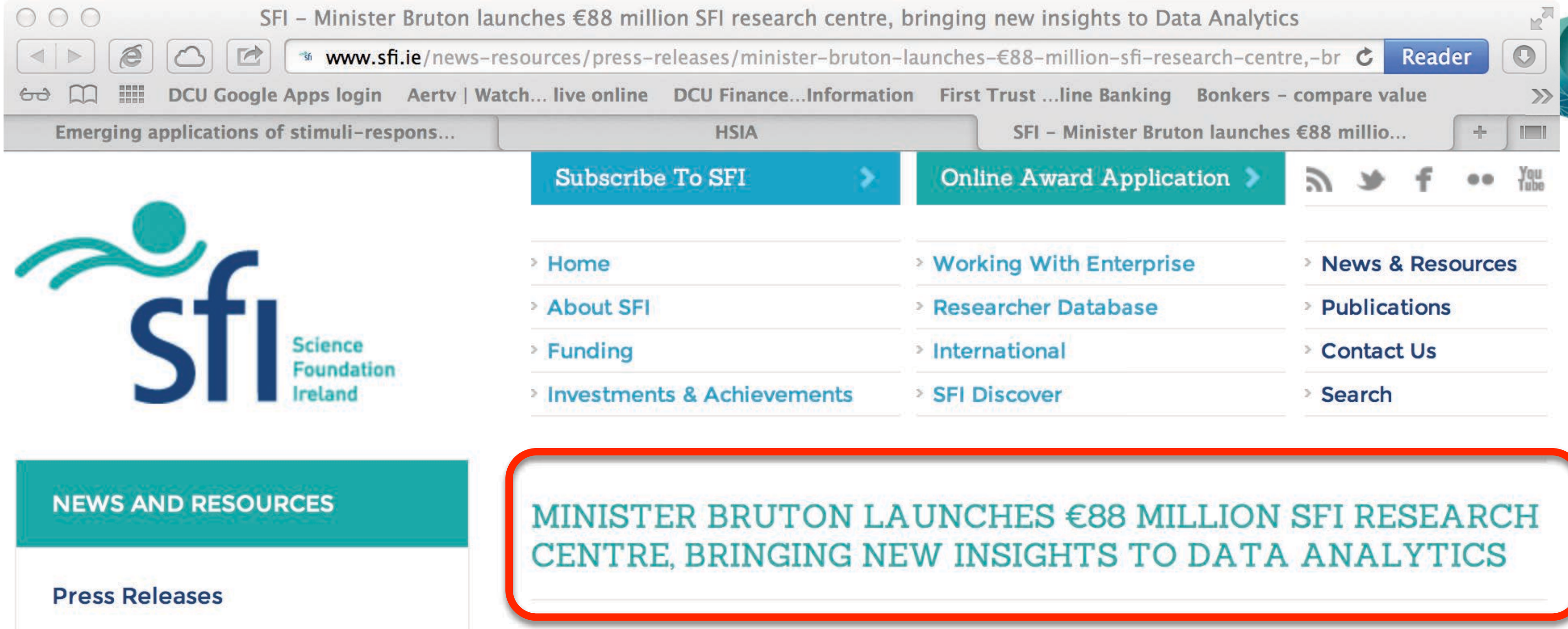
How Fundamental Materials Science will Generate Revolutionary Breakthroughs in Environmental Monitoring Technologies

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

Invited Lecture presented at the

Sensors100 'Sensors in the Environment Conference'
15 -16 October 2014, Radisson Blu Hotel, London



Insight Centre for Data Analytics

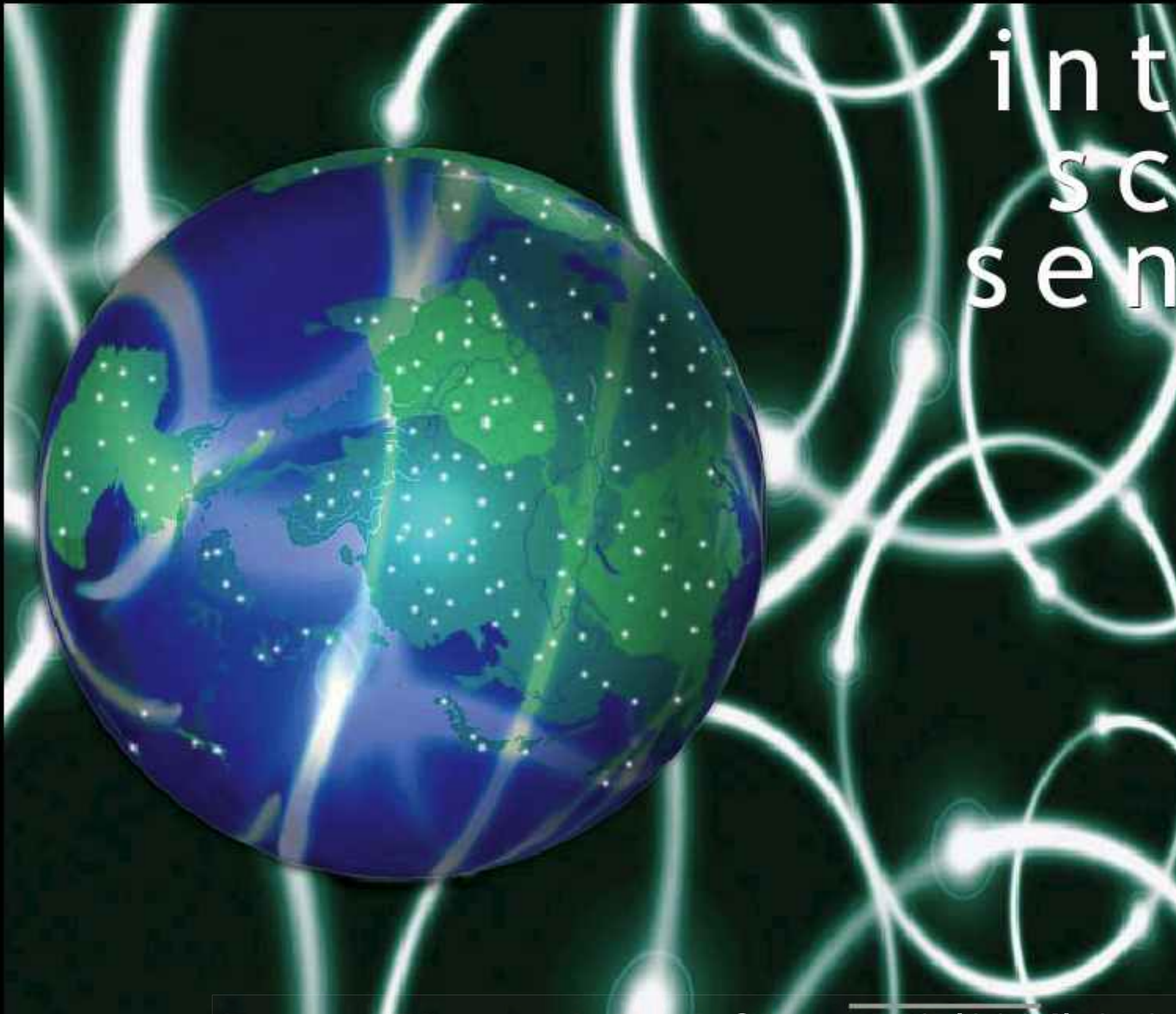
- Biggest single research investment ever by Science Foundation
- Biggest coordinated research programme in the history of the state
- Focus is on ‘big data’ related to health informatics and pHealth
- Materials science will play a central role in the practical realisation of new concepts in chemical sensing and biosensing

'Grand Challenge for Analytical Chemistry'

- "A **'Grand Challenge'** posed for analytical chemistry is to develop a capability for sampling and **monitoring air, water and soil much more extensively and frequently than is now possible**"
- "Such goals will require **improvements in sampling methodology** and in **techniques for remote measurements**, as well as approaches that **greatly lower per-sample and per-measurement costs**"

Royce Murray, Editorial, Analytical Chemistry, February 2010

Keynote Article: August 2004, Analytical Chemistry (ACS)



internet scale sensing

Dermot Diamond
Dublin City University
(Ireland)

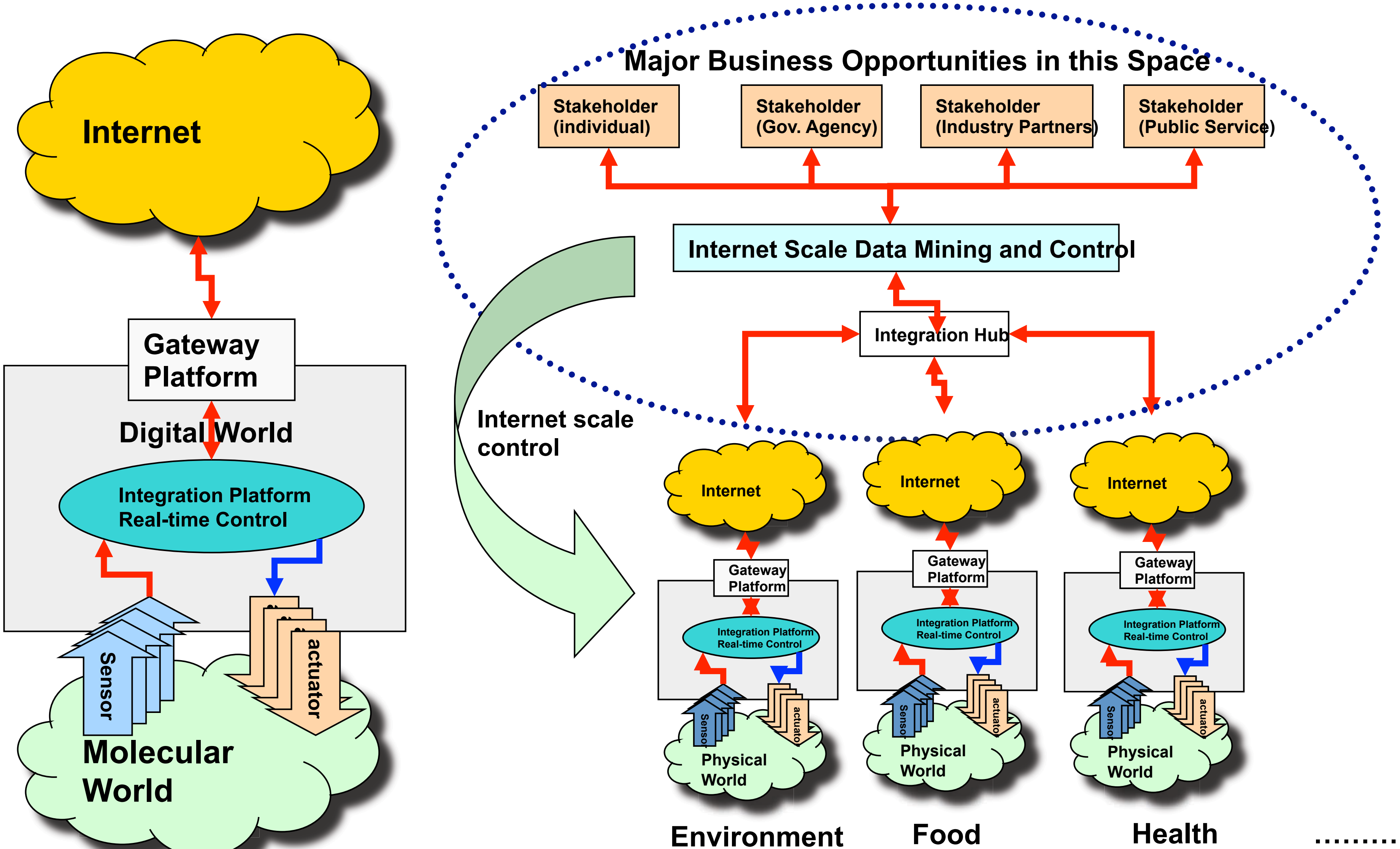
Incredible advances in digital communications and computer power have profoundly changed our lives. One chemist shares his vision of the role of analytical science in the next communications revolution.

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

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

Internet-enable every sensor measurement!



Apple, iWatch & Health Monitoring


Independent.ie Wednesday 7 May 2014

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Apple hiring medical device staff, shares break $600 mark

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Apple Inc CEO Tim Cook

May 7th 2014

'Over the past year, Apple has snapped up at least half a dozen prominent experts in biomedicine, according to LinkedIn profile changes.

Much of the hiring is in sensor technology, an area Chief Executive Tim Cook singled out last year as primed "to explode."

Industry insiders say the moves telegraph a vision of **monitoring everything from blood-sugar levels to nutrition, beyond the fitness-oriented devices now on the market.'**

"This is a very specific play in the bio-sensing space," said Malay Gandhi, chief strategy officer at Rock Health, a San Francisco venture capital firm that has backed prominent wearable-tech startups, such as Augmedix and Spire.

'Healthkit' personal health information platform developed in collaboration with Mayo Clinic

Google Contact Lens

United States Patent Application ***20140107445***
Kind Code A1 Liu; Zenghe April 17, 2014
Microelectrodes In An Ophthalmic Electrochemical Sensor

Abstract

An eye-mountable device includes an electrochemical sensor embedded in a polymeric material configured for mounting to a surface of an eye. The electrochemical sensor includes a working electrode, a reference electrode, and a reagent that selectively reacts with an analyte to generate a sensor measurement related to a concentration of the analyte in a fluid to which the eye-mountable device is exposed.

Google Smart Contact Lenses Move Closer to Reality

Google's Smart Contact Lens is like your contact lens, except it's a whole lot smarter.

IMAGE: GOOGLE

- **Use model is 24 hours max, then replace;**
- **likely to leverage Google Glass infrastructure;**
- **Novartis now working with Google.**

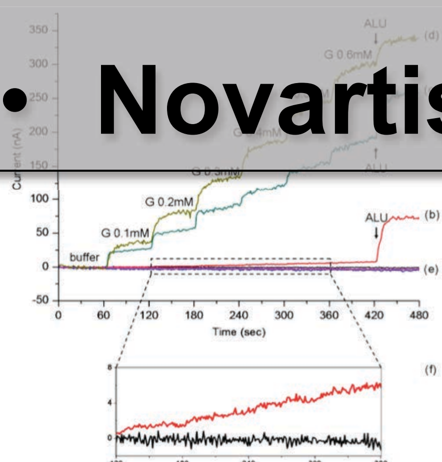
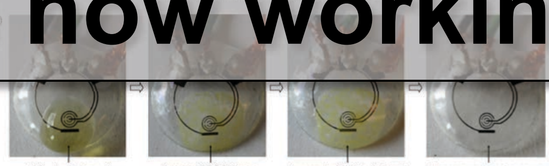


Fig. 2. Images of the sensor as it goes through surface functionalization and the related measured responses: (a) sequential images of sensor pre-treatment with GOD/titania/Nafion®; (b) measured amperometric response for the sensor just incubated with GOD; (c) measured amperometric response for the sensor prepared with GOD/titania sol–gel film; (d) measured amperometric response for the sensor prepared with GOD/titania/Nafion®; (e) three controls (signals for buffer) for the same pre-treatment of (b), (c), and (d); (f) the enlarged view of curve (b) and control of (b) for 120–360 s.



