Sensing at the Global-Scale: Current Status and Future Possibilities

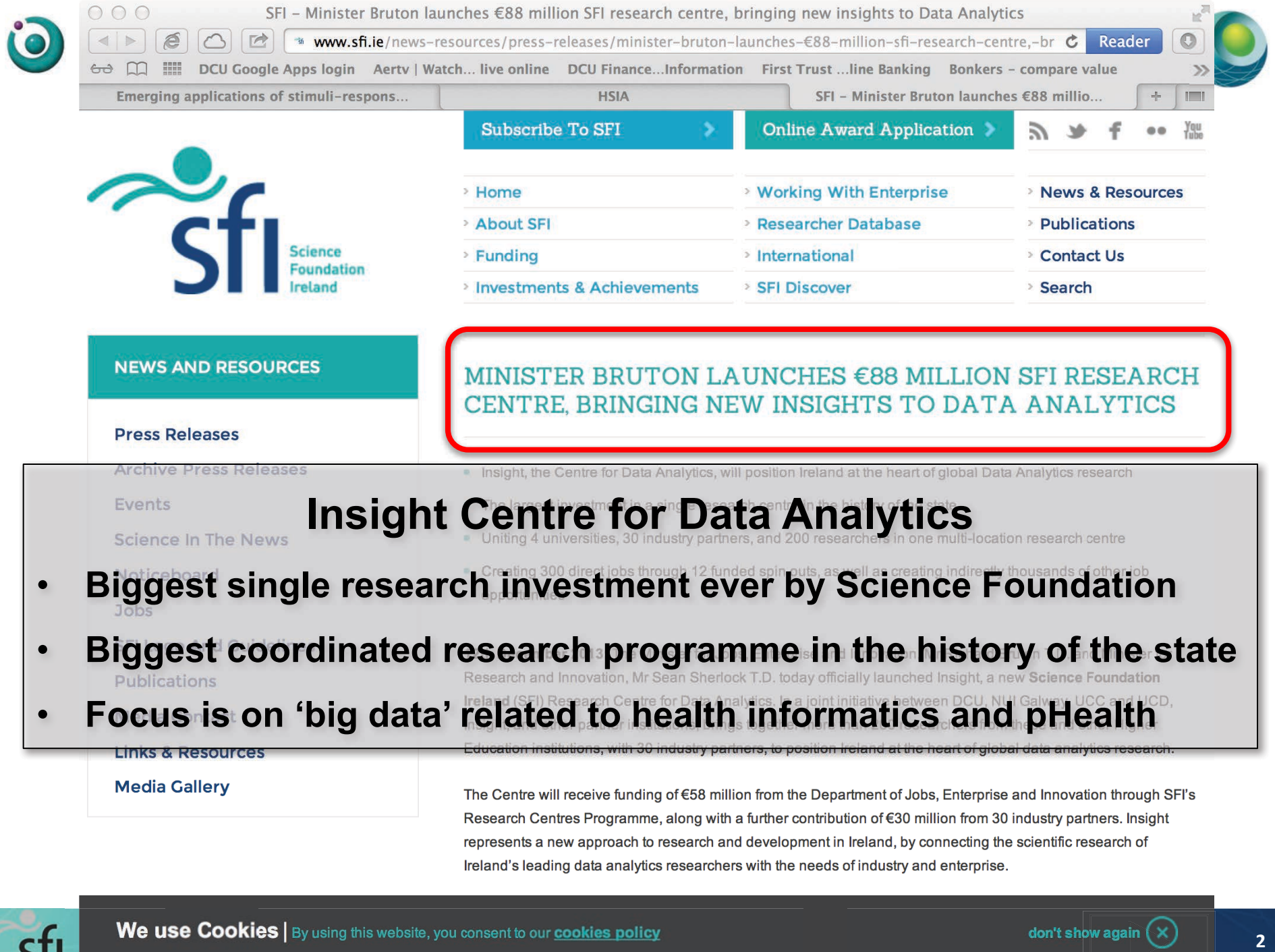
Dermot Diamond,

INSIGHT Centre for Data Analytics, National Centre for Sensor Research, Dublin City University, Dublin 9, Ireland

Invited presentation for the Workshop

Future Water Resource Needs for the Nation: Water Science and Research at the U.S. Geological Survey

23 January 2018



Insight Centre for Data Analytics

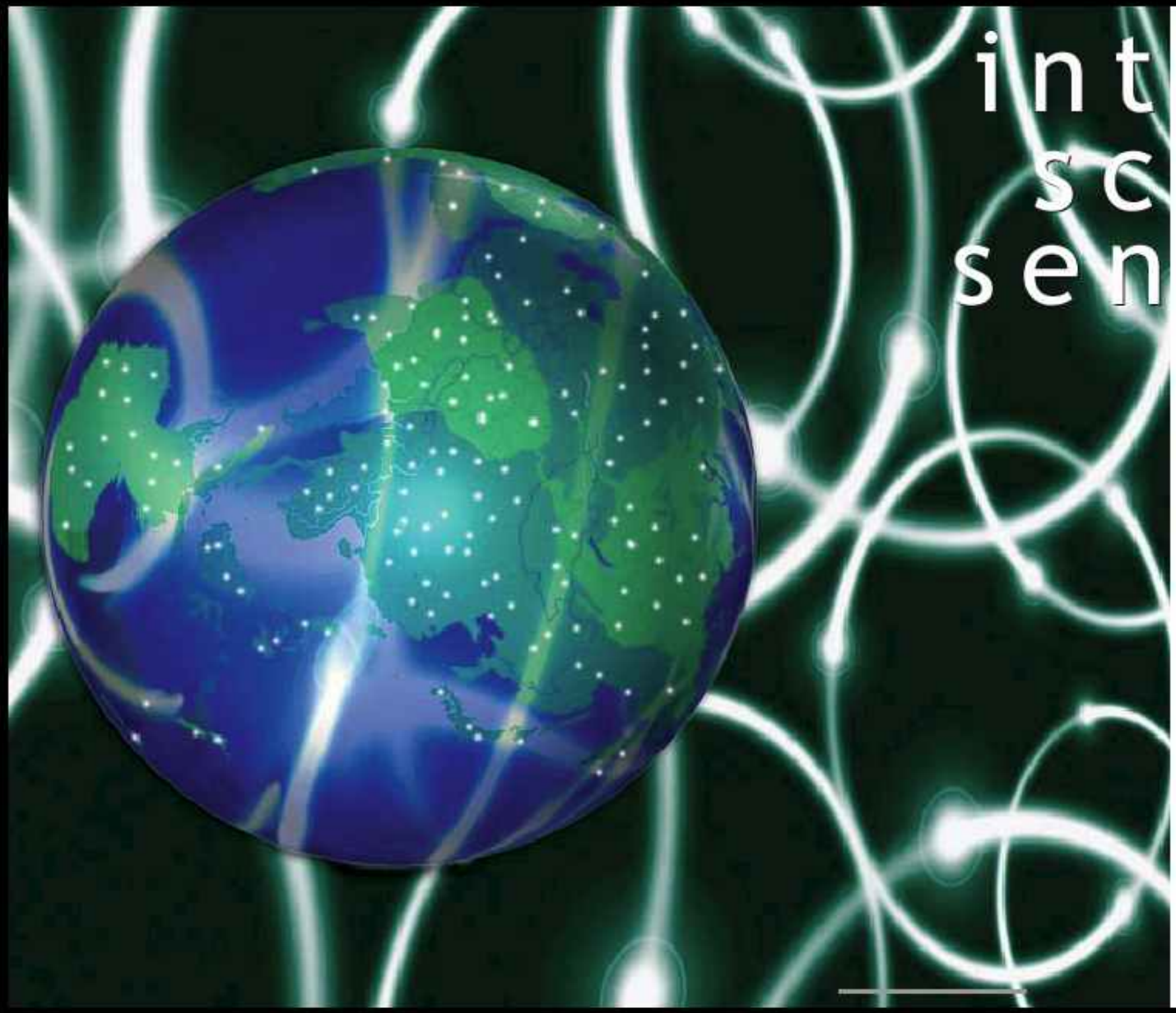
- **Biggest single research investment ever by Science Foundation**
- **Biggest coordinated research programme in the history of the state**
- **Focus is on 'big data' related to health informatics and pHealth**

Fundamental Challenge for Delivering Large Scale Environmental Sensor Networks:

Can we deliver chem/bio-sensing platforms capable of long-term autonomous operation in remote (hostile) environments at a reasonable cost?

‘Deploy and Forget’ long-term use model

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



internet scale sensing

Dermot Diamond
Dublin City University
(Ireland)

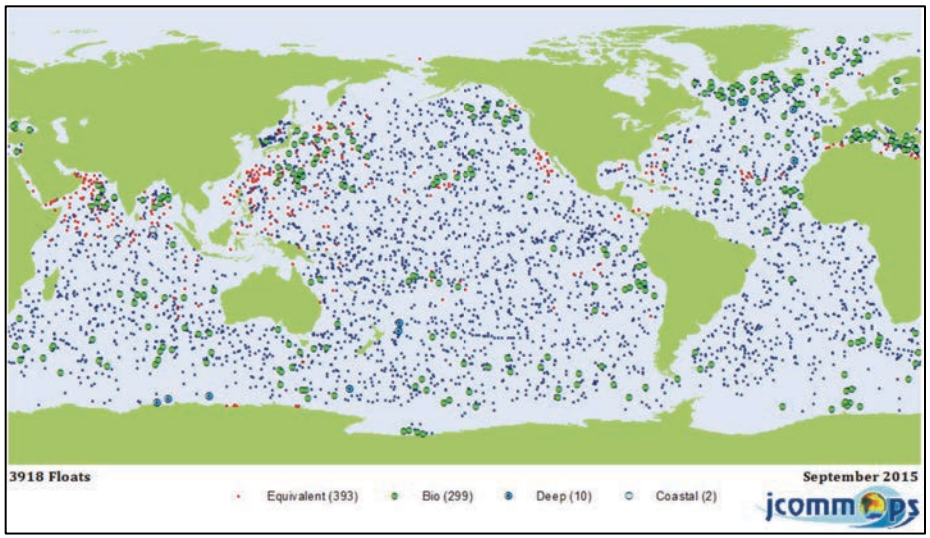
Incredible advances in digital communications and computer power have profoundly changed our lives. One chemist shares his vision of the role of analytical science in the next communications revolution.