***A contact lens with embedded sensor for monitoring tear glucose level*, H. F. Yao, A. J. Shum, M. Cowan, I. Lahdesmaki and B. A. Parviz, *Biosensors & Bioelectronics*, 2011, 26**, 3290-3296.

BY LANCE ULANOFF
1 DAY AGO

...technology.

Known among scientists as "Ophthalmic Electrochemical Sensors," these contact lenses will feature flexible electronics that include sensors and an antenna. The sensors are designed to read chemicals in the tear fluid of the wearer's eye and alert her, possibly through a little embedded LED light, when her blood sugar falls to dangerous levels.

SEE ALSO: 7 Incognito Wearables You'd Never Guess Were Gadgets

According to the patent:

> "Human tear fluid contains a variety of inorganic electrolytes (e.g., Ca.sup.2+, Mg.sup.2+, Cl.sup.-), organic solutes (e.g., glucose, lactate, etc.), proteins, and lipids. A

http://www.gmanetwork.com/news/story/360331/scitech/technology/google-s-smart-contact-lenses-may-arrive-sooner-than-you-think

pH sensing – wasn't that solved by Nikolskii in the 1930's?

EVENT	DATE
Launch (San Francisco)	September 2013
PHASE 1: Innovation Phase	
Registration opens	January 1, 2014
Early-bird Registration deadline	March 2014
OA Solutions Fair and Kick-Off Event	March 2014

Overview

Competition Guidelines

Competition Schedule

Registration Process

OVERVIEW

The Challenge: Improve Our Understanding of Ocean Acidification

The Wendy Schmidt Ocean Health XPRIZE is a $2 million global competition that challenges teams of engineers, scientists and innovators from all over the world to create pH sensor technology that will affordably, accurately and efficiently measure ocean chemistry from its shallowest waters… to its deepest depths.

There are two prize purses available (teams may compete for, and win, both purses):

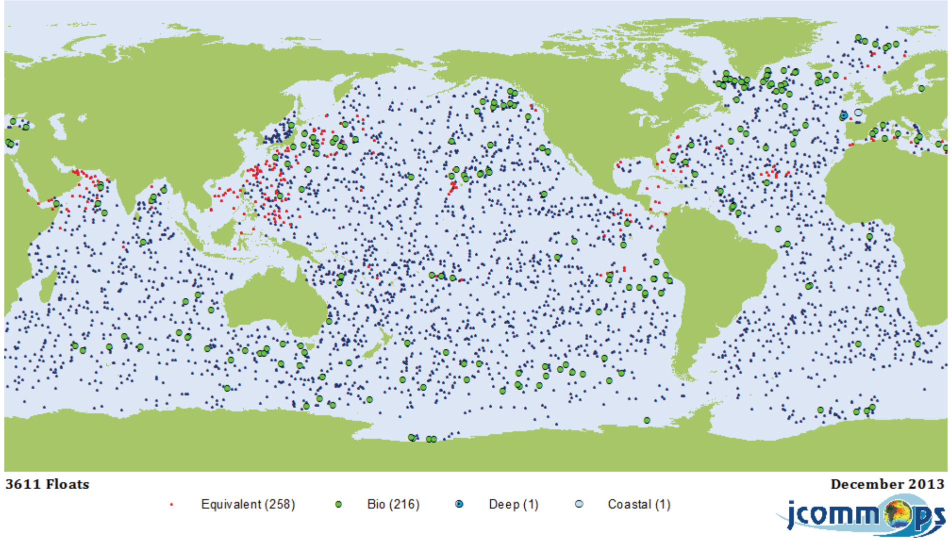
A. $1,000,000 Accuracy award – Performance focused ($750,000 First Place, $250,000 Second Place): To the teams that navigate the entire competition to produce the most accurate, stable and precise pH sensors under a variety of tests.

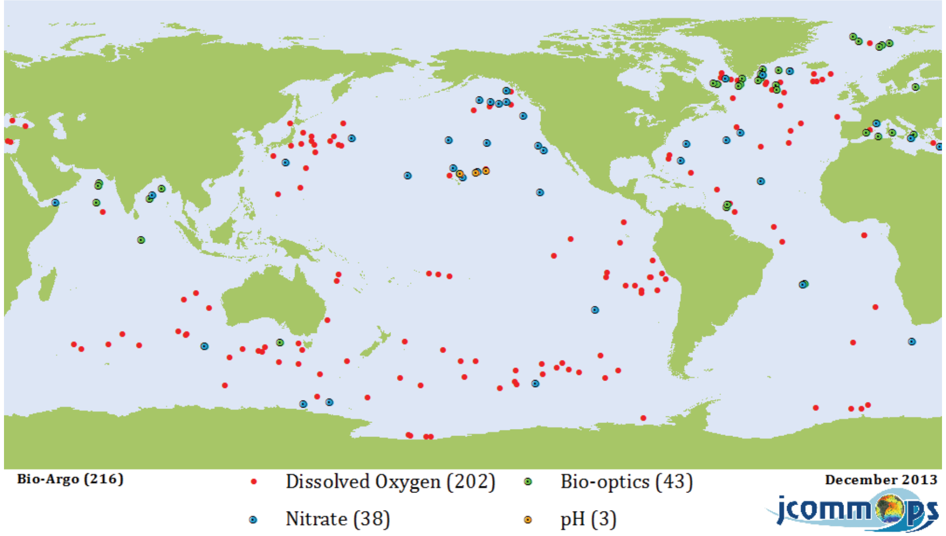
Wendy Schmidt Ocean Health XPRIZE

$2,000,000 up for grabs!
Task is to provide a way to do reliable measurements of pH in the ocean environment

The winner will almost certainly be a reagent based platform, not a conventional chemical sensor

Argo Project (accessed March 9 2014)





- **Ca. 3,600 floats: temperature and salinity**
- **Only 216 reporting chem/bio parameters (ca. 6%)**
- **Of these nitrate (38), DO (202), Bio-optics (43), pH (3)**

@€60K ea!

DO is by Clark Cell (Sea Bird Electronics) or Dynamic fluorescence quenching (Aanderaa)

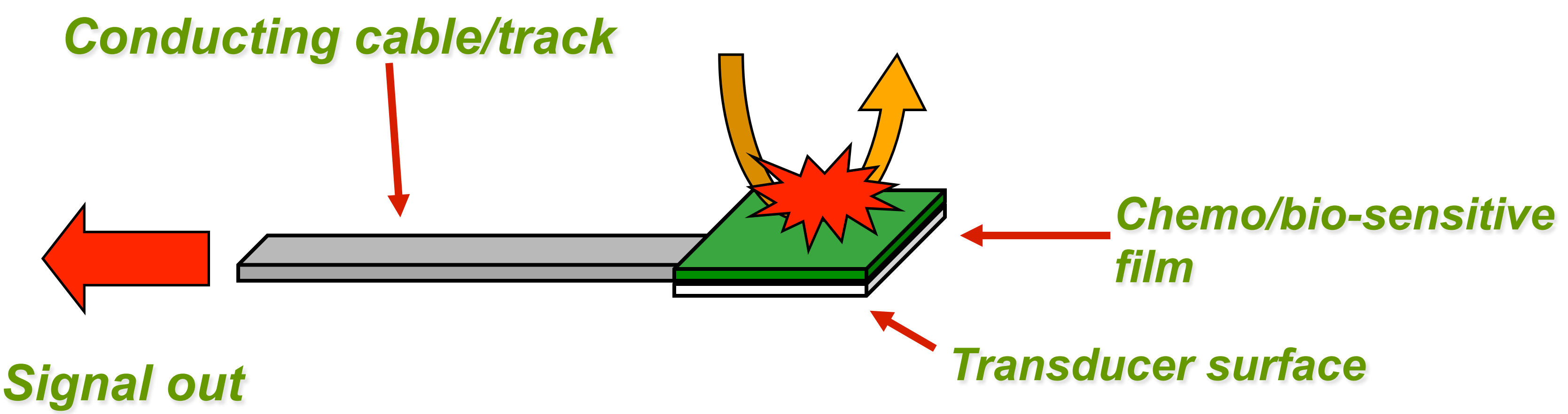
See https://picasaweb.google.com/JCOMMOPS/ArgoMaps?authuser=0&feat=embedwebsite

'calibration of the DO measurements by the SBE sensor remains an important issue for the future', Argo report 'Processing Argo OXYGEN data at the DAC level', September 6, 2009, V. Thierry, D. Gilbert, T. Kobayashi

After decades of intensive research, our capacity to deliver successful long-term deployments of chemo/bio-sensors in remote locations is still very limited

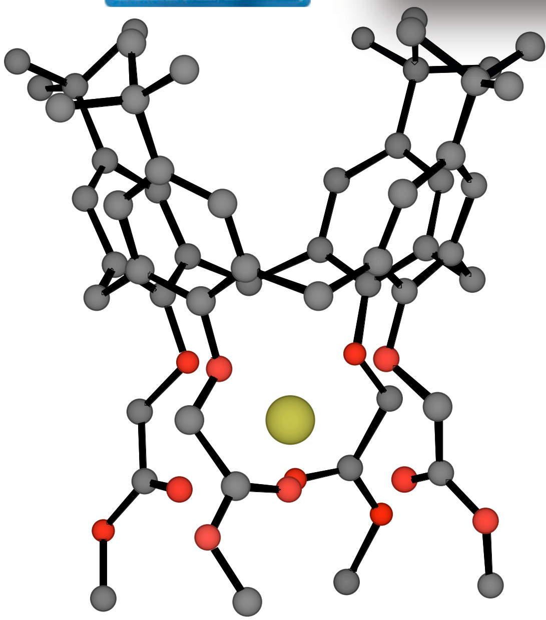
What is a Chemo/Bio-Sensor?

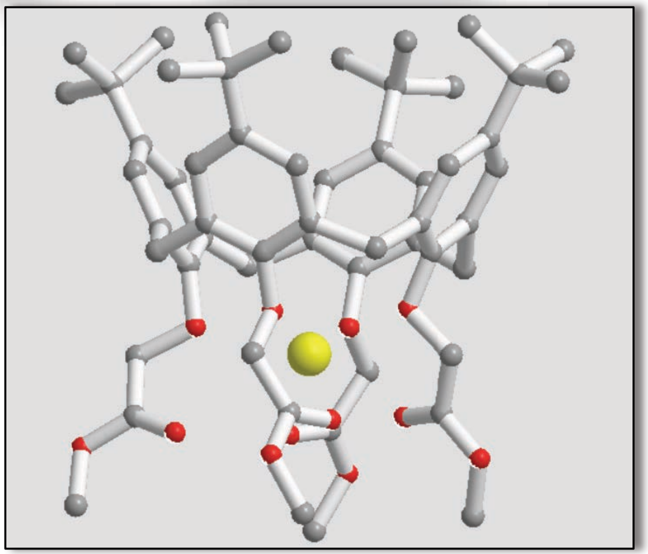
'a device, consisting of a transducer and a chemo/bio-sensitive film/membrane, that generates a signal related to the concentration of particular target analyte in a given sample'

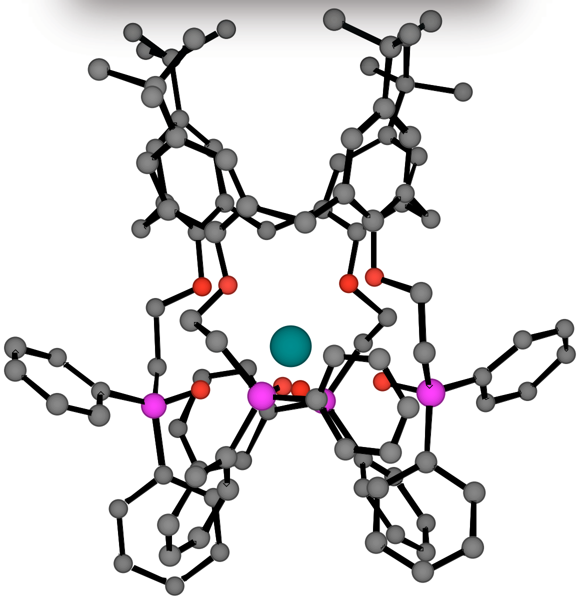


Conventionally, chem/Bio-sensors employ selective **BINDING** & **TRANSDUCTION** at the device surface, which is pre-functionalised with binding sites selective for a chosen analyte. Binding events at the surface provide a signal observable in the macroscopic world (**COMMUNICATION**)

History: Calixarenes, 1984/5

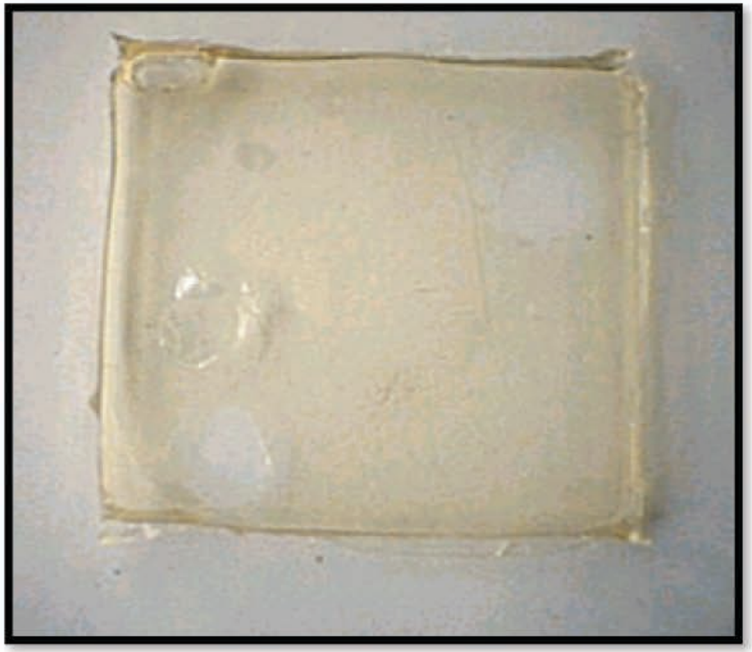


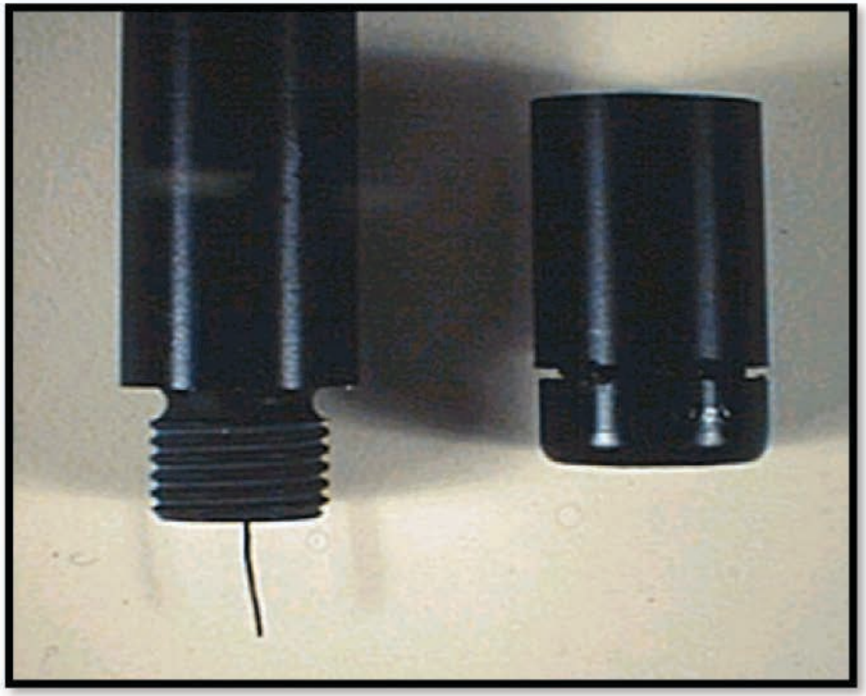




Neutral Carrier Based Ion-Selective Electrodes, D.Diamond, Anal. Chem. Symp. Ser., 25 (1986) 155.
A sodium Ion-Selective Electrode based on Methyl p-t-Butyl Calix[4]aryl Acetate as the Ionophore, D.Diamond, G.Svehla, E.Seward,and M.A.McKervey, Anal. Chim. Acta., 204 (1988) 223-231.
Sodium Selective Polymeric 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.

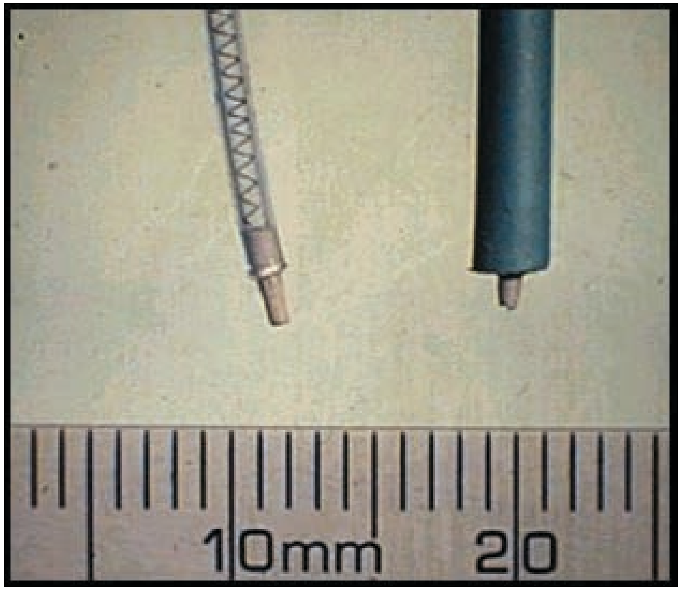
PVC - Membrane ISEs





Typical membrane cocktail (%w/w); PVC:33%, NPOE (plasticiser):66%; ionophore/exchanger: 1% (ratio at least 2:1 by mole); dissolve in a volatile solvent e.g. THF and cast membrane from this solution

Blood Analysis; Implantible Sensors



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

Dr. David Band, St Thomas's Hospital London

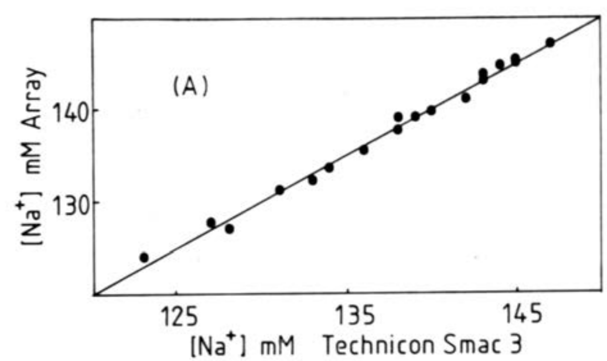
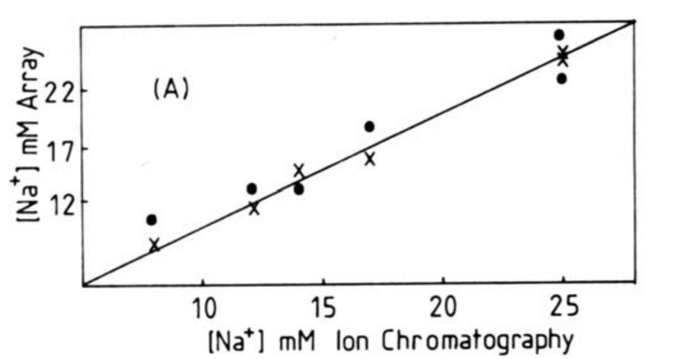


Fig. 3. Comparison of plasma sodium analysis using the array-FIA approach with a SMAC analyser. Good correlation without bias is obtained [5].



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

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

Lowering the LOD of ISEs (1999)

Anal. Chem. **1999,** *71,* 1204−1209

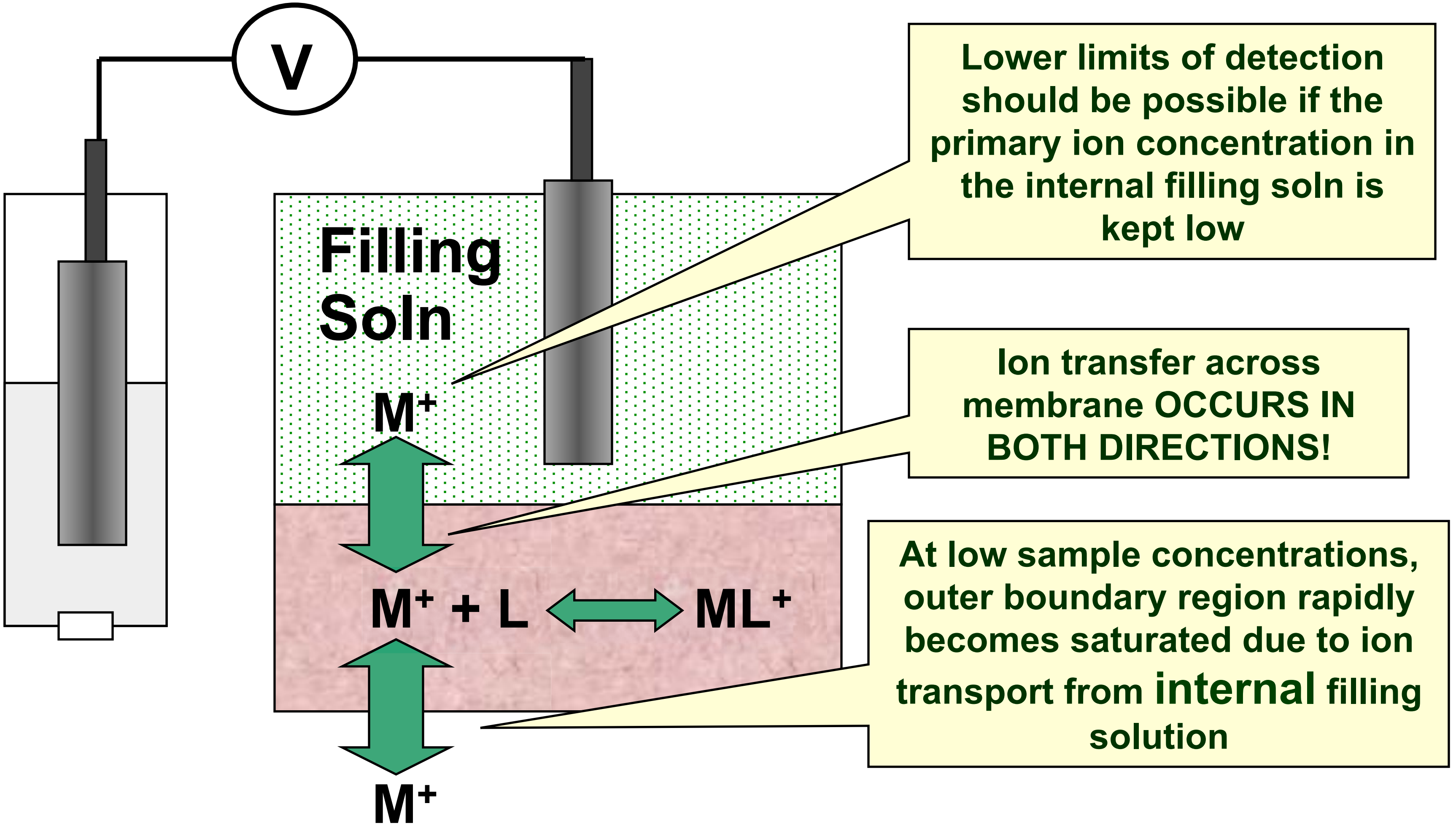
Lowering the Detection Limit of Solvent Polymeric Ion-Selective Electrodes. 1. Modeling the Influence of Steady-State Ion Fluxes

Tomasz Sokalski,[*,†,§] Titus Zwickl,[†] Eric Bakker,[*,‡] and Ernö Pretsch[*,†]

Department of Organic Chemistry, Swiss Federal Institute of Technology (ETH), Universitätstrasse 16, CH-8092 Zürich, Switzerland, and Department of Chemistry, Auburn University, Auburn, Alabama 36849

ISEs: Low Limit of Detection

- See series of papers by Pretsch, Bakker and Sokalski



Lead in Zurich Tap Water

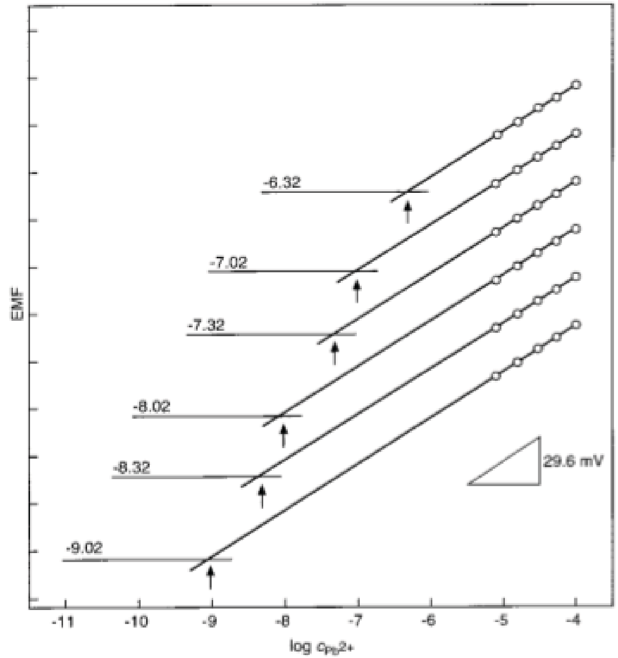


Figure 2. Measurement procedure of potentiometric trace level determinations of Pb^{2+} by calibrating with a series of lead ion solutions at higher concentration. Shown are the emf responses as a function of the sample activity for each of the separate measurements. The slopes for each of the five-point calibrations are, from top to bottom, 28.5, 28.4, 28.6, 28.6, 28.5, and 28.9 mV/decade.

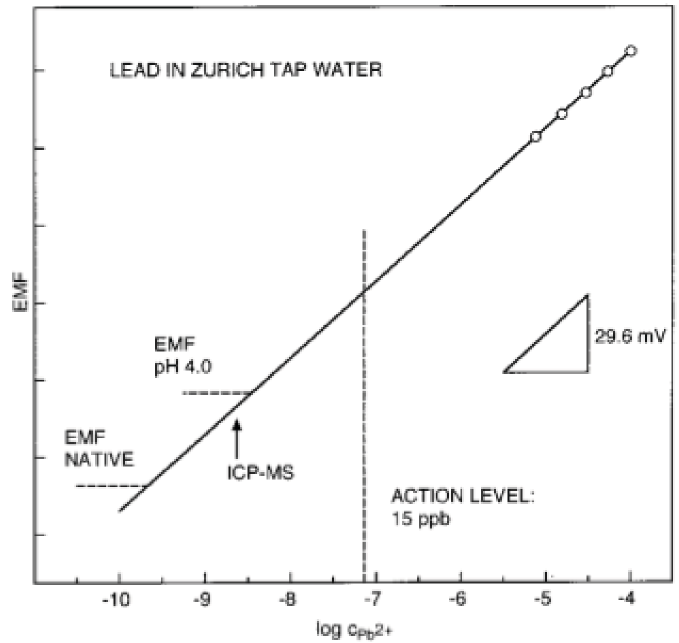


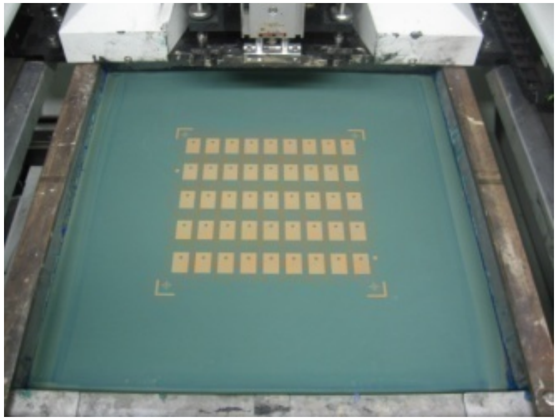
Figure 6. Potentiometric determination of Pb^{2+} in unspiked Zurich tap water at different pH values (see also Figure 5). Horizontal dotted lines: measurement of free lead in the native sample (lower value) and of total lead after buffering the pH to 4.0 (higher value). Vertical arrow: lead concentration obtained with ICPMS.