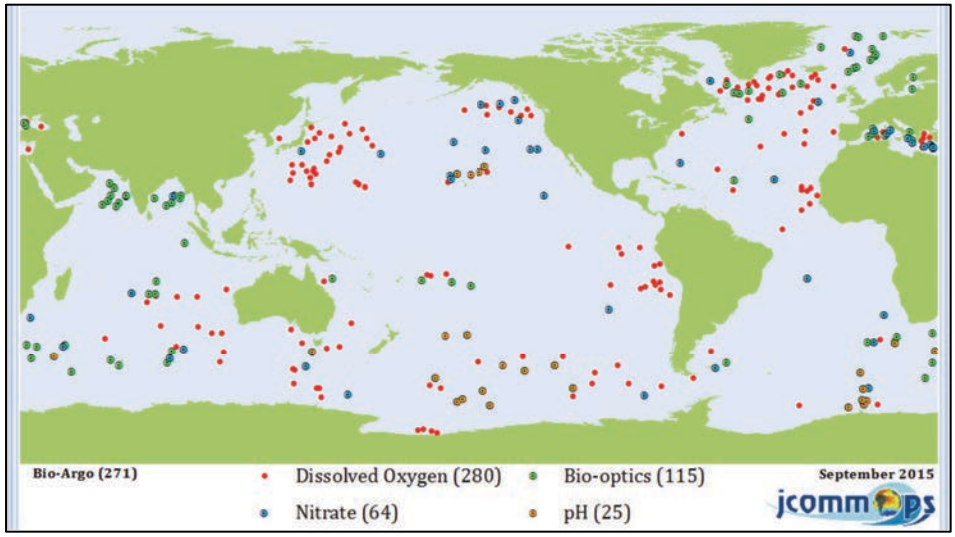
Digital communications networks are at the heart of modern society. The digitization of communications, the development of the Internet, and the availability of relatively inexpensive but powerful mobile computing technologies have established a global communications network capable of linking billions 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

Argo Project (accessed March 20 2016)





- Ca. 4,000 (3918) floats: temperature and salinity
- Bio/Chem: Nitrate (64), DO (280), Bio-optics (115), pH (25)

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

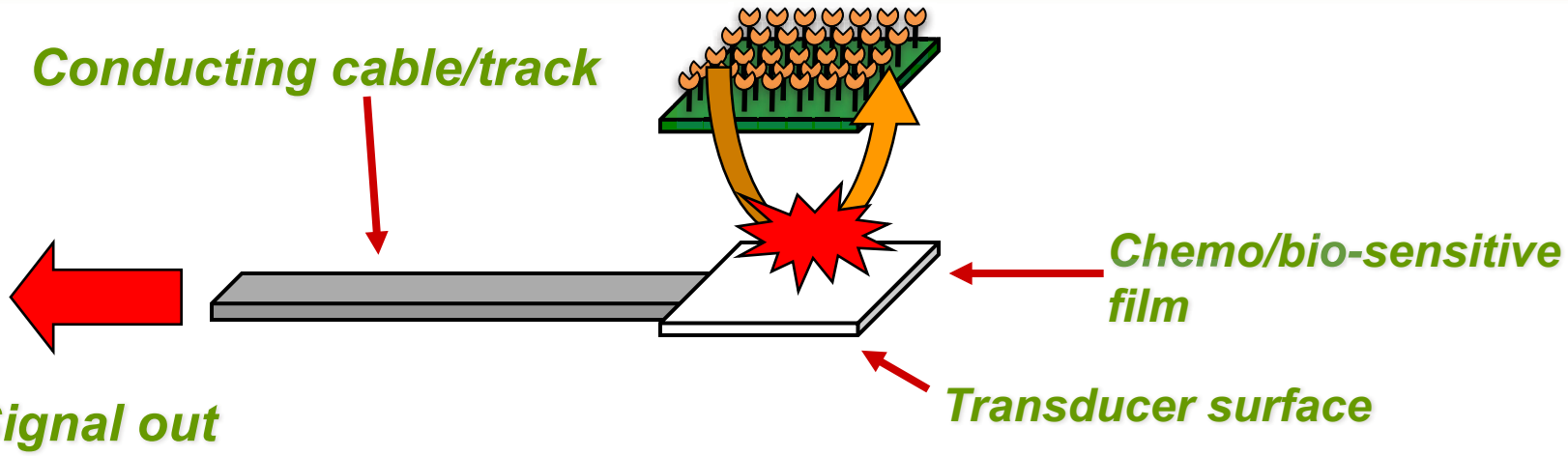
@€60K ea!

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

What is a Chemo/Bio-Sensor?

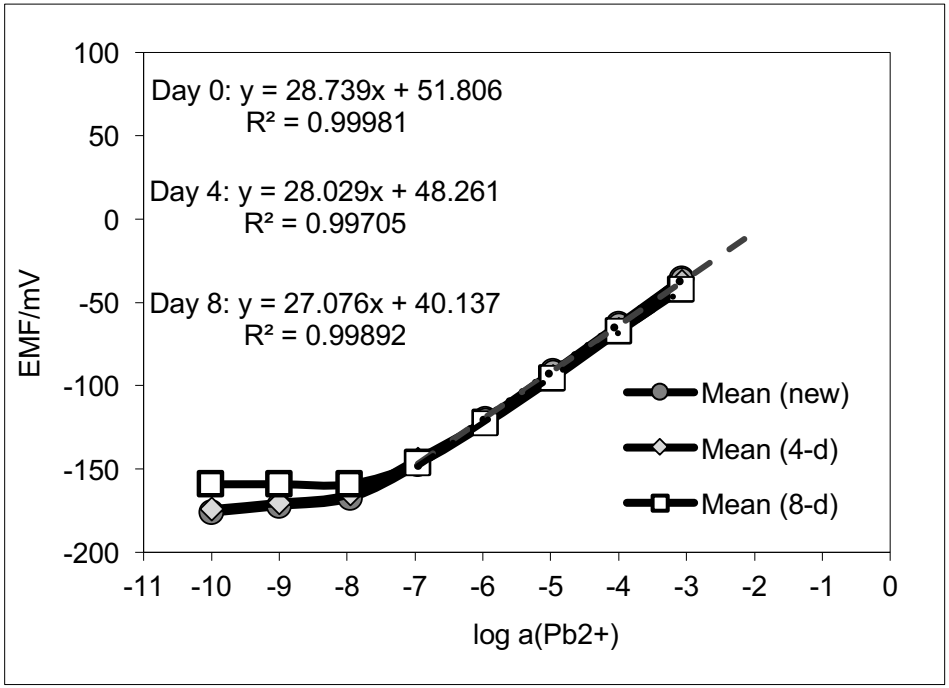
'a device, consisting of a transducer and a chemo/bio-sensitive film/membrane, that generates a signal related to the concentration of particular target analyte in a given sample'



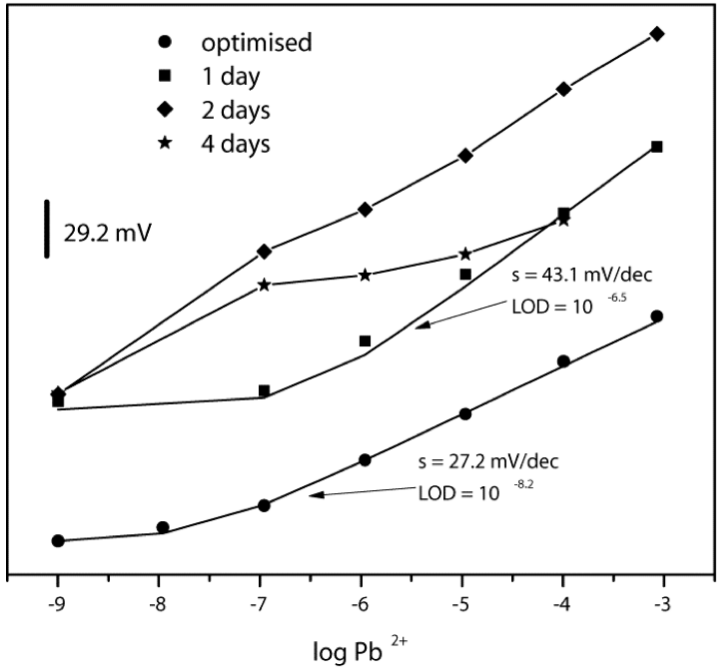
Chemo/Bio-sensing involves selective **BINDING** & **TRANSDUCTION** on the device surface; this also implies the target analyte MUST meet the device surface (**LOCATION** & **MOVEMENT**). It provides a signal observable in the macroscopic world (**COMMUNICATION**)

Change in Electrode Function over Time

See Electrochimica Acta 73 (2012) 93–97



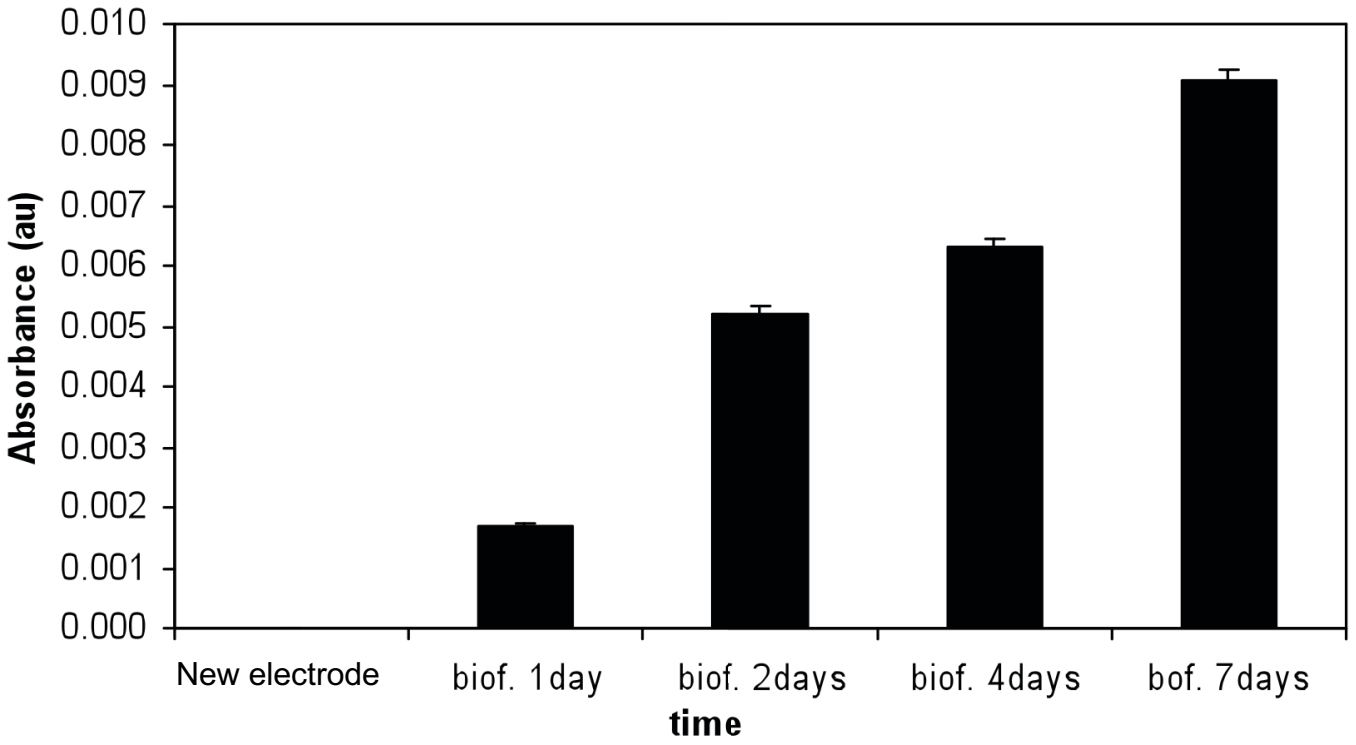
stored in 10^{-9}M Pb^{2+}, pH=4



Continuous contact with river water

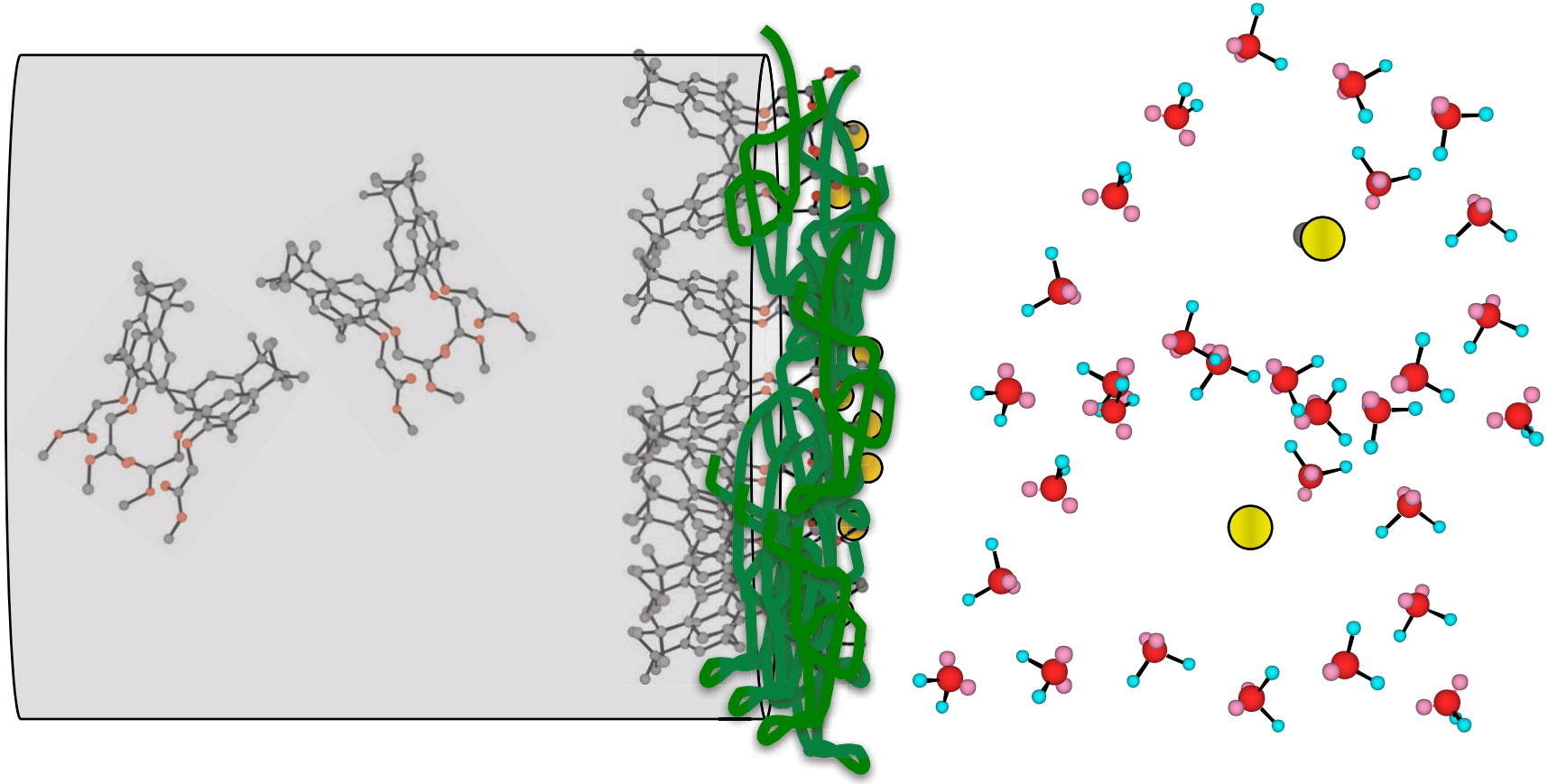
Conventional PVC-membrane based ISEs

Biofilm Formation on Sensors



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

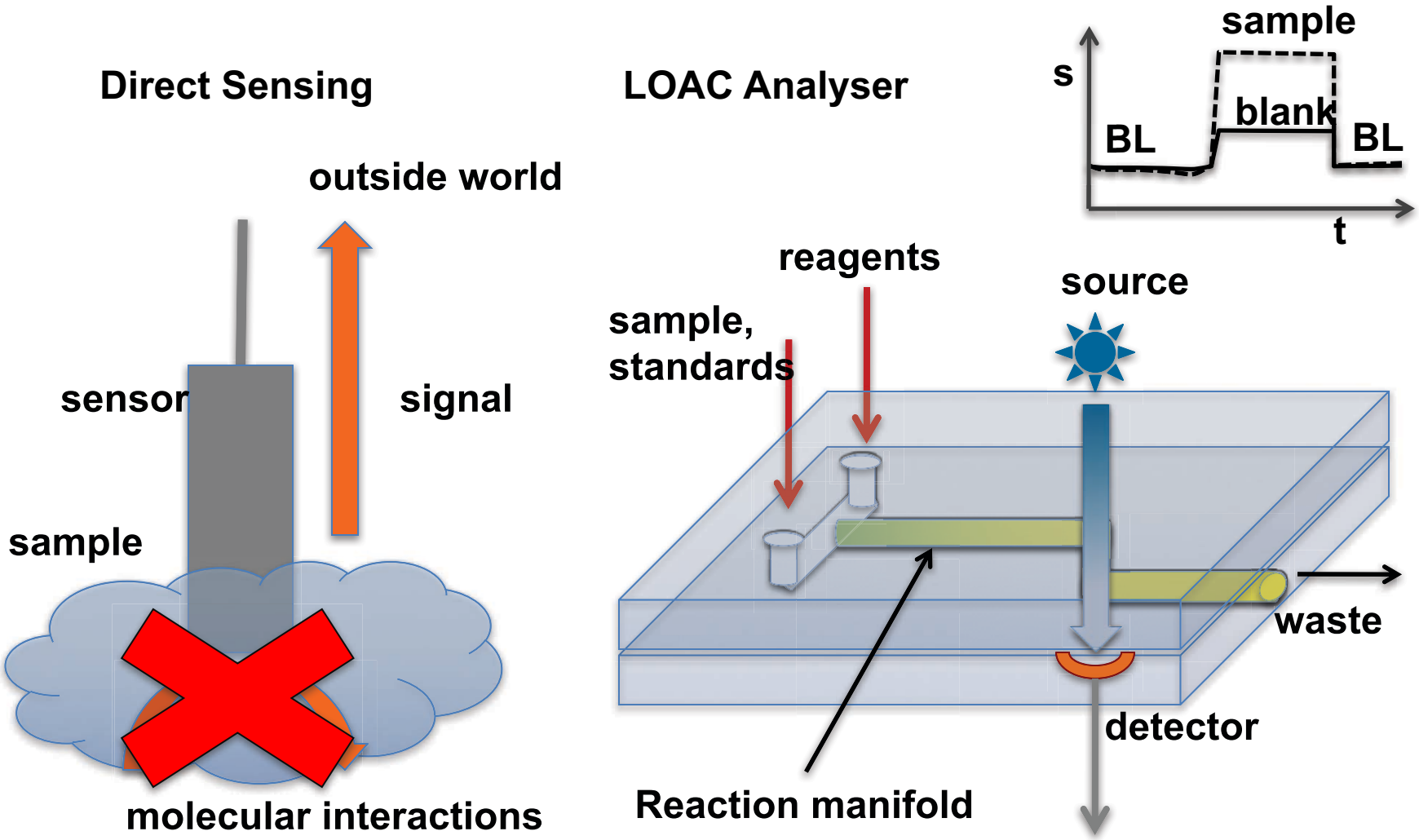
Control of membrane interfacial exchange & binding processes



Remote, autonomous chemical sensing is a tricky business!