- **Anal. Chem. 2001, 73, 343-351; 'Potentiometric Polymeric Membrane Electrodes for Measurement of Environmental Samples at Trace Levels: New Requirements for Selectivities and Measuring Protocols, and Comparison with ICPMS', Alan Ceresa, Eric Bakker, Bodo Hattendorf, Detlef Gunther, and Erno Pretsch**

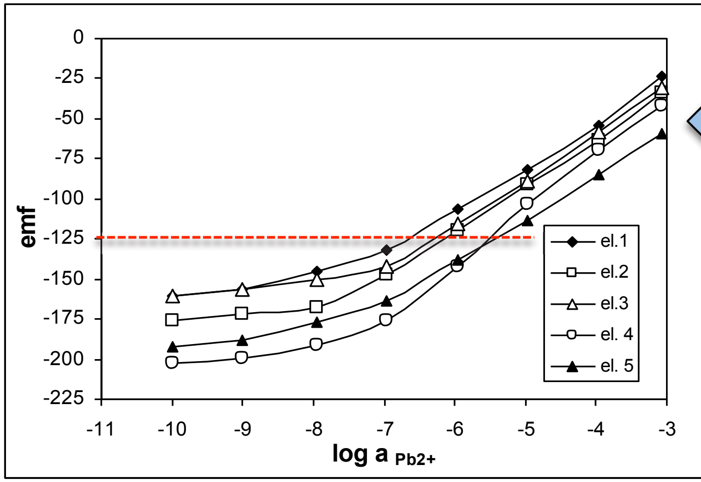
Mass production of SCISEs and SCREs

(Alek Radu and Salzitsa Anastasova)

- Using Screen Printer DEK 248 silver paste was printed on plastic sheets.
- Next, carbon was printed twice, with 15 minutes of curing in oven at 200^{o}C between successive prints.
- After finishing carbon, the insulating layer was printed and UV-cured.
- Conducting polymer Poly (3-octylthiophene) (10^{-2} M in Chloroform) was dropcast (initially) or grown electrochemically (later) on printed platforms.
- The CP is covered with a PVC membrane cocktail containing active components for ISEs and reference electrodes (Fluka)

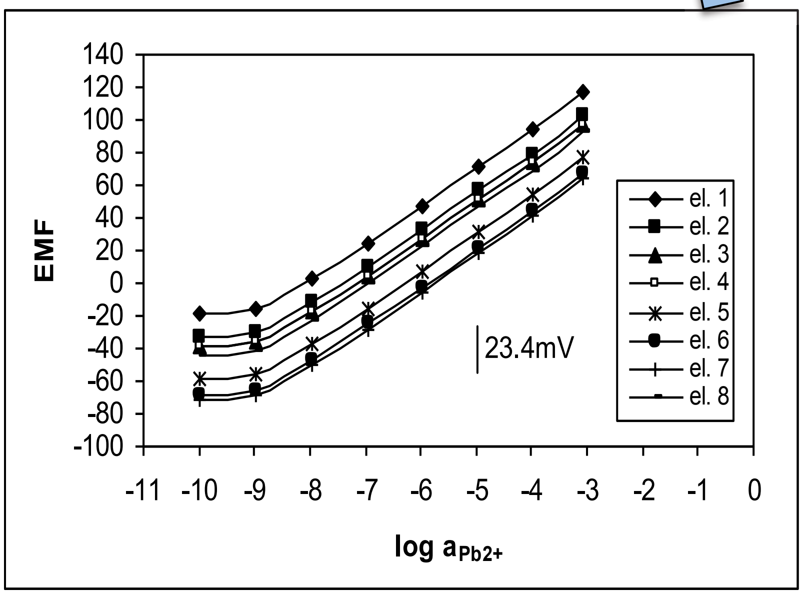


Improving sensor reproducibility

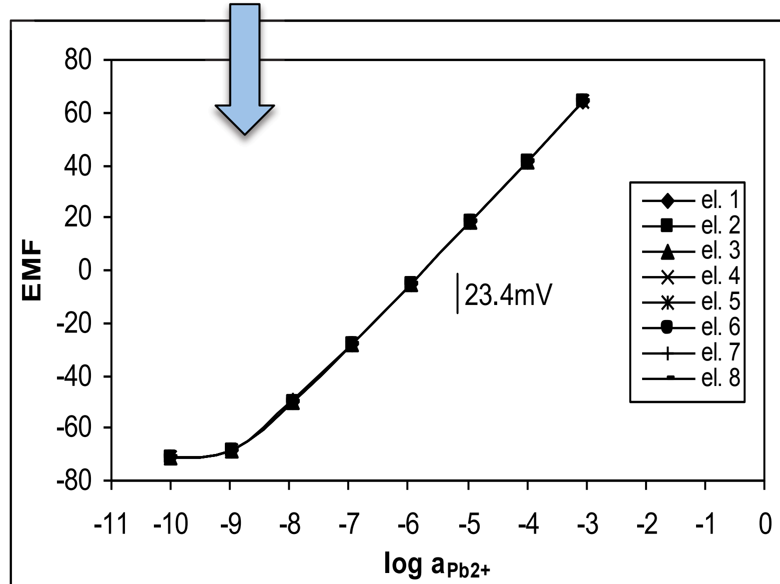


Manual fabrication, conventional design

SP fabrication, **manual deposition of CP layer (POT) and sensing layer**

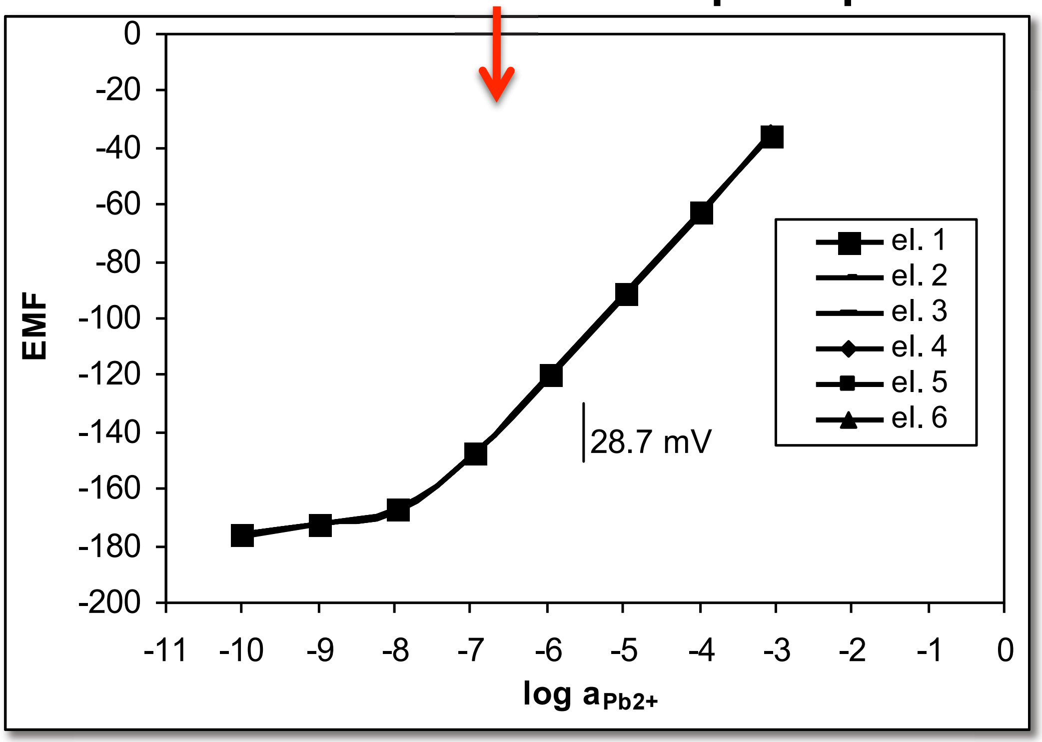


After zero point correction, slopes are virtually identical: single point calibration for each sensor



EC-deposition of CP Layer -> highly Reproducible Sensors

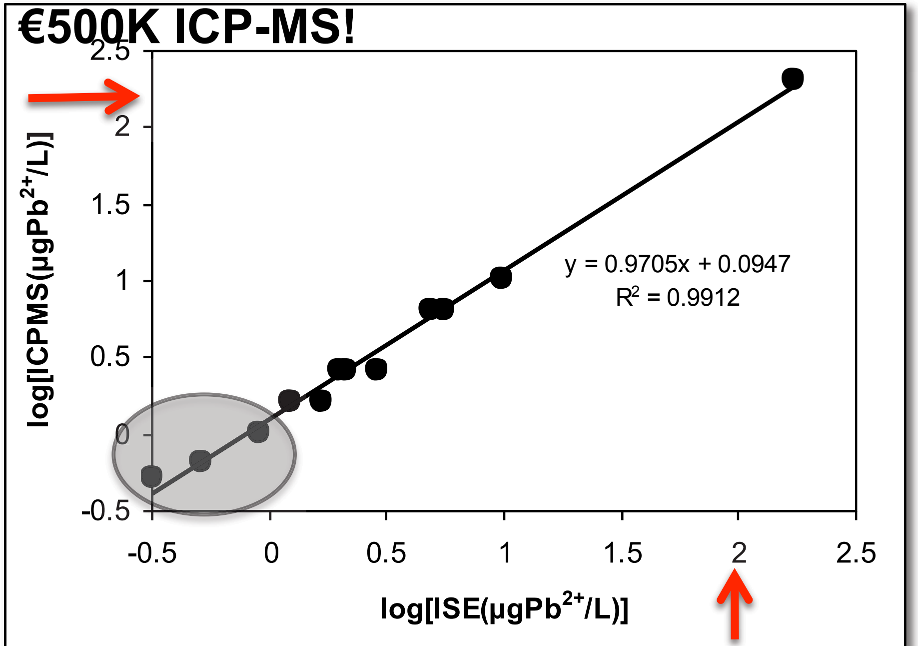
6 calibration curves superimposed!



electrode number	Baseline, mV Day0	Slope, mV Day0	LOD Day0	Eo/mV Day0
1	-176.11	28.75	-8.00	53.87
2	-176.08	28.75	-8.00	53.90
3	-176.40	28.75	-7.95	52.14
4	-176.23	28.74	-7.90	50.83
5	-176.13	28.72	-7.92	51.32
6	-176.16	28.74	-8.00	53.73
Mean	-176.18	28.74	-7.96	52.63
SD	0.12	0.01	0.04	1.38

SP fabrication**, electrochemical deposition of CP (PEDOT)**, manual deposition of sensing layer;
Applied to analysis of river water samples

Disposable solid-contact ion-selective electrodes for environmental monitoring of lead with ppb limit-of-detection, S. Anastasova, A. Radu, G. Matzeu, C. Zuliani, U. Mattinen, J. Bobacka and D. Diamond, *Electrochimica Acta*, 2012, 73, 93-97.



10¢ ISE vs.

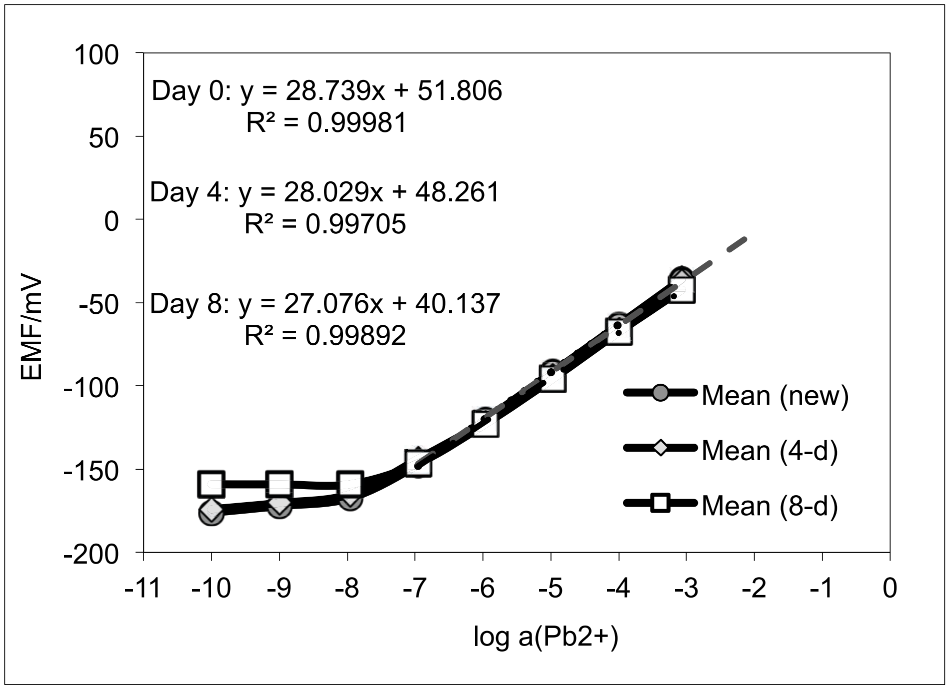
Screen Printed ISEs

- V. low cost (cents), mass-produced
- Almost perfect reproducibility -> calibrate 1 per batch!
- V. high sensitivity -> LOD in low PPB for Pb^{2+}; better than ICP-MS!, ….. & V. selective
- Each ISE used once; unknown estimated using 4-point standard additions

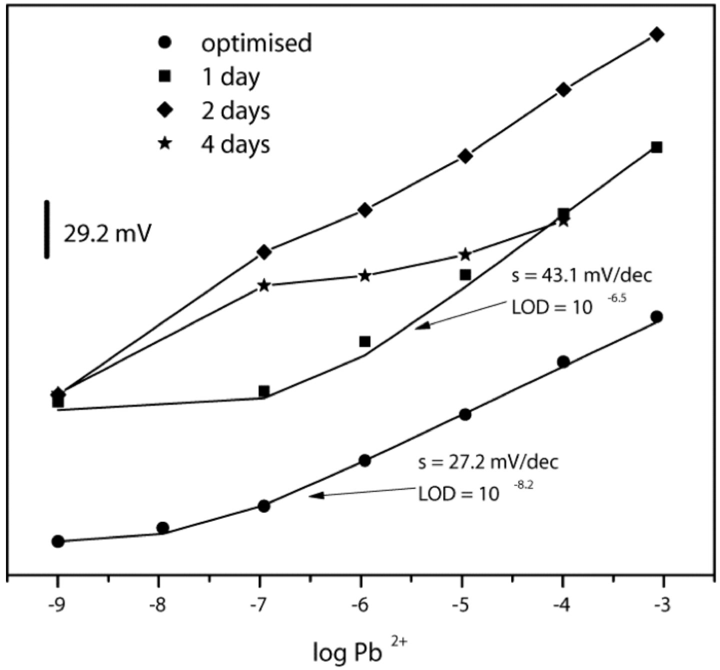
Would it be possible to use these electrodes in a remote autonomous instrument?