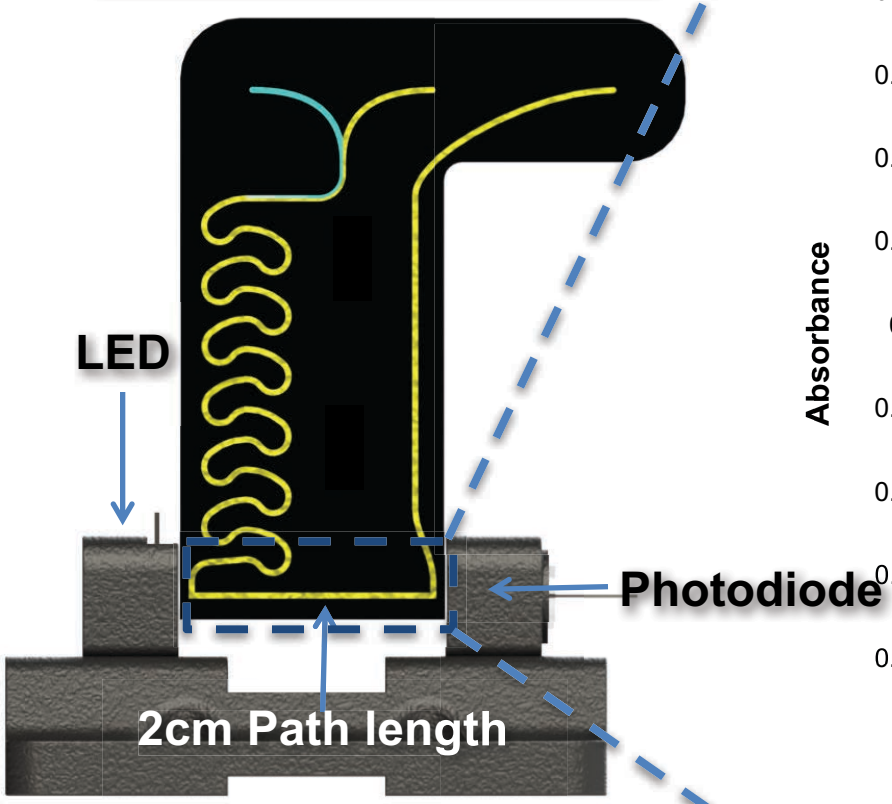
Osberstown – 3 week deployment

Direct Sensing vs. Reagent Based LOAC/ufluidics



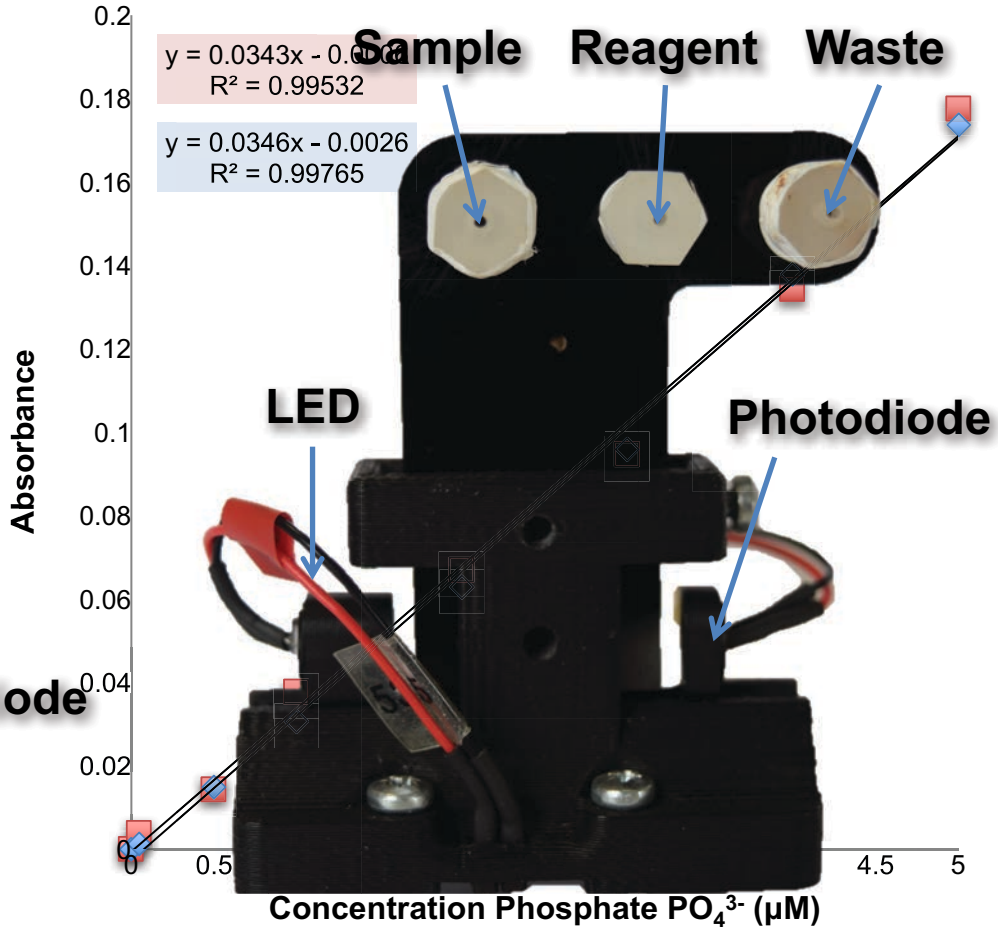
Reading on Chip

Phosphate detection on-chip



3D Render

Phosphate (0-5µM)



Manufactured Chip

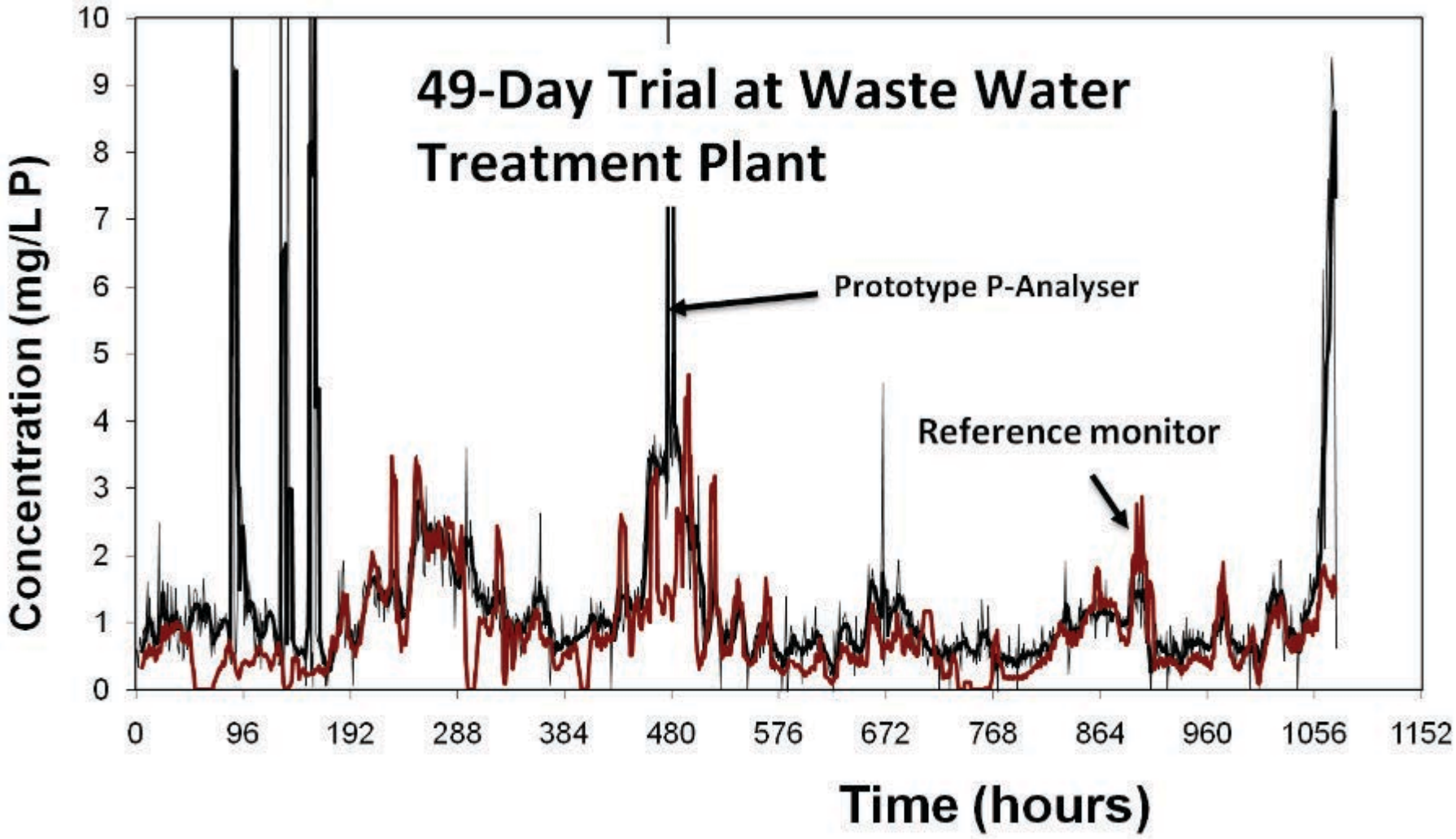
Prototype Testing – Generation 3

Milano San Rocco WWTP

Available Sampling Points:

1. Output water after Sand Filtration
2. Output water after the Clarifier
3. Activated Sludge (Biological Tank)
4. Input Water

Autonomous Chemical Analyser



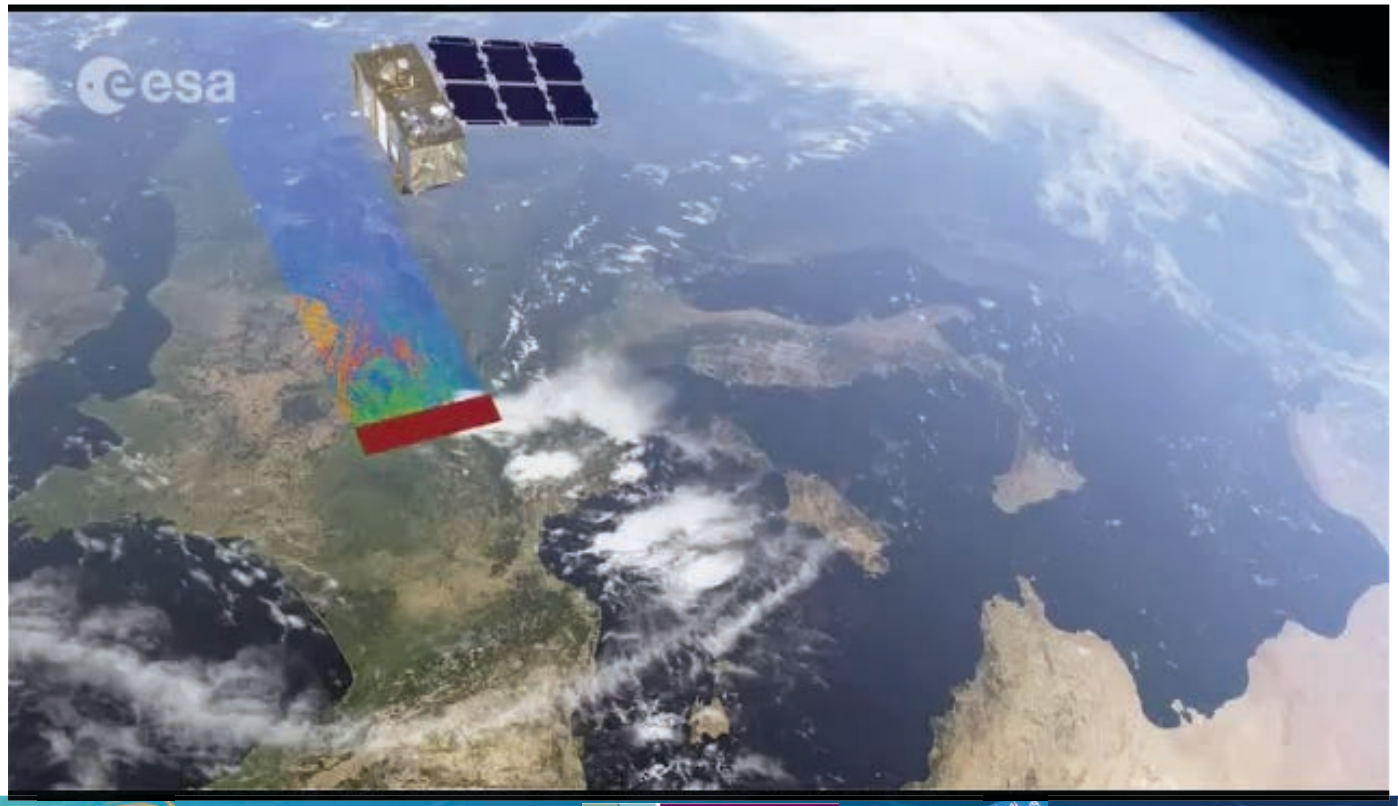
J. Cleary, C. Slater, D. Diamond, Analysis of phosphate in wastewater using an autonomous microfluidics-based analyser, World Academy of Science, Engineering and Technology. 52 (2009) 196–199.

Integrate Data from in-situ and Satellite Sources: Surrogate Sensing

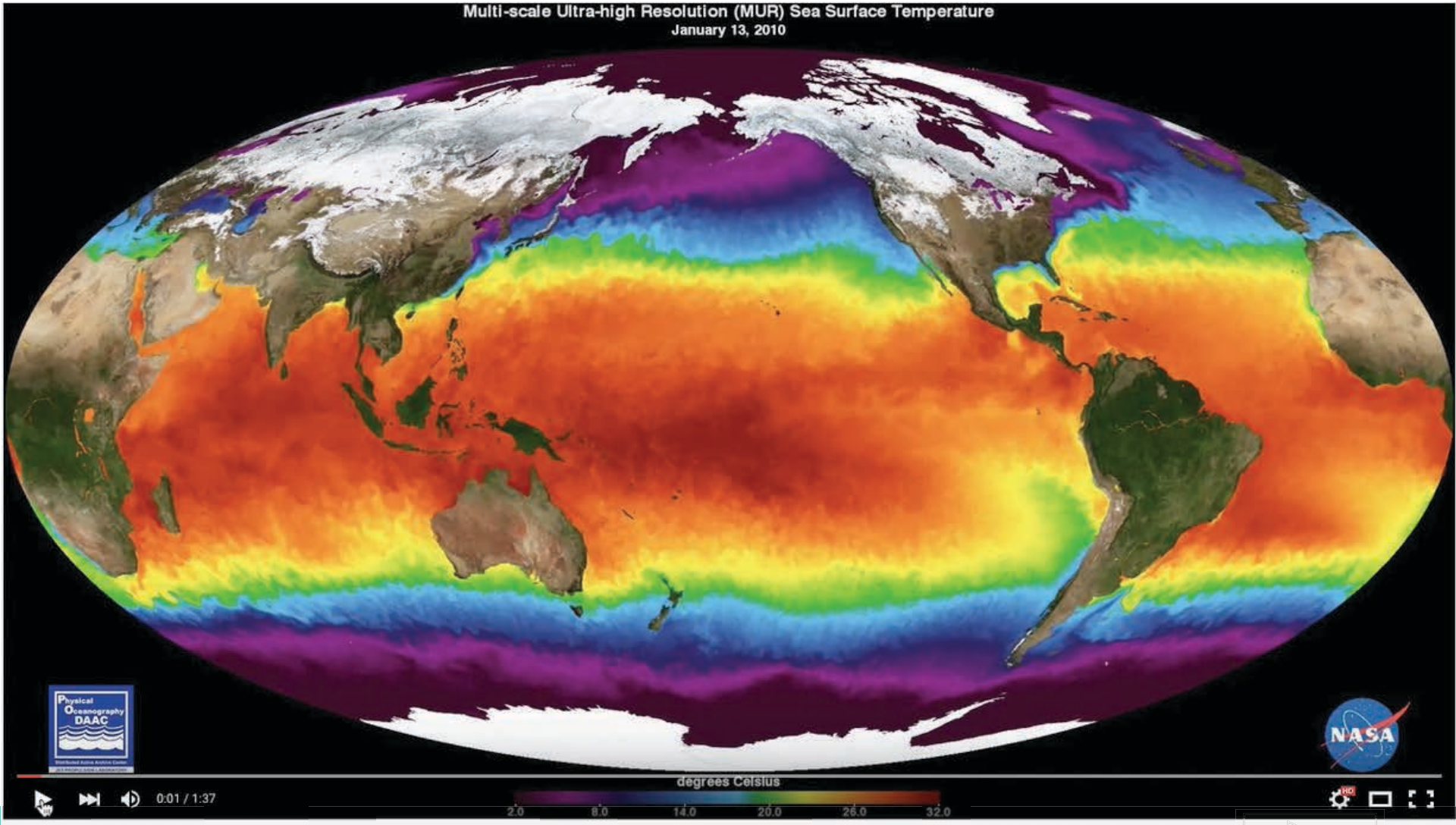
- **In-Situ Physical Sensors/Transducers**
  - Temperature, salinity/conductivity, colour ->**ground truth**
- **Chemical Sensors and Biosensors**
  - pH, DO, Nutrients, Heavy Metals, Biotargets
- **Earth Observation – satellite remote sensing**
  - Global Coverage, spatial resolution improving
  - Sensors for Physical Parameters e.g. temperature, colour,
  - Specific gases in the atmosphere via multispectral imaging
  - Drones increasingly being used

Satellite Remote Sensing

- **Big Data:** An IKONOS **4-band multispectral image** at **1-m** pixel size covering an area of 10 km by 10 km, digitized at 11 bits (stored at 16 bits), has a data volume of **200 MB per image**.
- Coverage is not continuous
- Image quality depends on weather

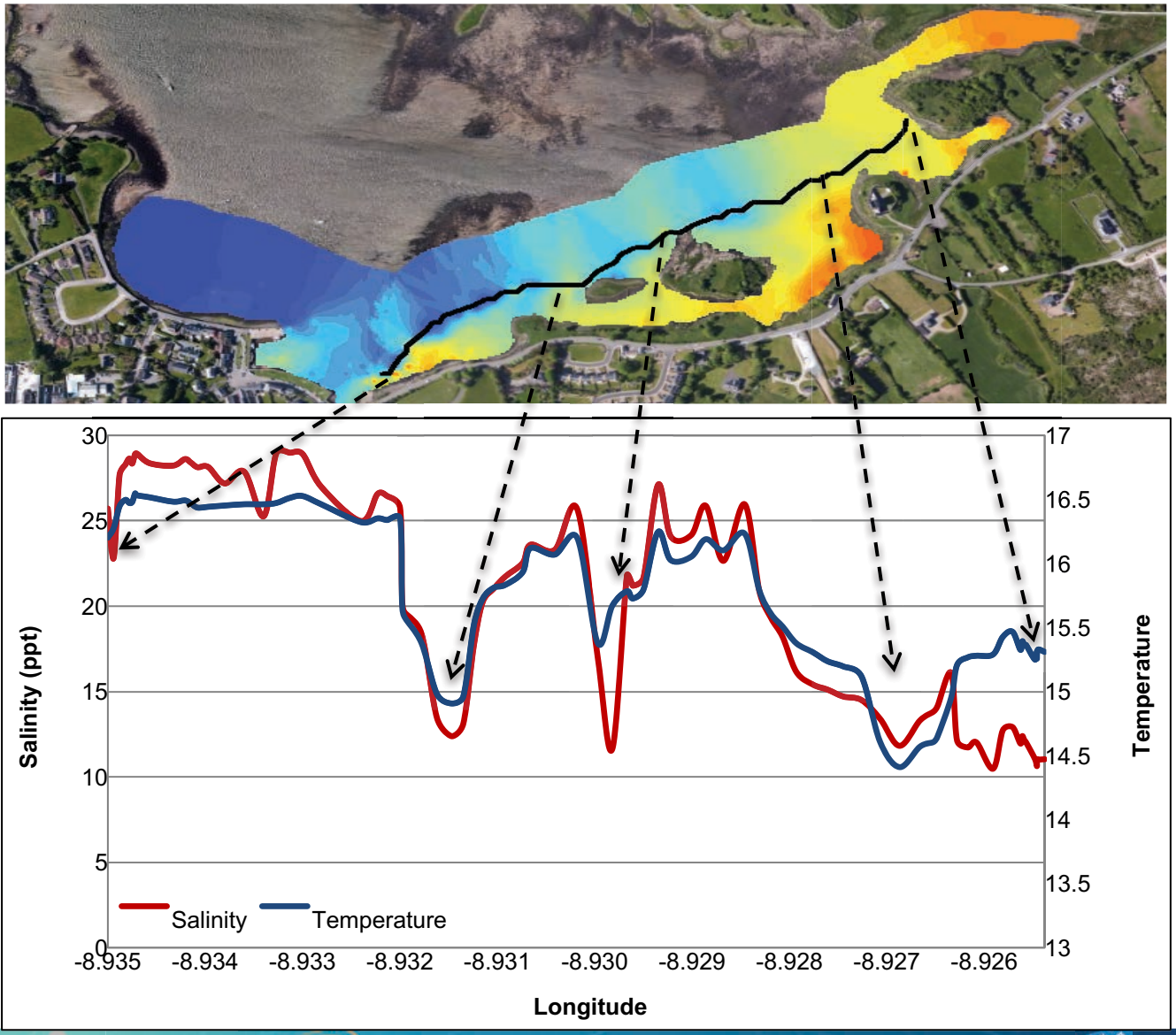


Global Sea Surface Temperature Patterns



The Multi-Scale Ultra-High Resolution (MUR) Sea Surface Temperature (SST) Data Set Animation

Correlation of In-Situ Temperature and Salinity Measurements (East-West Transect)

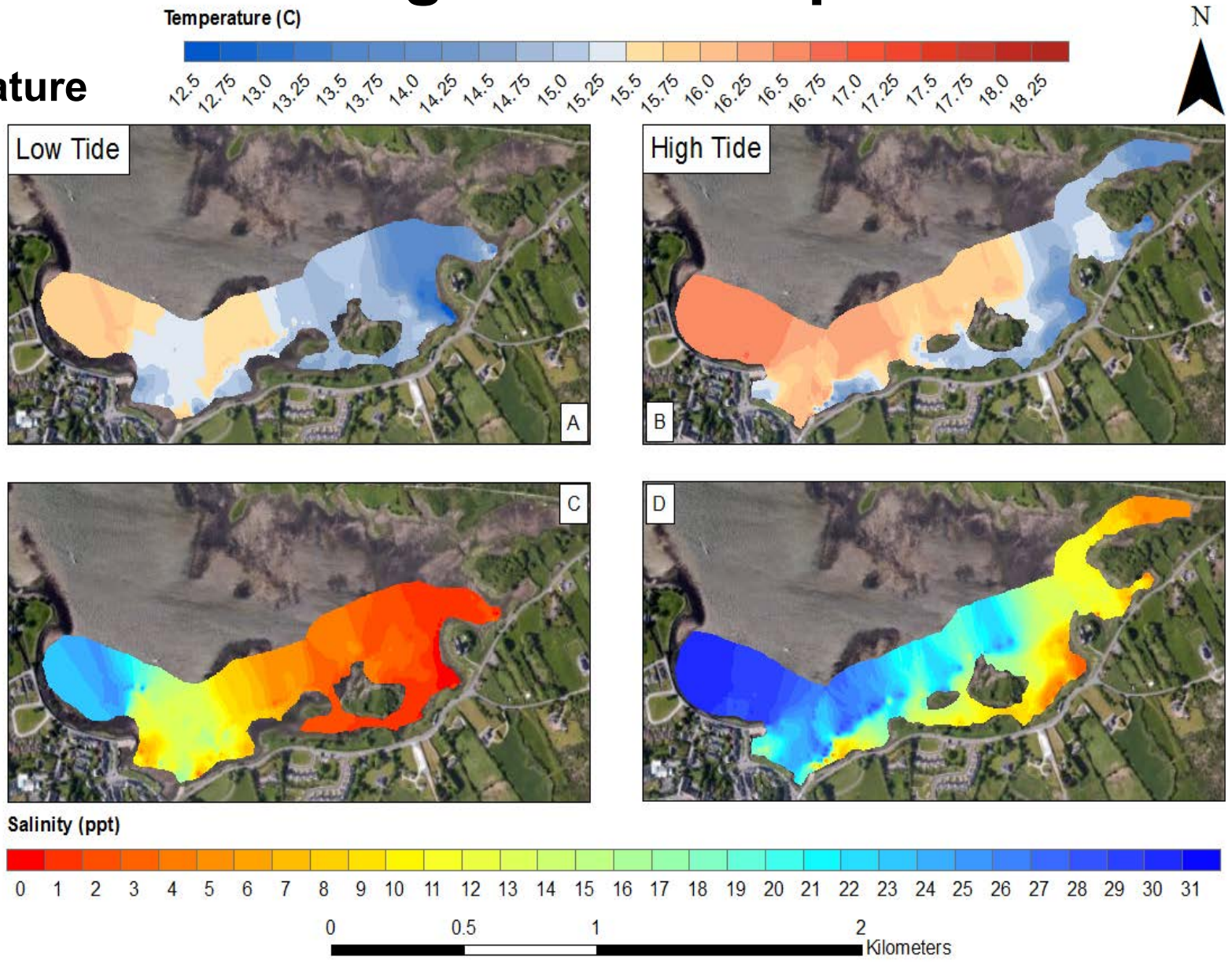


Temperature and salinity transect, stretching left to right from Kinvara pier (west) to Dunguaire castle (east); with salinity contour plot from in-situ bay survey

The effect of individual cold-water plumes is clearly evident in the salinity and temperature data.