Change in Electrode Function over Time

See Electrochimica Acta 73 (2012) 93–97



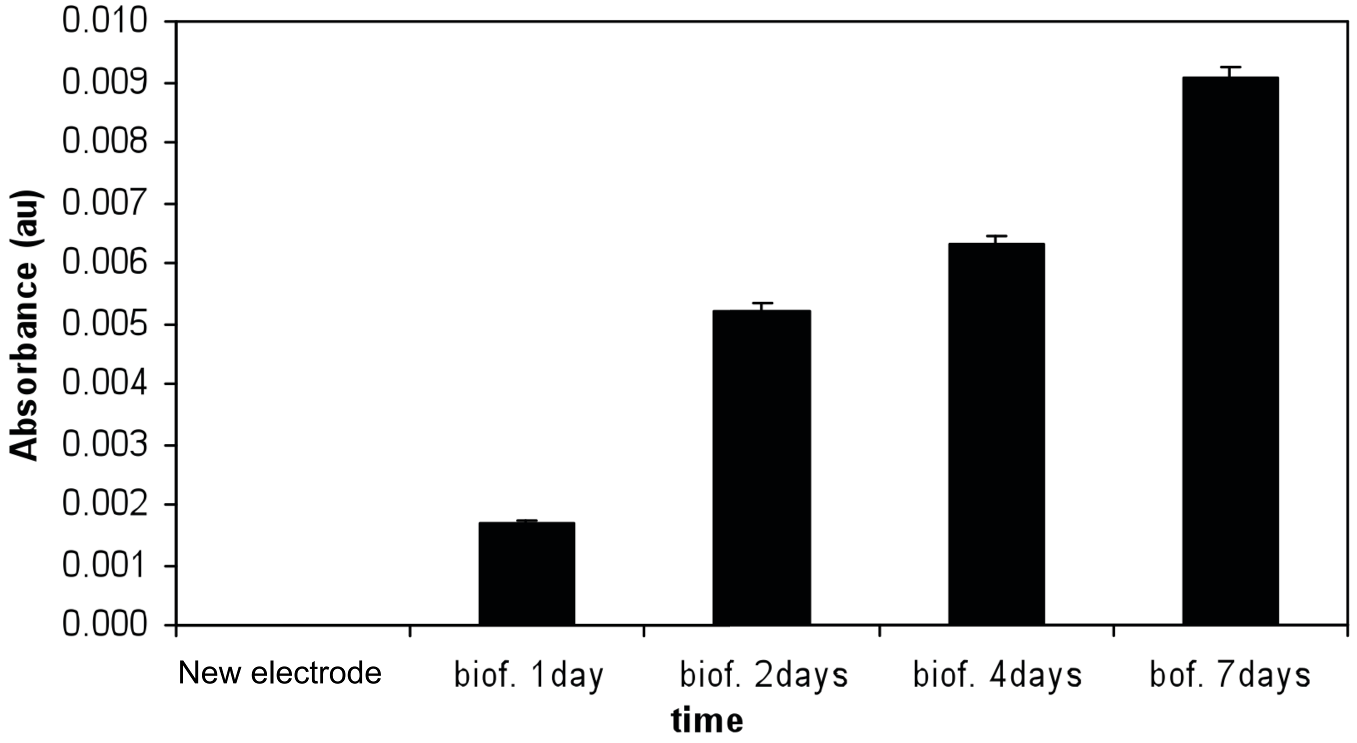
stored in 10^{-9}M Pb^{2+}, pH=4



Continuous contact with river water

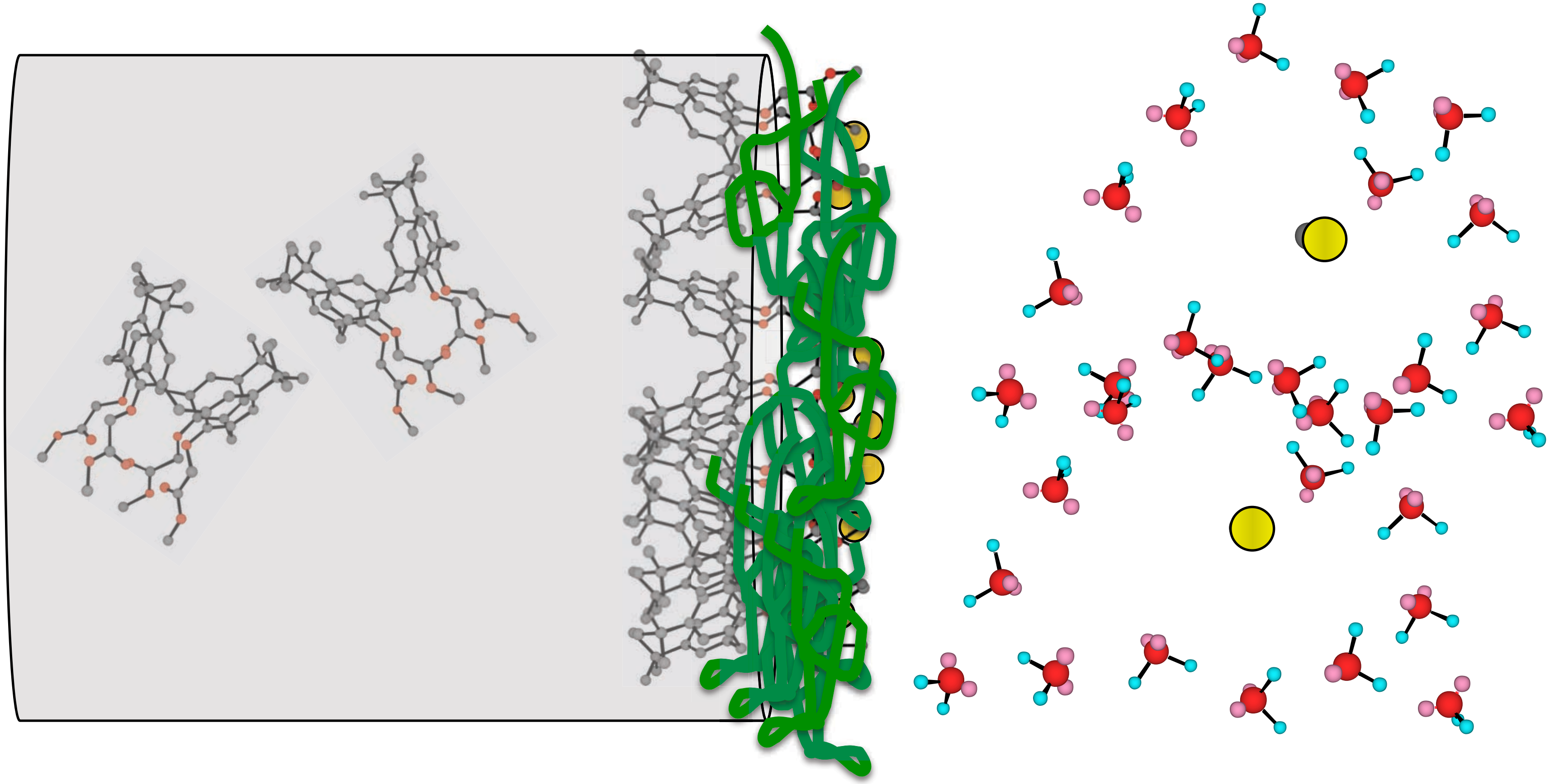
Conventional PVC-membrane based ISEs

Biofilm Formation on Sensors



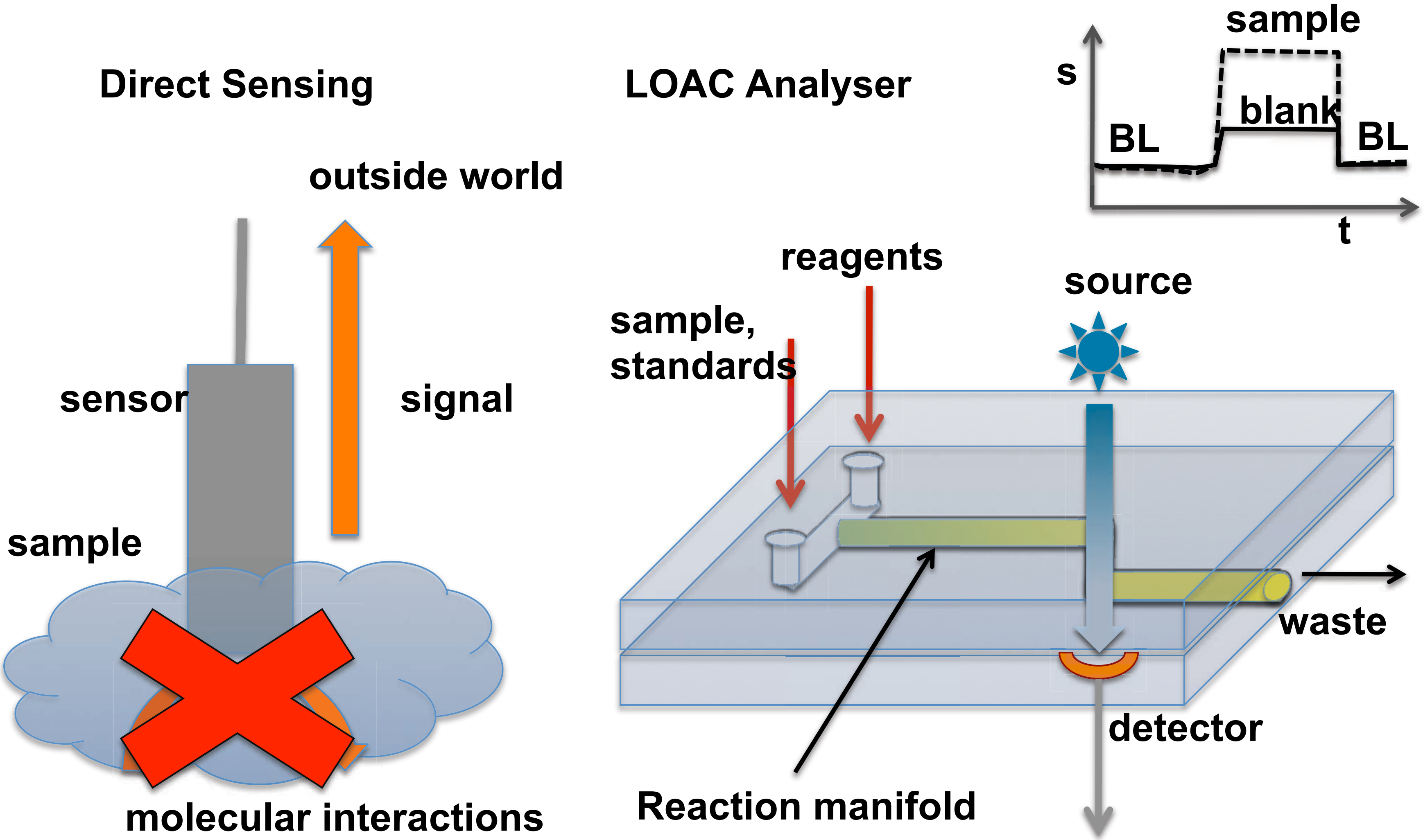
- Electrodes exposed to local river water (Tolka)
- 'Slime test' shows biofilm formation happens almost immediately and grows rapidly

Control of membrane interfacial exchange & binding processes



Remote, autonomous chemical sensing is a tricky business!

Direct Sensing vs. Reagent Based LOAC/ufluidics



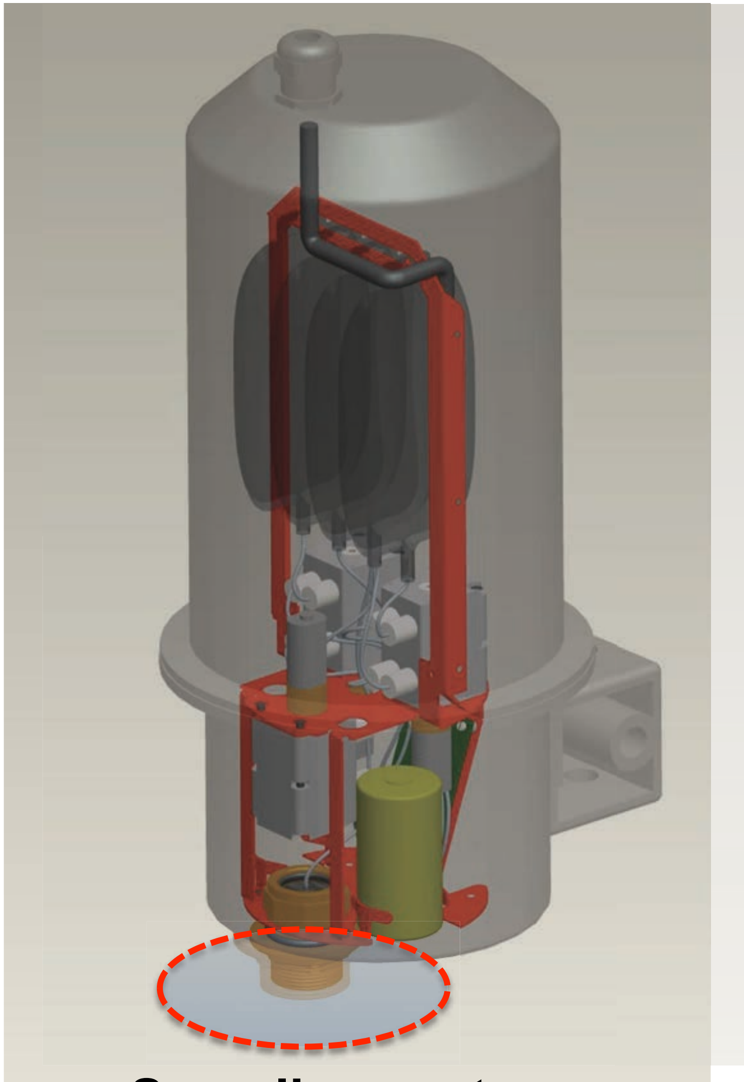
MicroTAS/Lab on a Chip/Microfluidics

Many people, myself included, expected that the ability to manipulate fluid streams, in microchannels, easily, would result in a proliferation of commercial LoC systems, and that we would see applications of these devices proliferating throughout science. In fact, it has not (yet) happened.

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

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

Autonomous platform – water Analysis



Sampling port

Phosphate: The Yellow Method

Mixture (Reagent)

$(NH_4VO_3) + (NH_4)_6Mo_7O_{24}.4H_2O$, HCl conc.

+

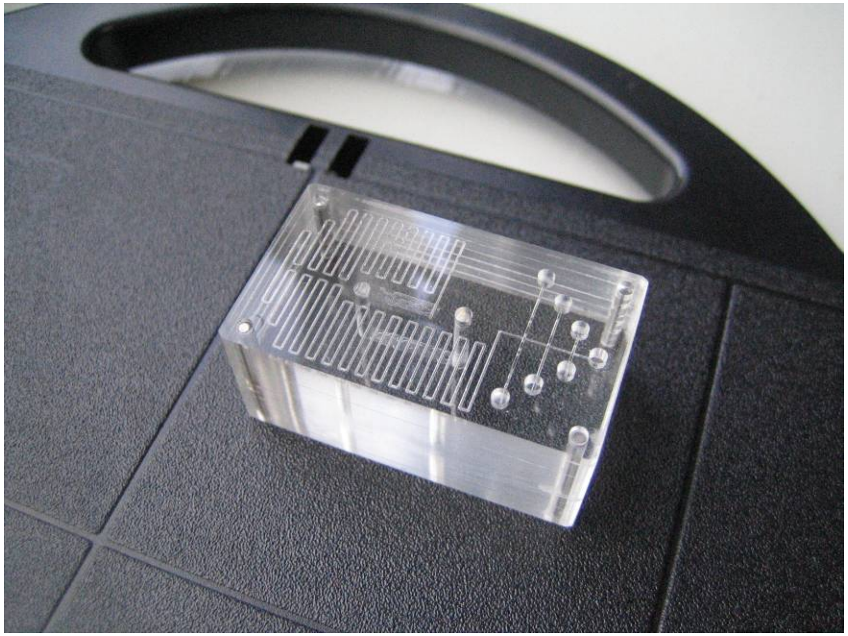
Sample

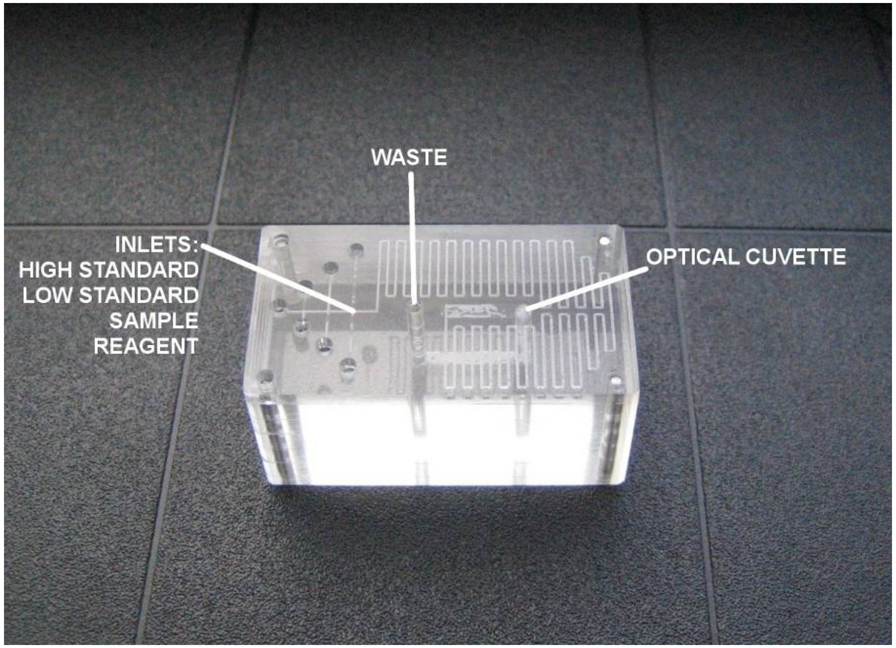
(KH_2PO_4)

$$(NH_4)_3PO_4.NH_4VO_3.16MoO_3$$

- yellow vanaomolybdophosphoric acid is formed when ammonium metavanadate and ammonium molybdate (mixture) reacts with phosphate (acidic conditions)
- In conventional (molybdate) method, **ascorbic acid** is used to generate the well-known deep blue complex (**v. fine precipitate**)

Microfluidic Chip





- **Micromilled PMMA**
- **12.5mm Optical Cuvette Length**
- **200um wide serpentine mixing channel**

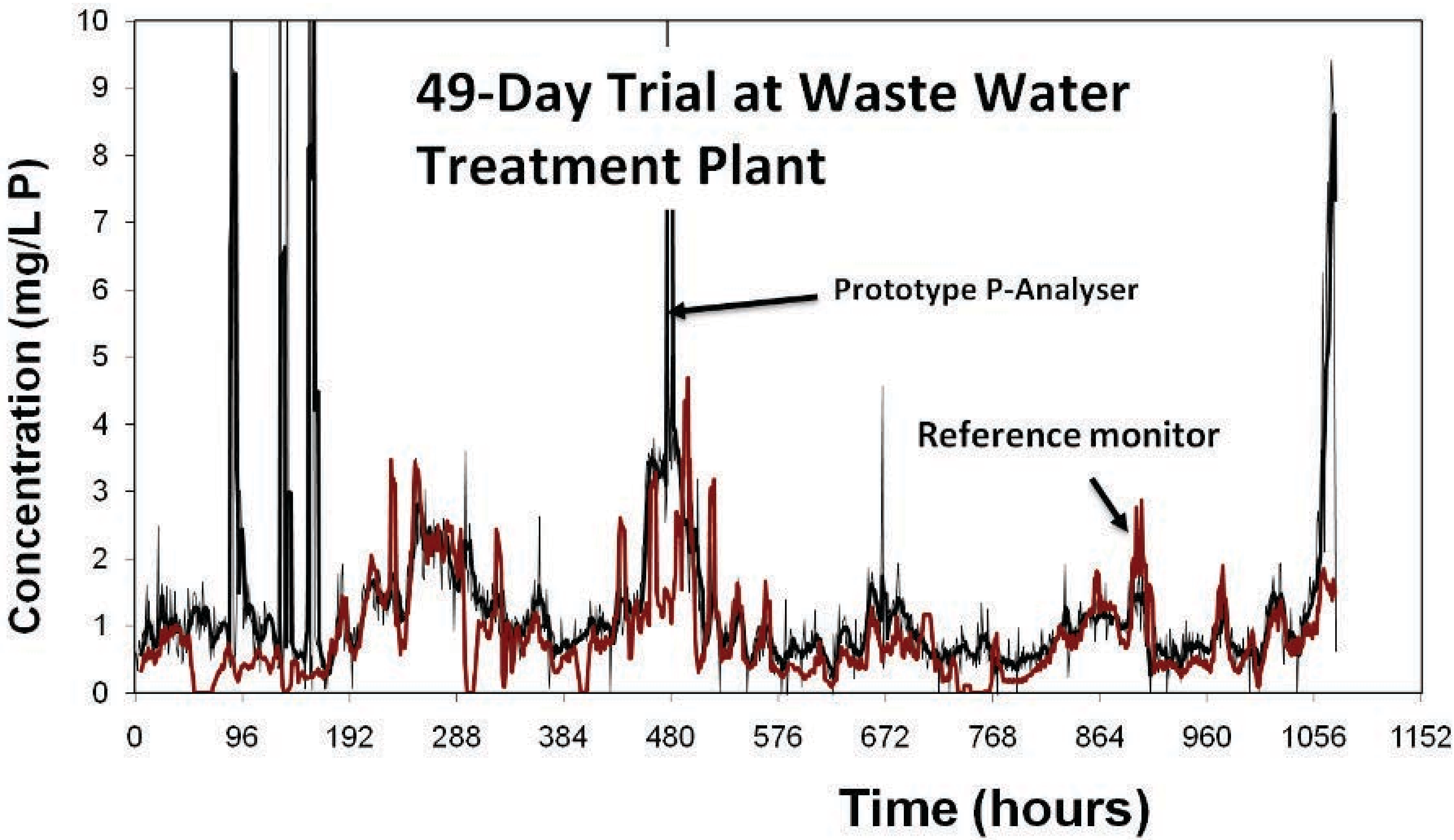
Deployment at Osberstown WWTP

- Phosphate monitoring unit deployed
- System is fully immersed in the treatment tank
- Wireless communications unit linked by cable
- Data transmitted to cloud

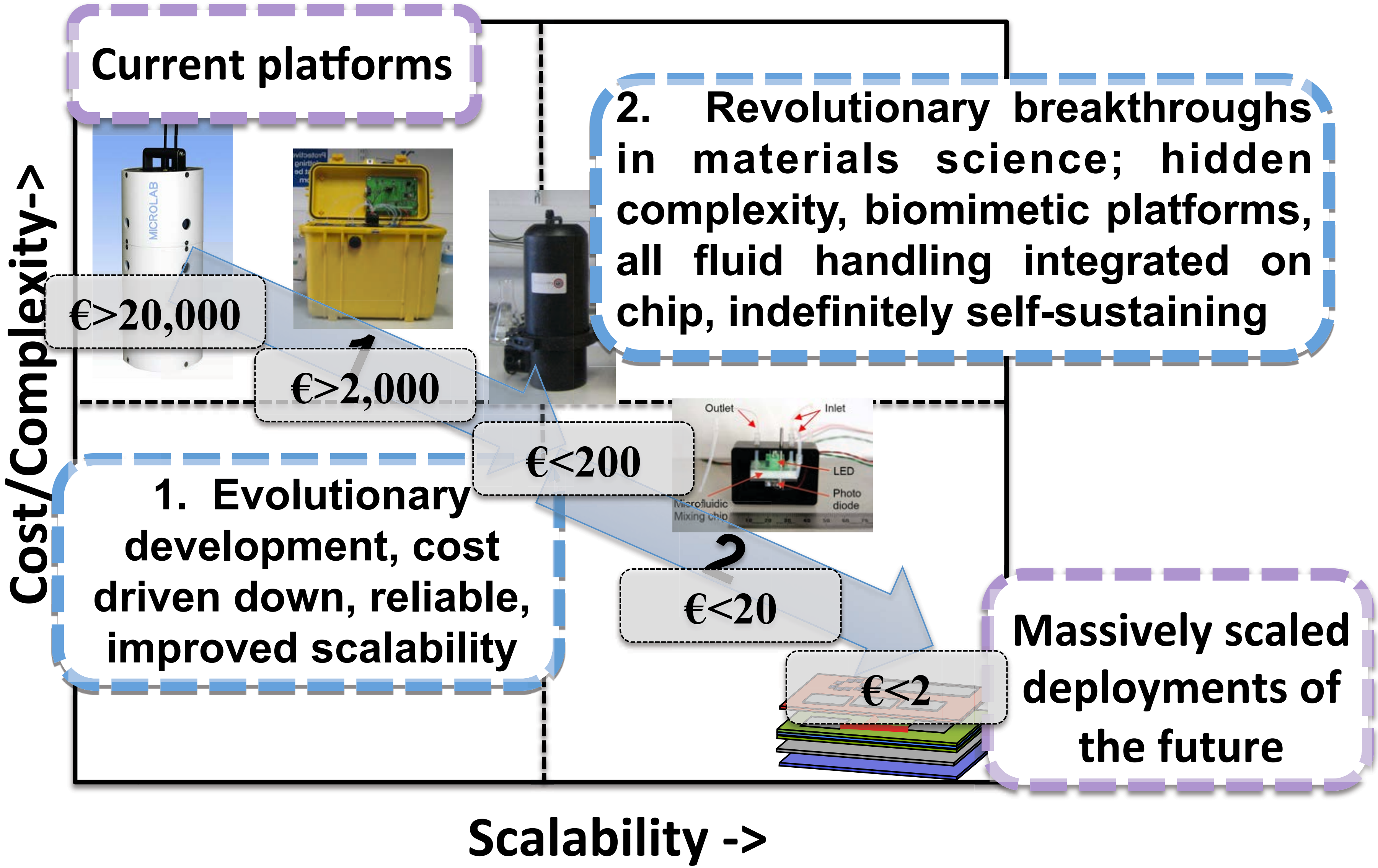
Osberstown – 3 week deployment

Biofouling of sensor surfaces is a major challenge for remote chemical sensing – both for the environment and for implantable sensors

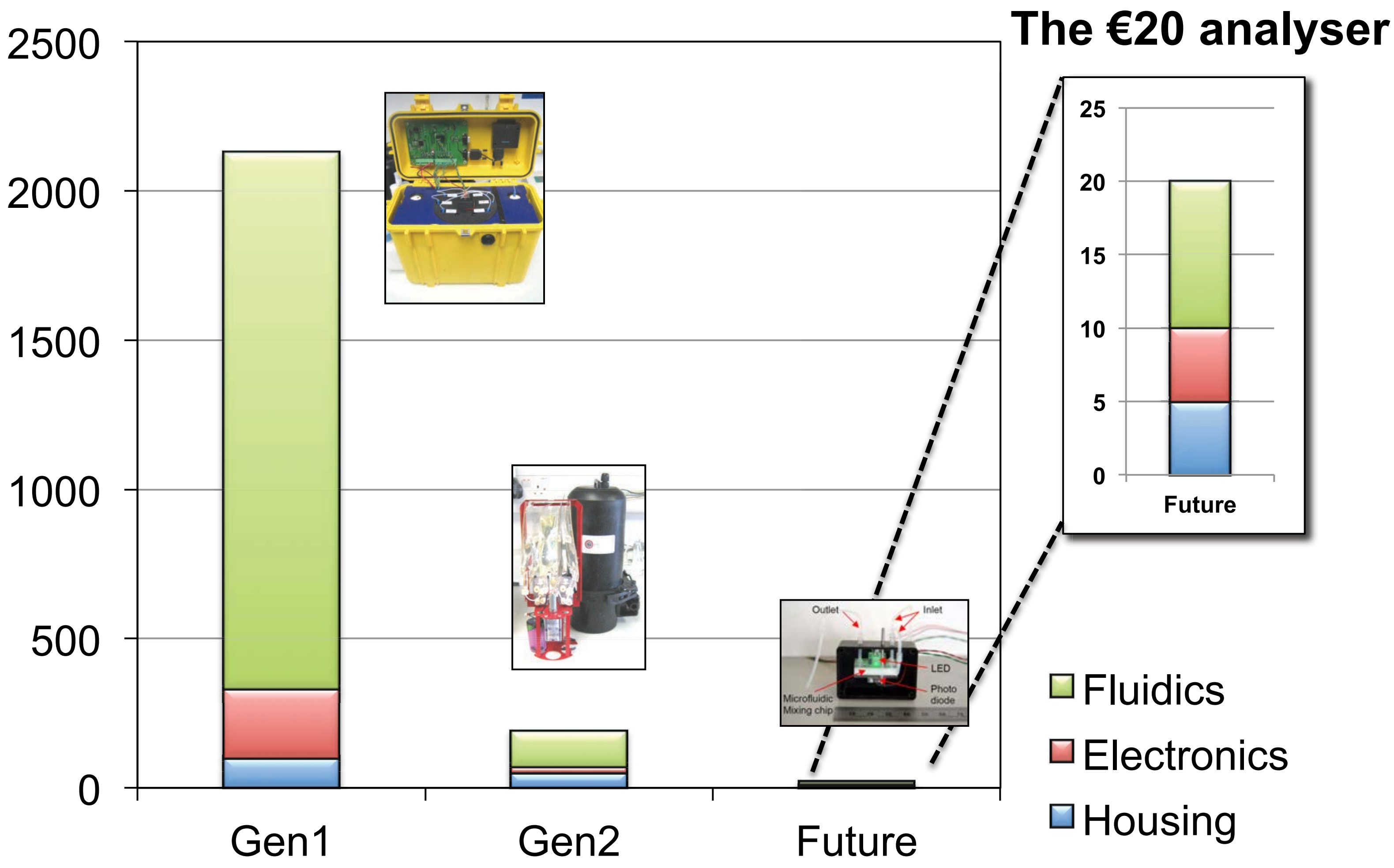
Autonomous Chemical Analyser



Achieving Scale-up

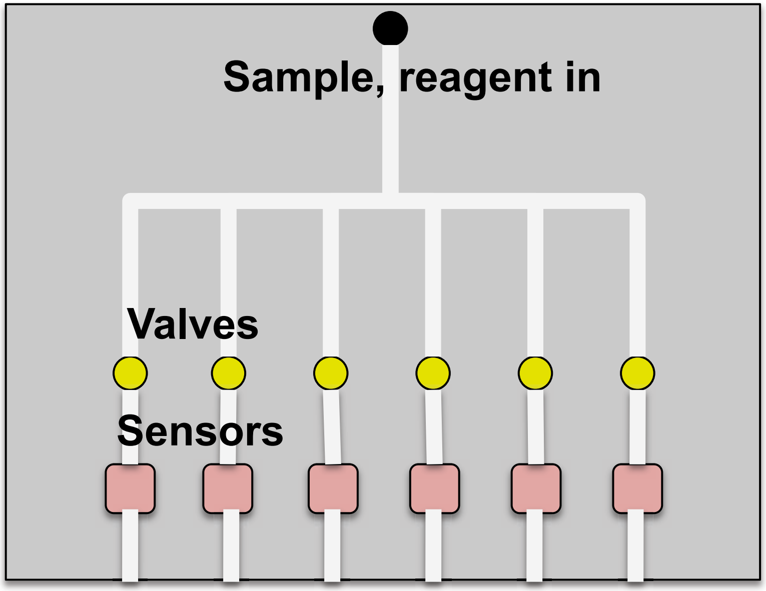


Cost Comparison Analyser (€)



Use Arrays of Sensors….?