Low Tide/High Tide Comparison

Temperature



Salinity

Achieving Scale-up for Environmental Sensor Networks

Current platforms

2. Revolutionary breakthroughs in materials science; hidden complexity, biomimetic platforms, all fluid handling integrated on chip, indefinitely self-sustaining

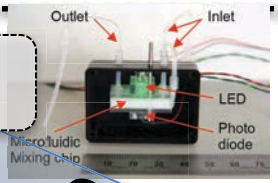
Cost/Complexity->

€>20,000

1

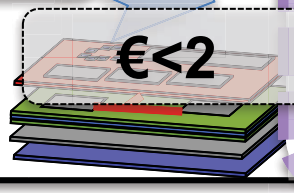
€>2,000

€<200



2

€<20



€<2

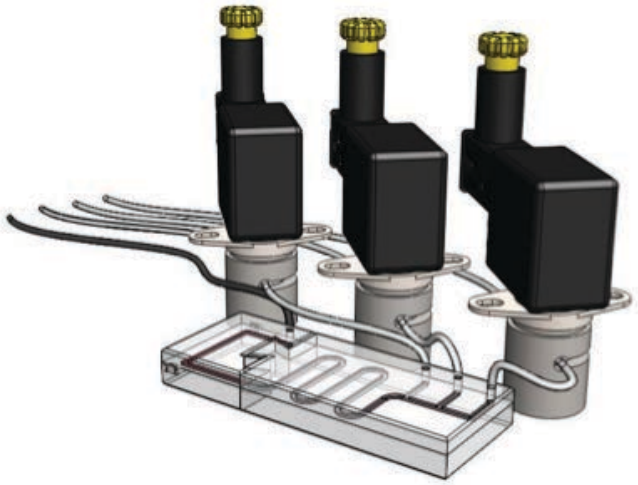
1. Evolutionary development, cost driven down, reliable, improved scalability

Massively scaled deployments of the future

Scalability ->

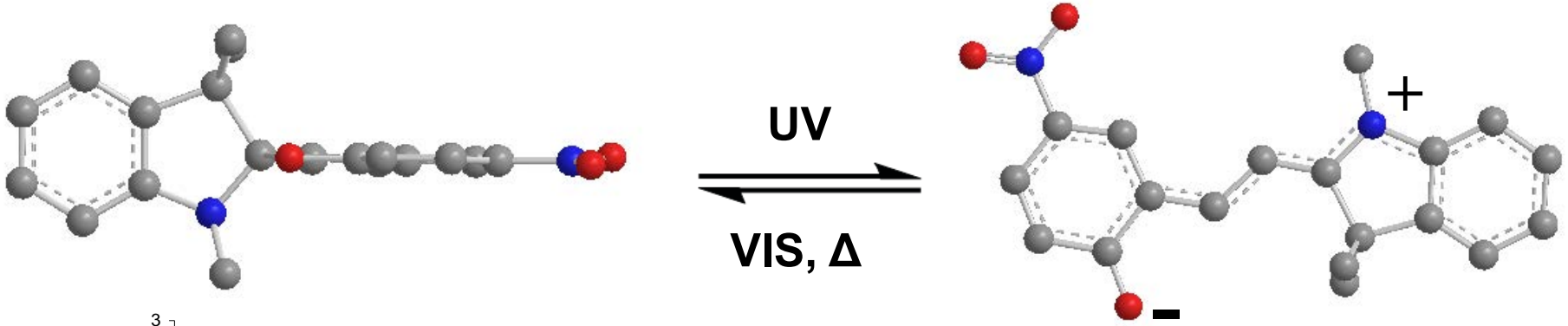
How to advance fluid handling in LOC platforms: re-invent valves (and pumps)!

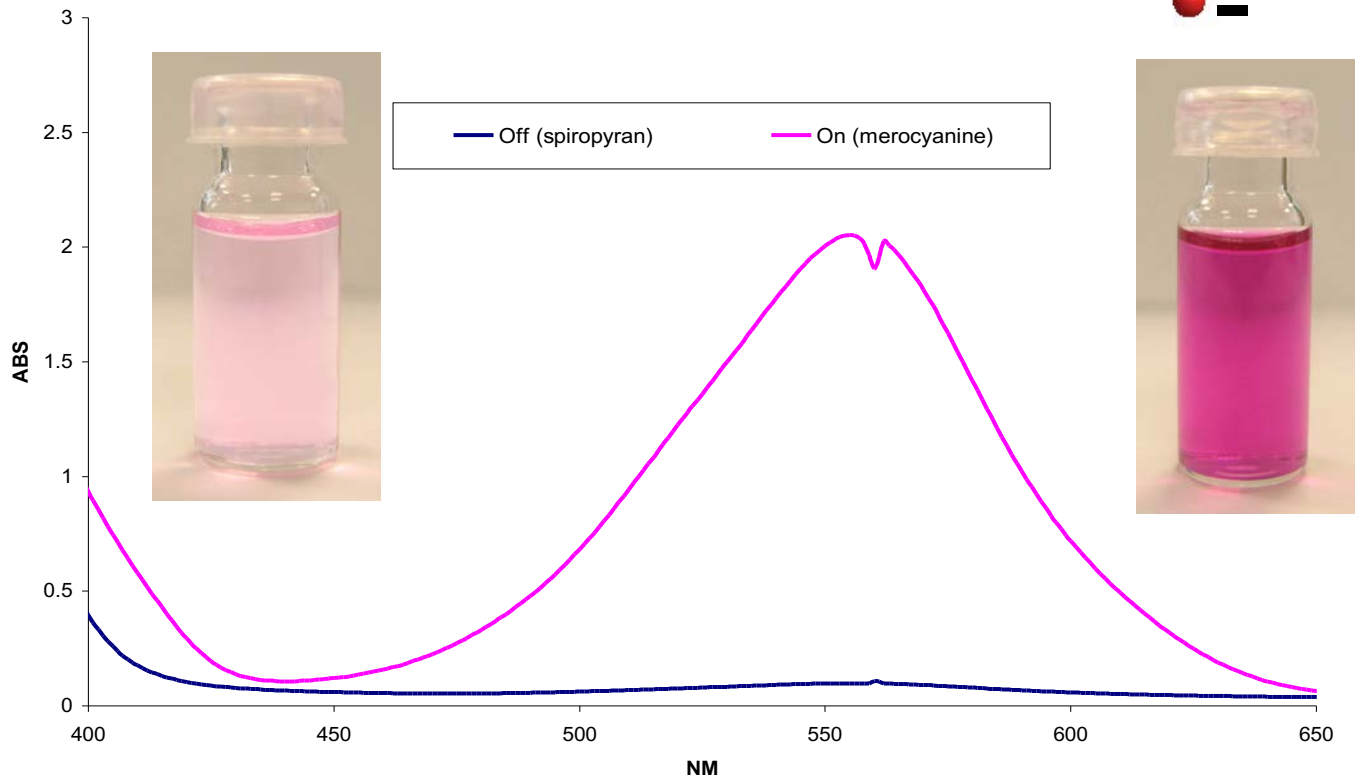
- **Conventional valves cannot be easily scaled down - Located off chip: fluidic interconnects required**
  - Complex fabrication
  - Increased dead volume
  - Mixing effects
- **Based on solenoid action**
  - Large power demand
  - Expensive



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

Photoswitchable Soft Actuators

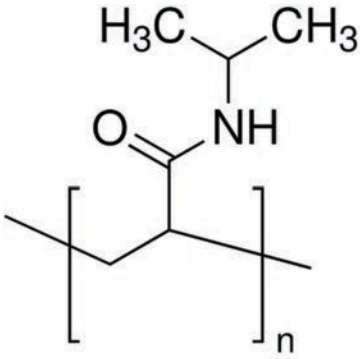




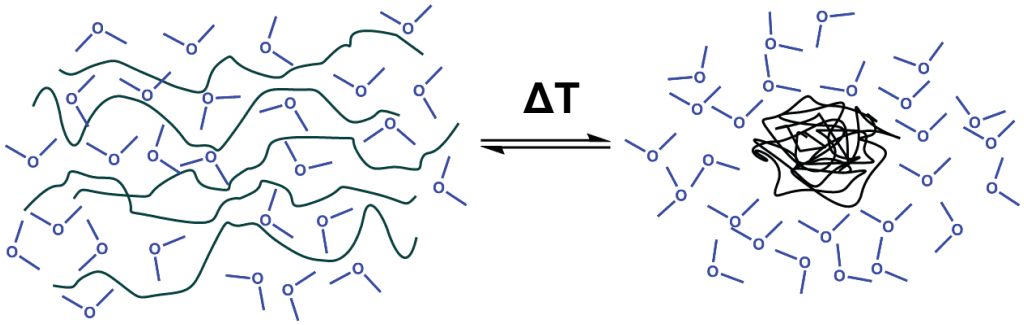
Poly(*N*-isopropylacrylamide)