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

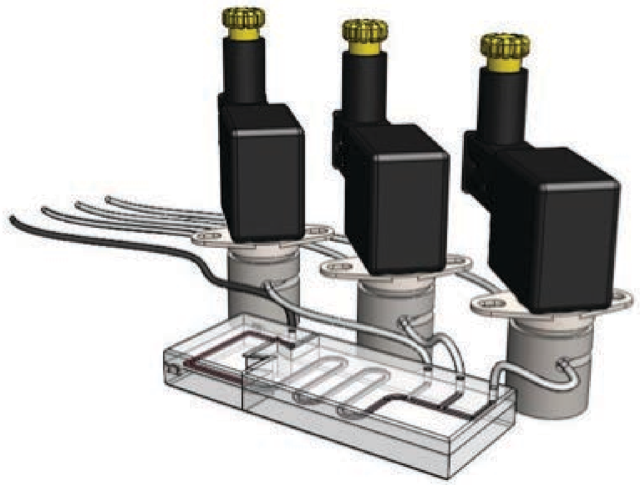


Then 50 sensors when used sequentially could provide an aggregated in-use lifetime of around 1 year

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

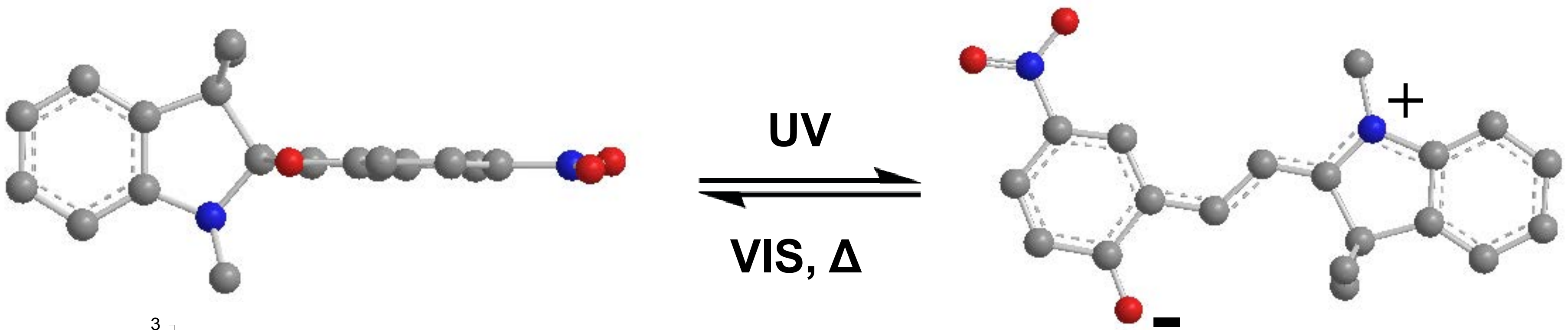
How to advance fluid handling in LOC platforms: re-invent valves (and pumps)!

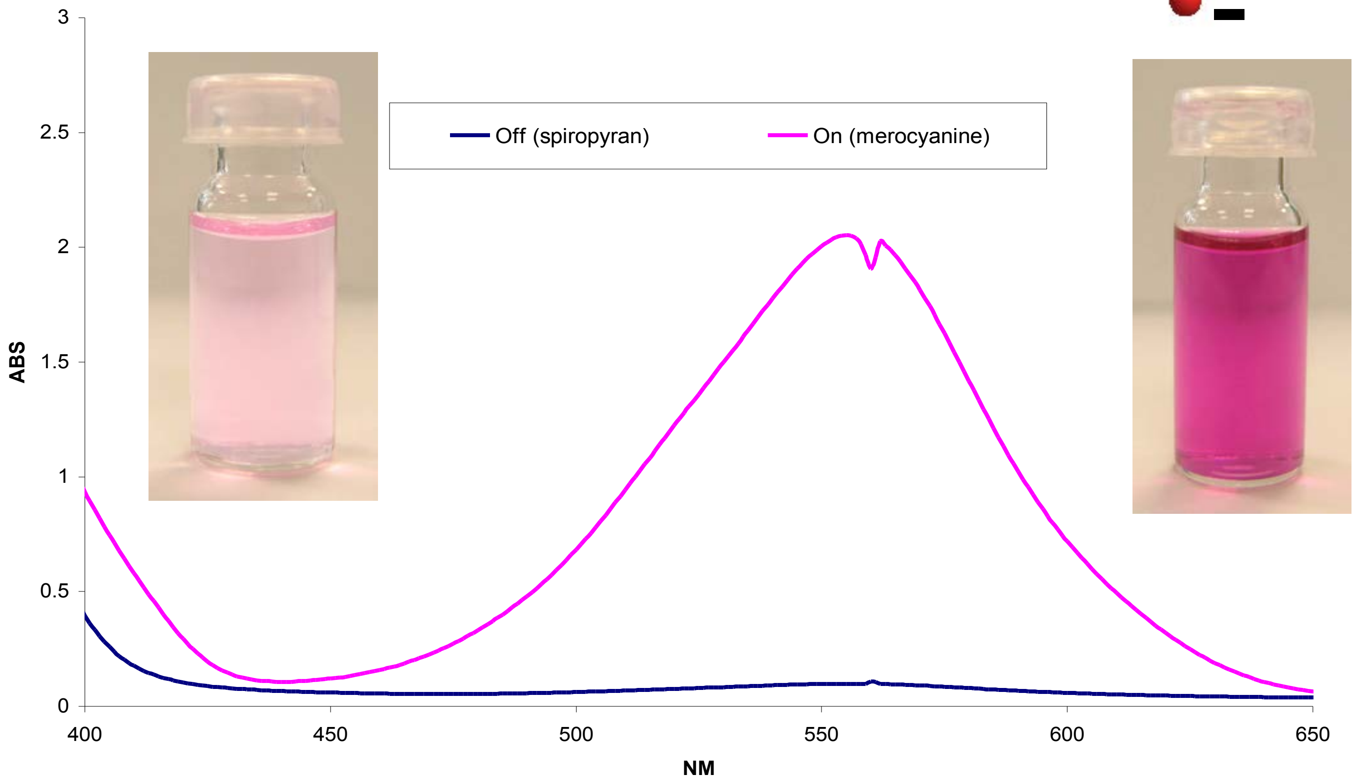
- **Conventional valves cannot be easily scaled down - Located off chip: fluidic interconnects required**
  - Complex fabrication
  - Increased dead volume
  - Mixing effects
- **Based on solenoid action**
  - Large power demand
  - Expensive



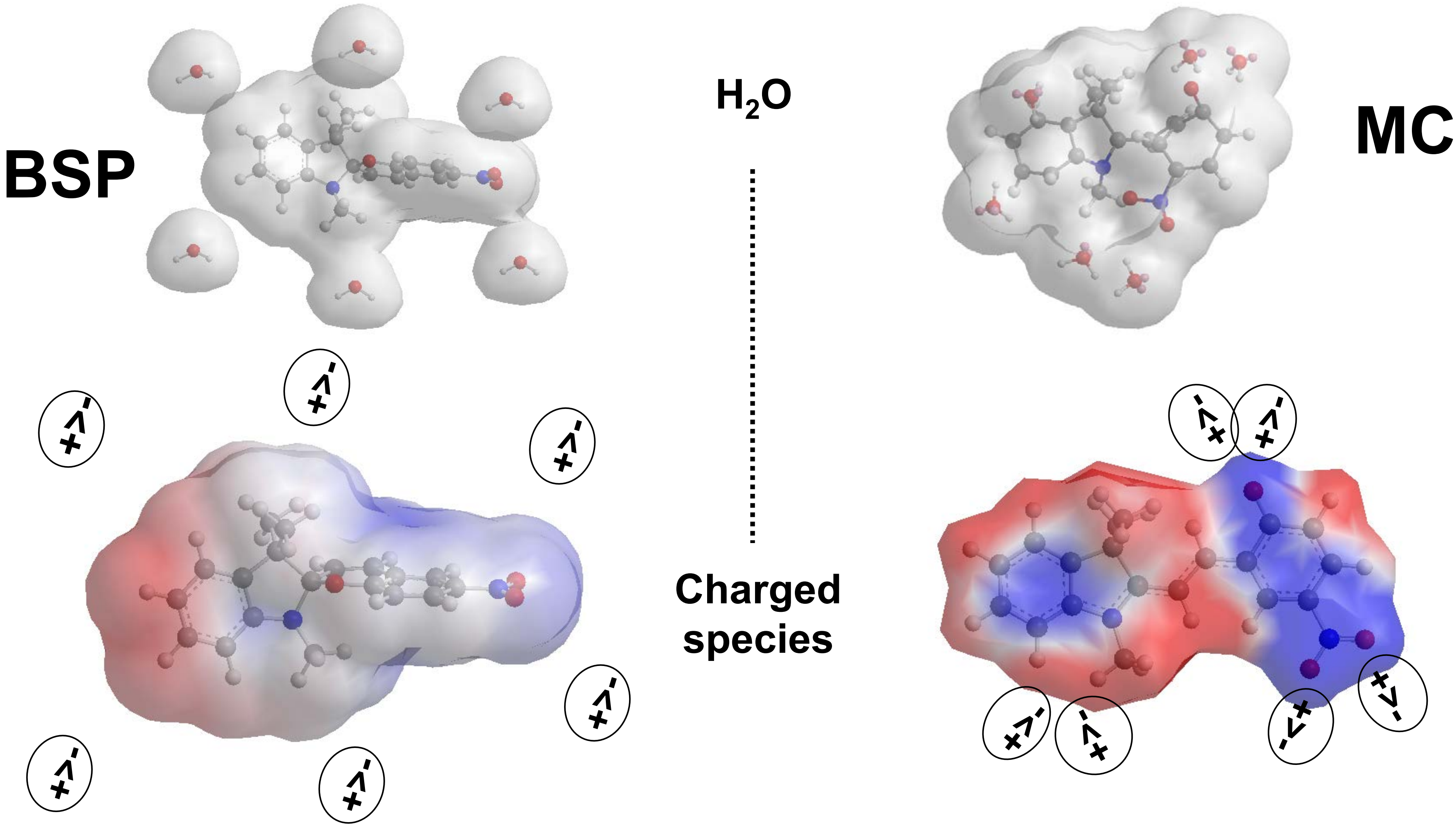
Solution: soft-polymer (biomimetic) valves fully integrated into the fluidic system

Photoswitchable Materials





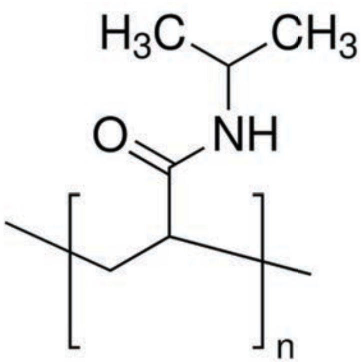
Non-specific (BSP) and specific (MC) Interactions

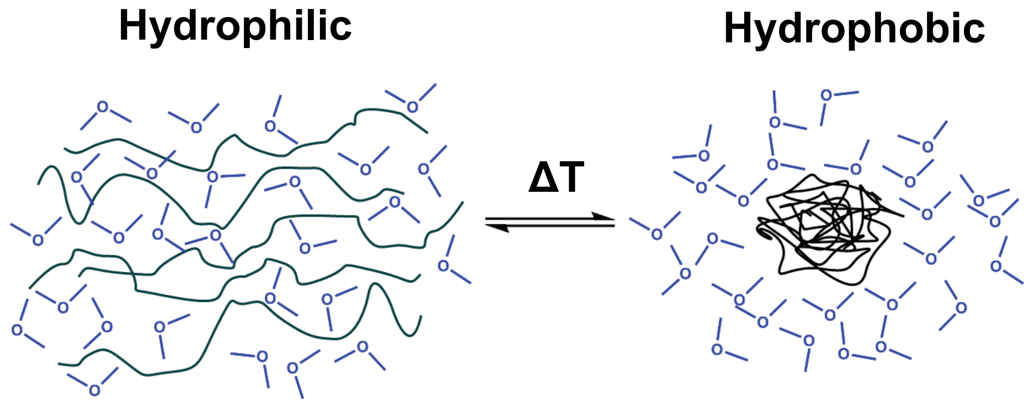


Poly(*N*-isopropylacrylamide)

- **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





Hydrated Polymer Chains

Loss of bound water -> polymer collapse

Polymer based photoactuators based on pNIPAAm

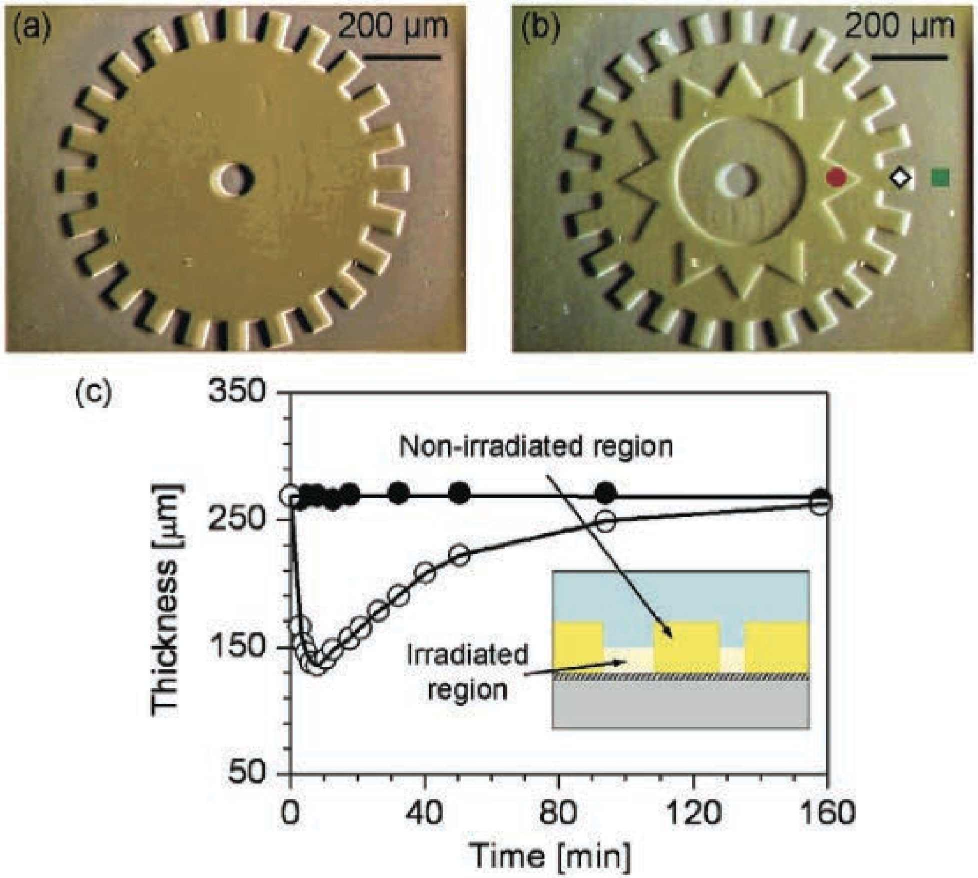
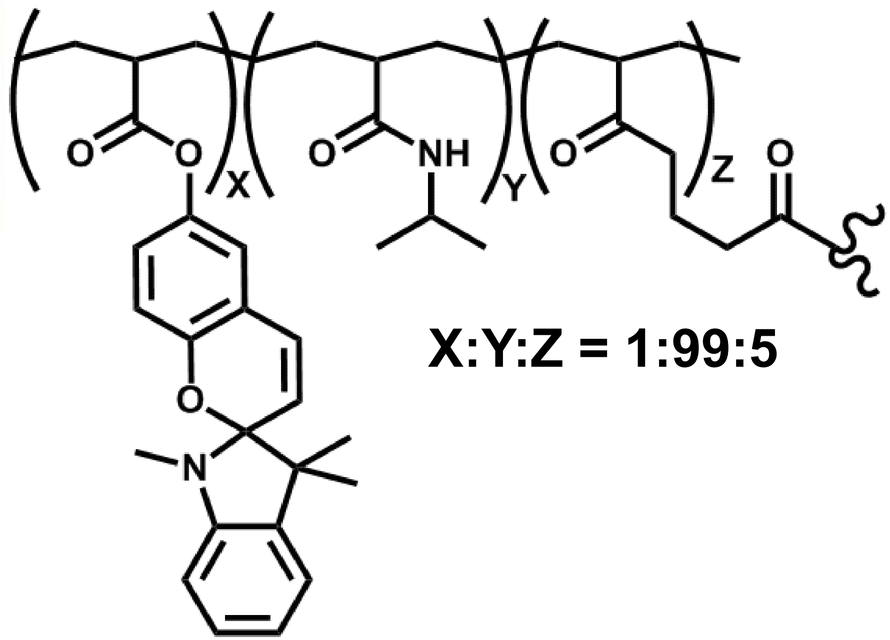