- 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



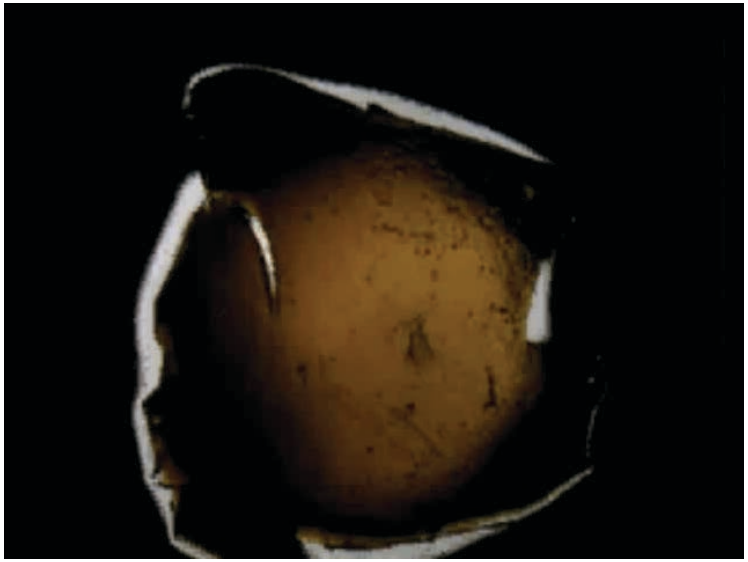
Hydrophilic **Hydrophobic**

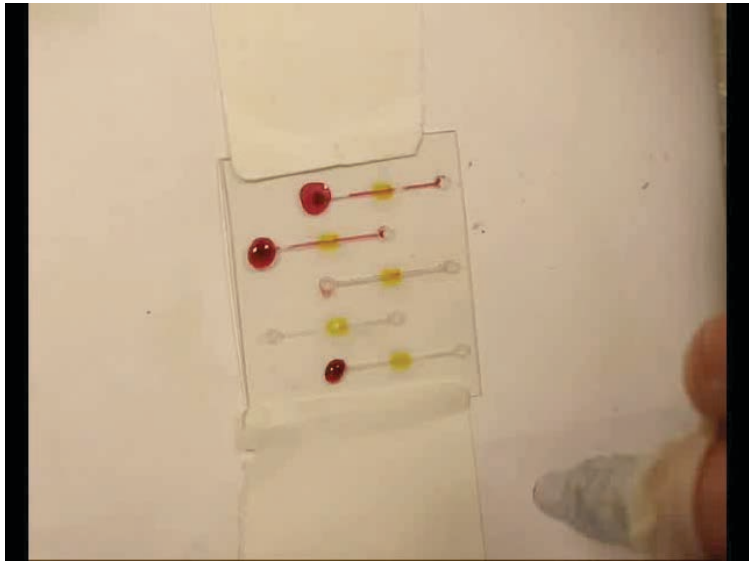


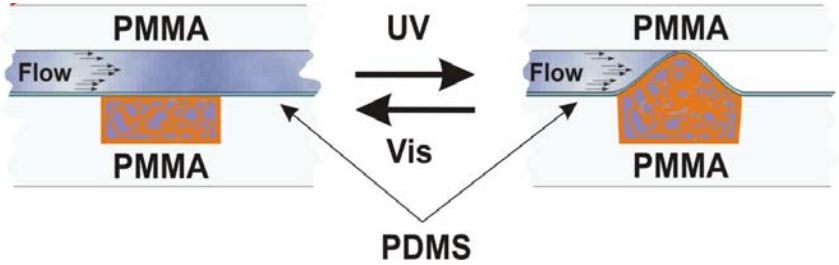
Hydrated Polymer Chains

Loss of bound water -> polymer collapse

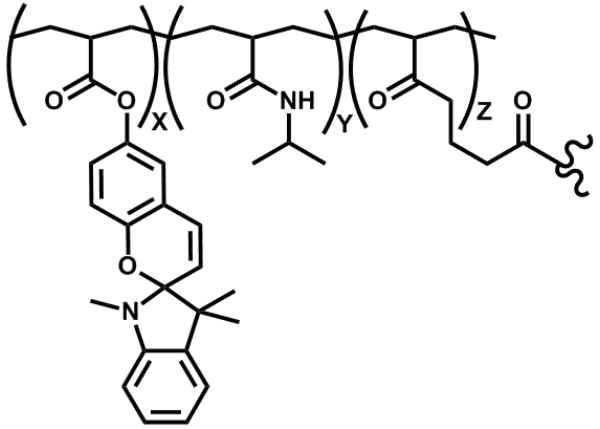
Photo-actuator polymers as microvalves in microfluidic systems

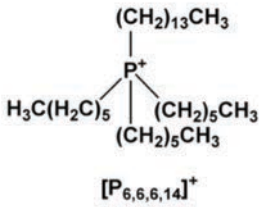


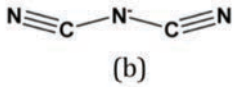




trihexyltetradecylphosphonium dicyanoamide $[P_{6,6,6,14}]^+[dca]^-$







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

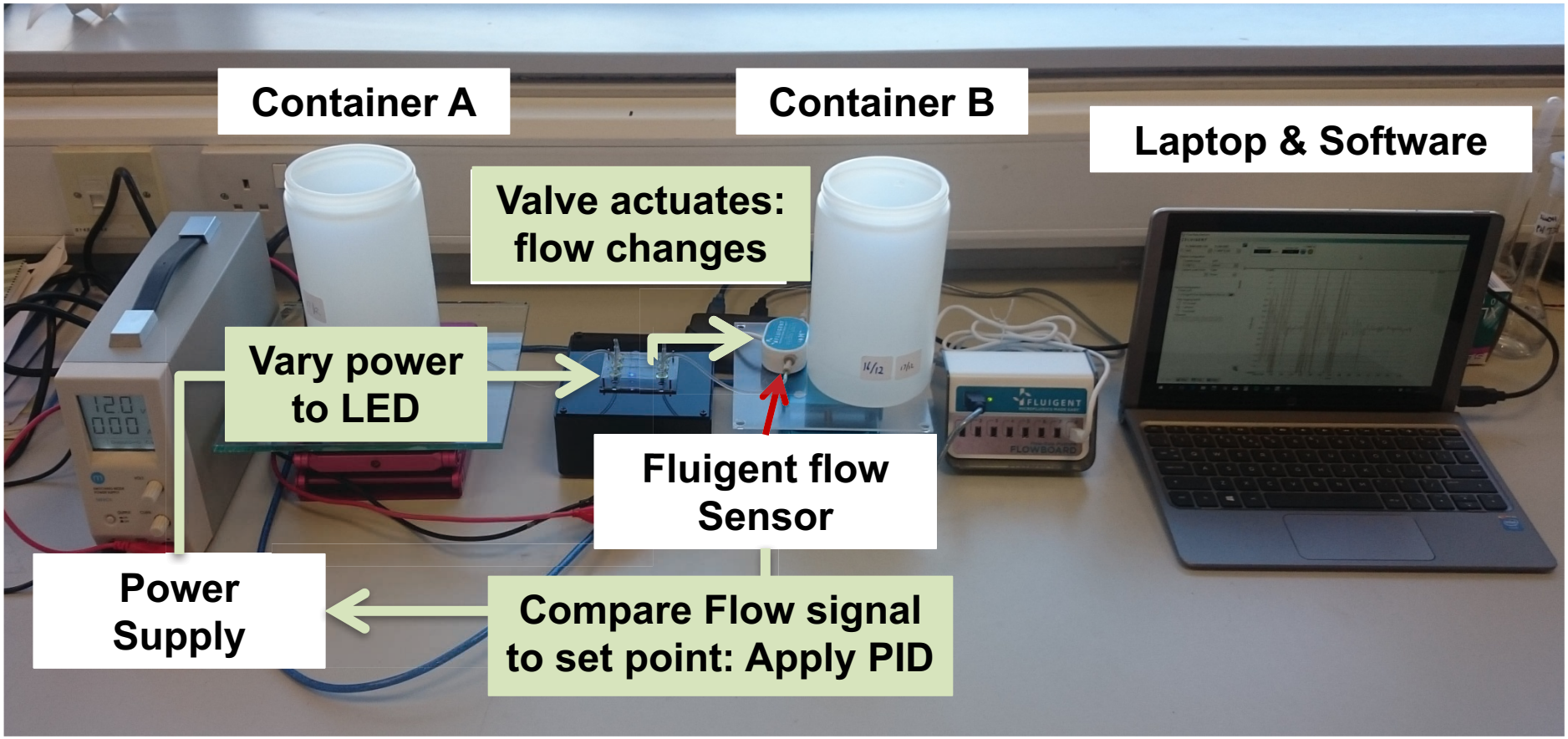
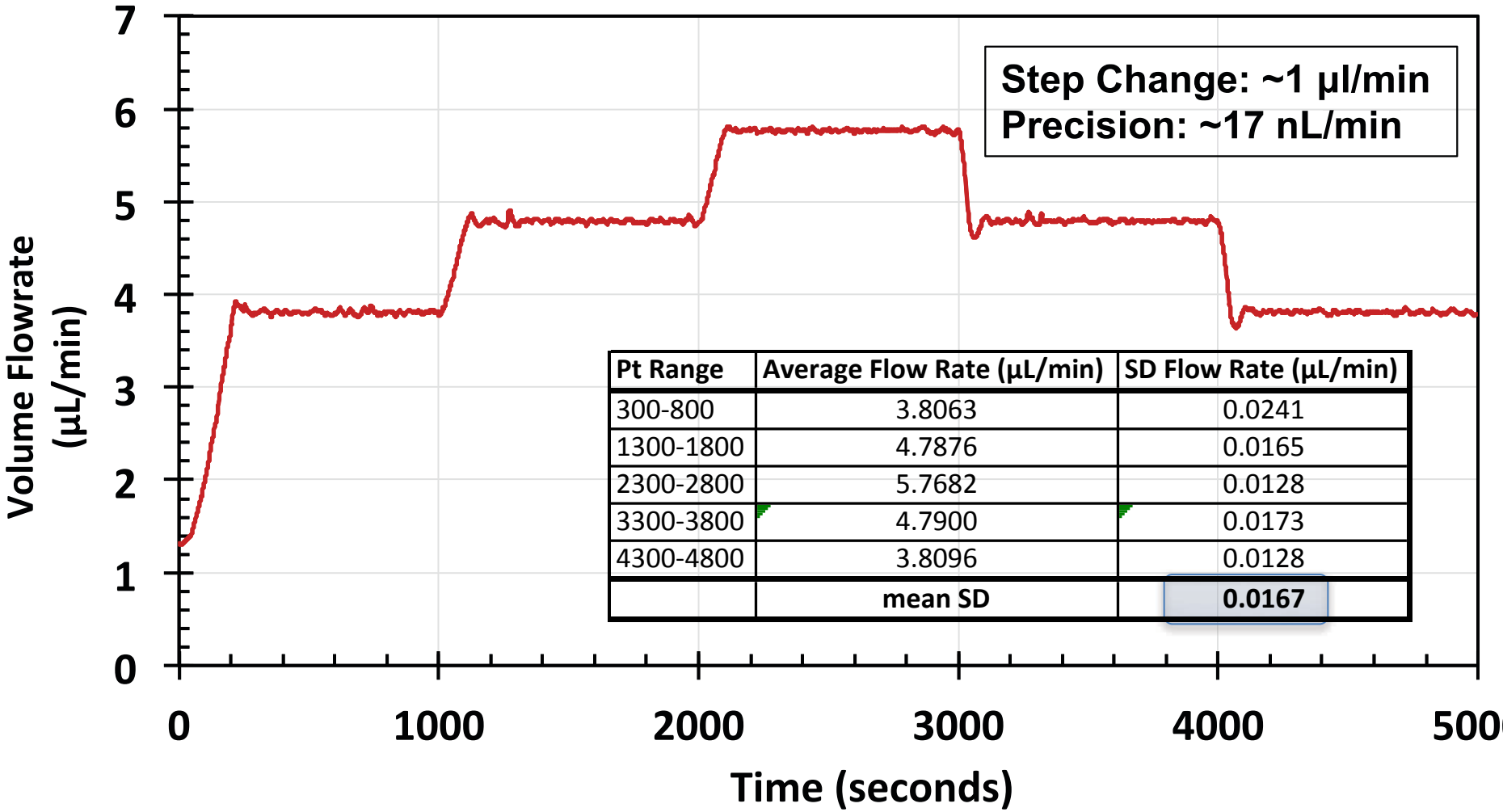