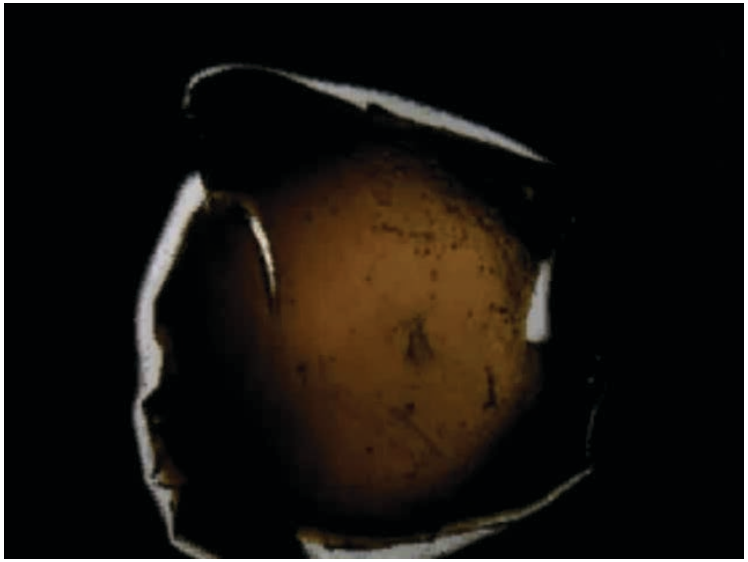
Figure 3. (a, b) Images of the pSPNIPAAm hydrogel layer just after the micropatterned light irradiation. Duration of irradiation was (●, red) 0, (◇) 1, and (■, green) 3 s. (c) Height change of the hydrogel layer in (●) non-irradiated and (○) irradiated region as a function of time after 3 s blue light irradiation.

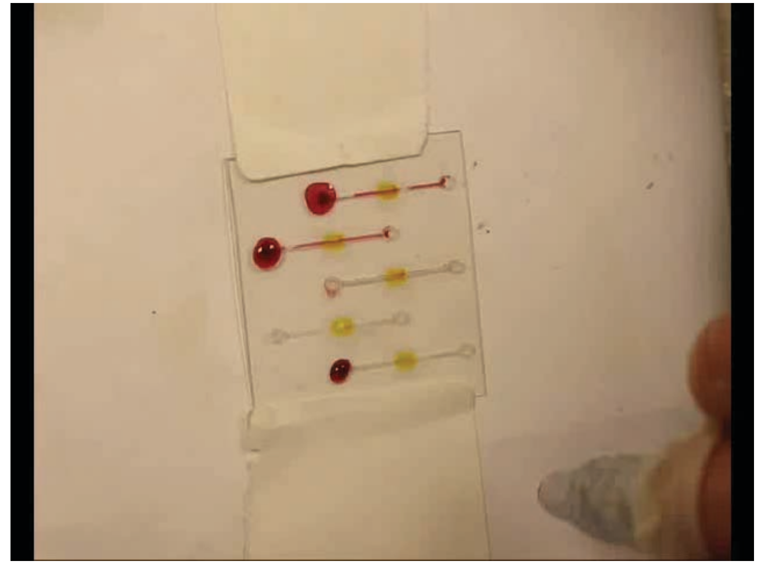


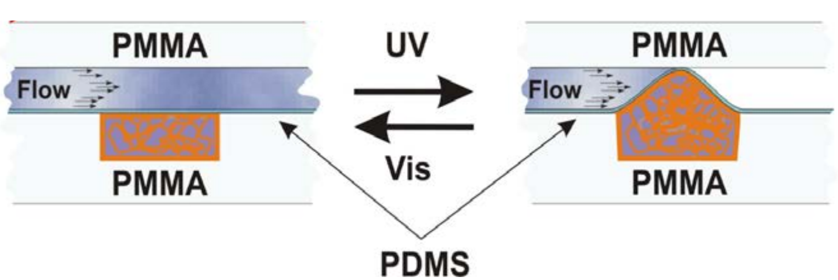
X:Y:Z = 1:99:5

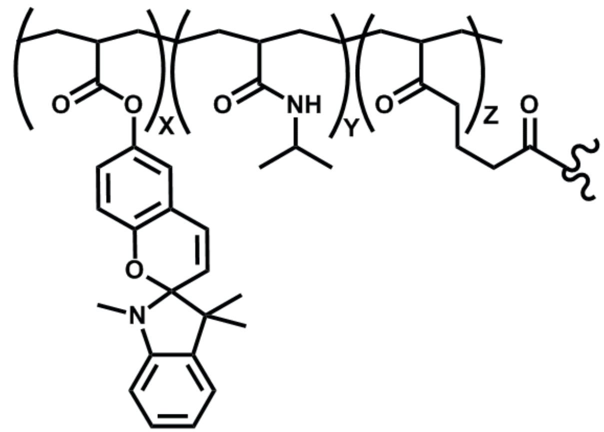
poly(N-isopropylacrylamide) (PNIPAAm)
Formulation as by Sumaru et al[1]
***1) Chem. Mater.*, 19 (11), 2730 -2732, 2007.**

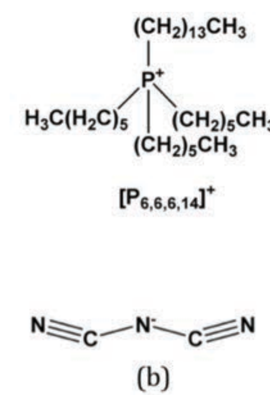
Photo-actuator polymers as microvalves in microfluidic systems







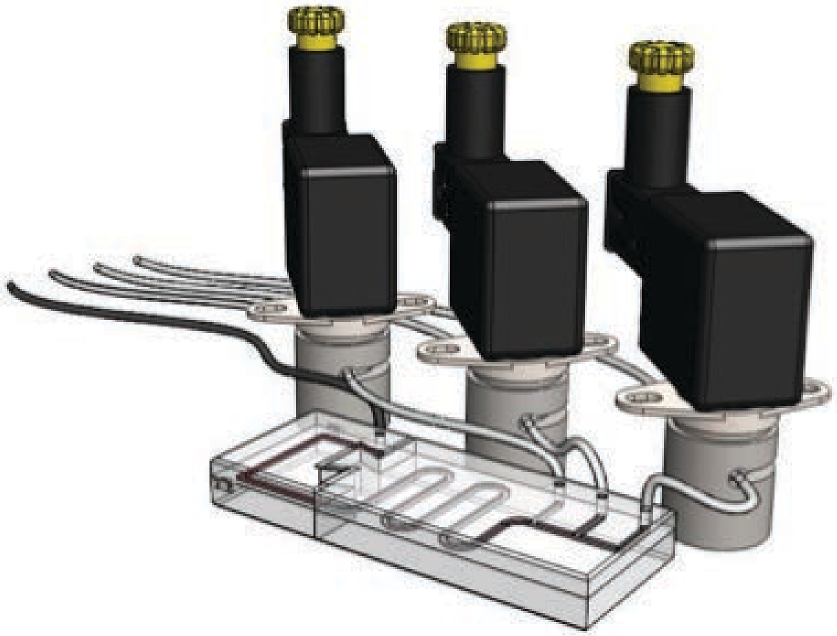




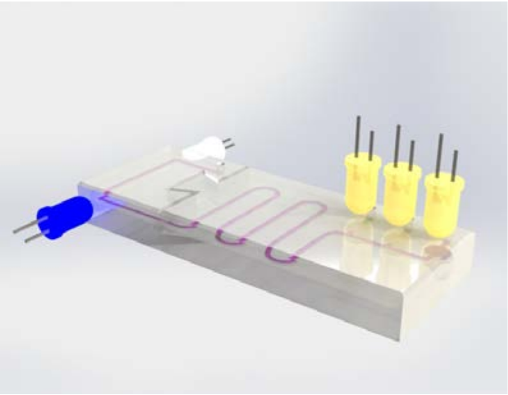
trihexyltetradecylphosphonium dicyanoamide $[P_{6,6,6,14}]^+[dca]^-$

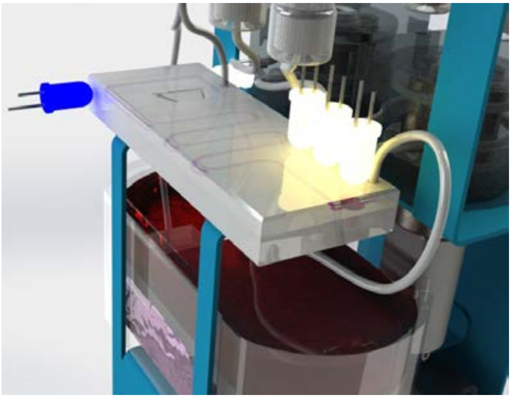
Ionogel-based light-actuated valves for controlling liquid flow in micro-fluidic manifolds, Fernando Benito-Lopez, Robert Byrne, Ana Maria Raduta, Nihal Engin Vrana, Garrett McGuinness, Dermot Diamond, Lab Chip, 10 (2010) 195-201.

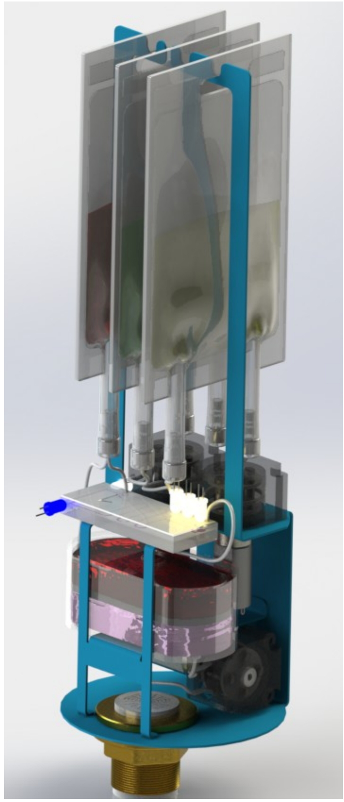
Can we go from this:



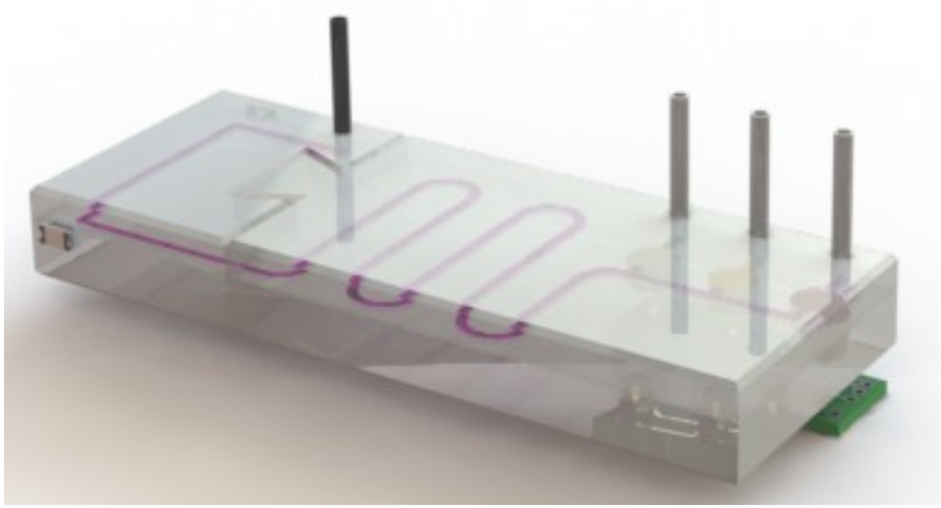
To Photo-Fluidics & Detection

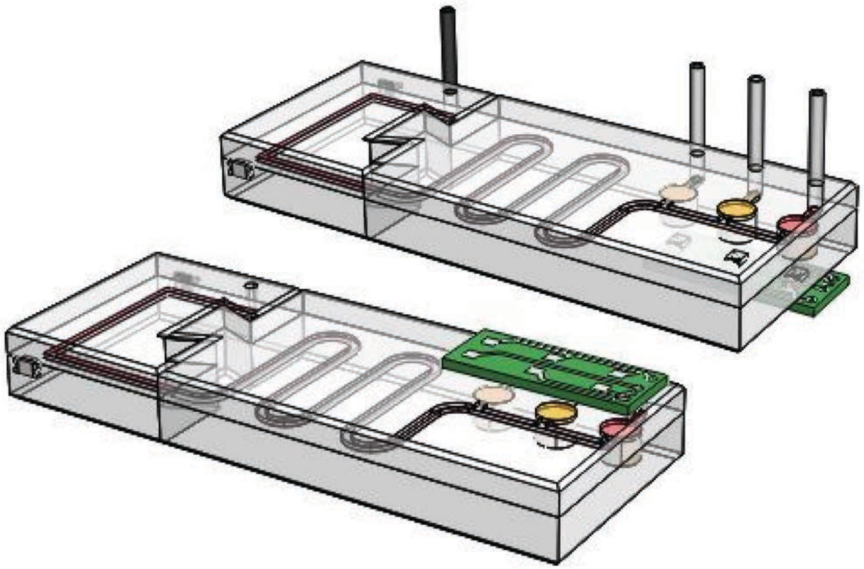






Fluidic Chip is completely sealed – no need for interconnects to detection/flow components





- **Fluidic handling completely integrated into the microfluidic chip**
- **Valve structures created post chip fabrication by in-situ photopolymerisation**
- **Valves actuated remotely using light (LEDs)**
- **Detection is via LED colorimetric/fluoescence measurements**

Thanks to…..

Thanks for the invitation

sfi DCU UCC OÉ Gaillimh NUI Galway UCD DUBLIN