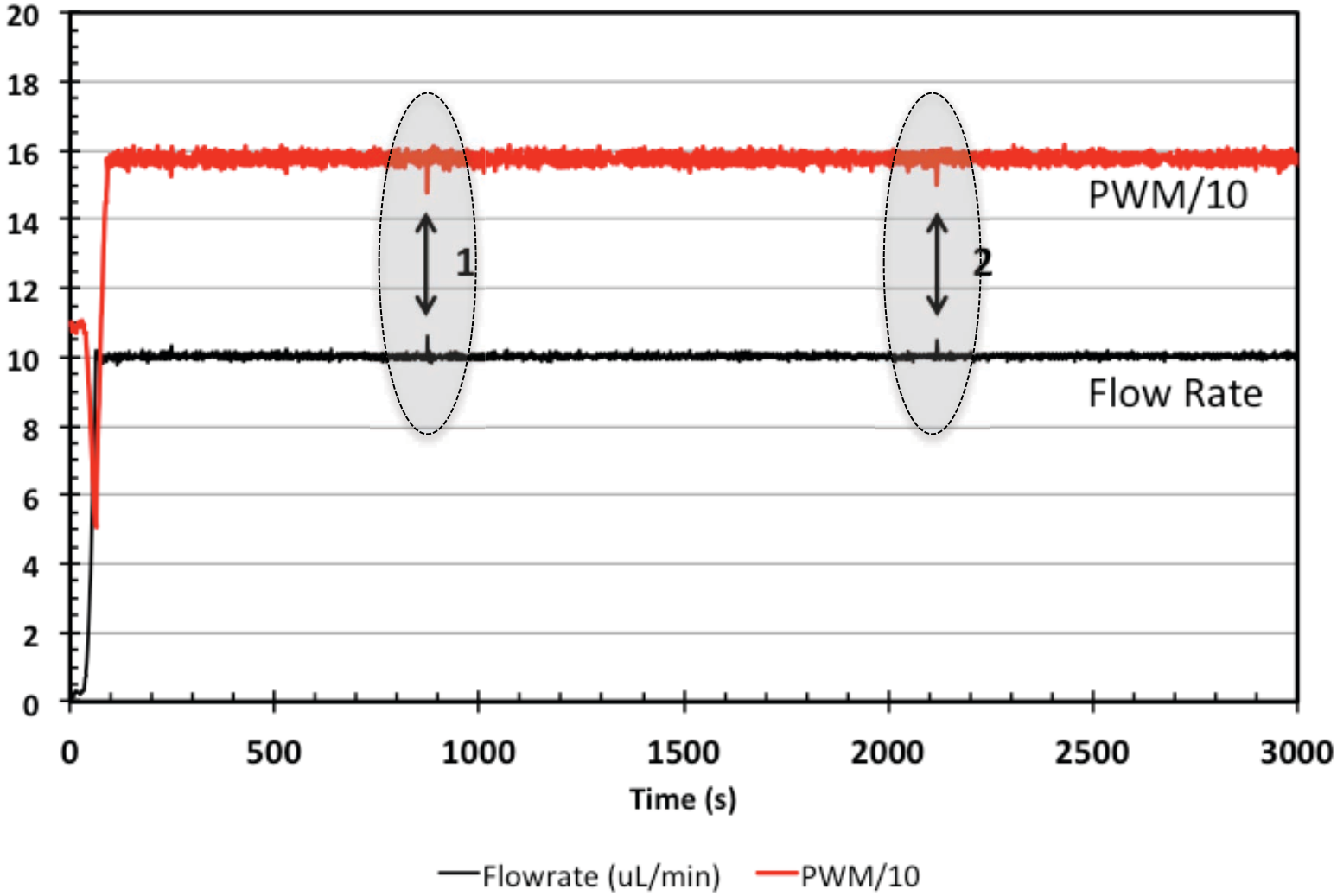
Photo-Controlled Flow Rate



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**

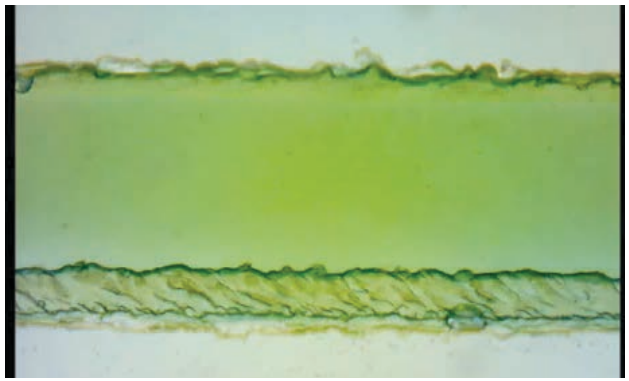
C. Delaney, P. McCluskey, S. Coleman, J. Whyte, N.J. Kent, D. Diamond, Precision Control of Flow Rate in Microfluidic Channels Using Photoresponsive Soft Polymer Actuators, Lab Chip. (2017). doi:10.1039/C7LC00368D.

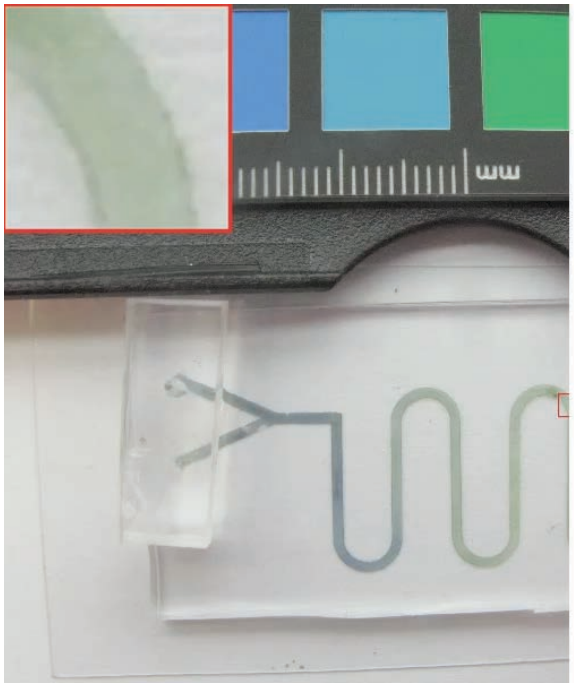
Power Supply to LED

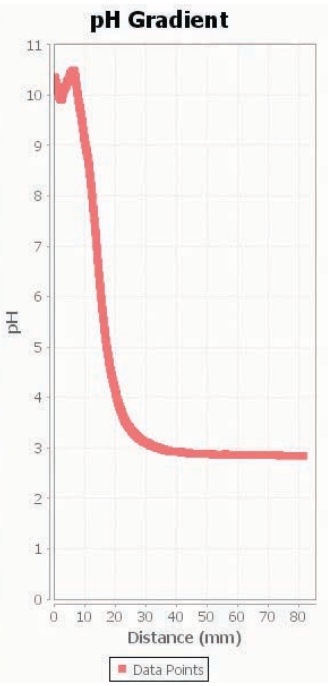


Over a period of 50 min constant maintenance of 10 µL/min flow rate there is no discernable change in LED power ➔ diagnostic information

Channels that can sense…

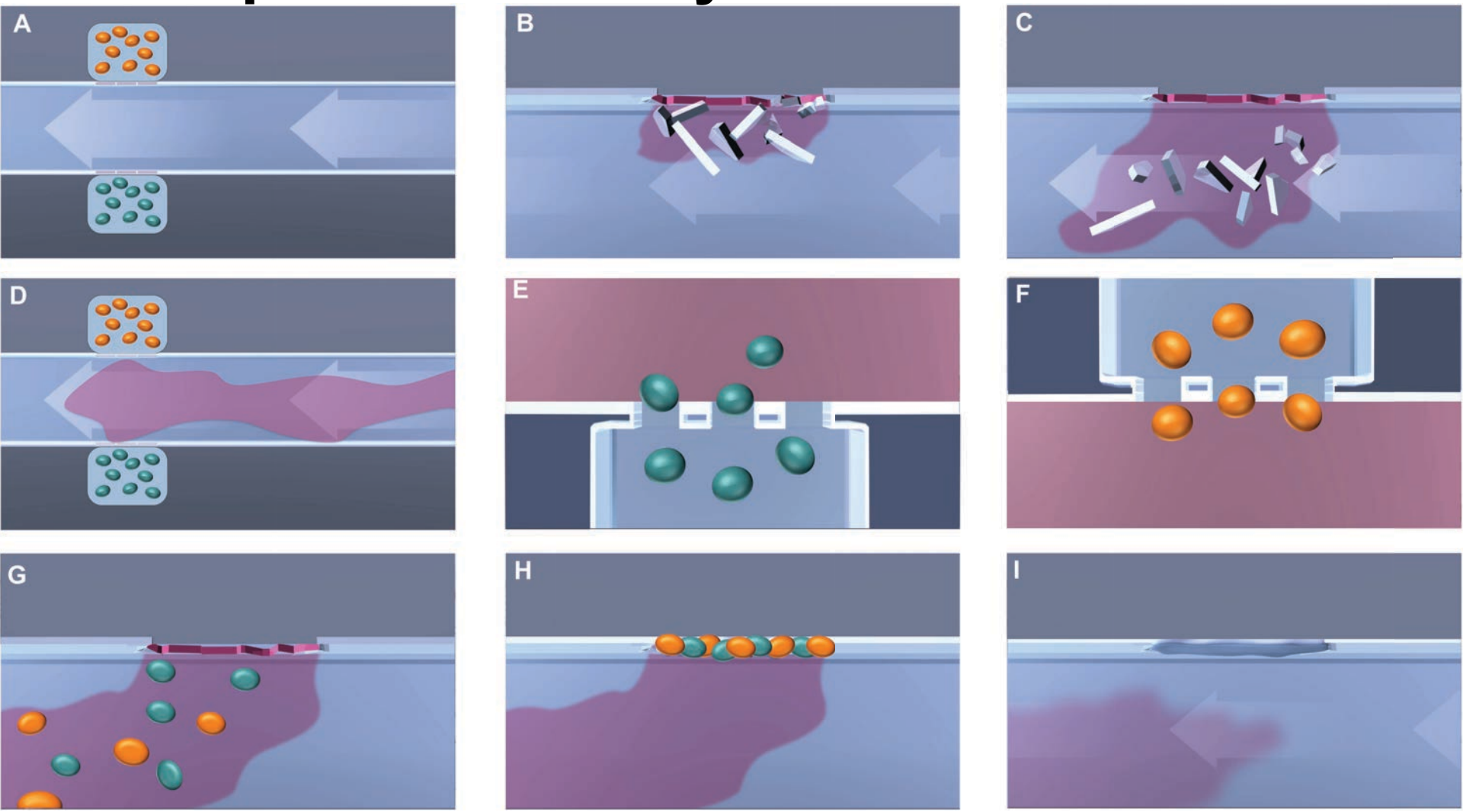






- PANi deposited on channel walls - Channels are now inherently responsive e.g. pH sensitive
- Status can be determined at any location within the channels using low cost digital imaging
- Presented at: µTAS 2011 (MicroTAS) Conference, Seattle, October 2-6, 2011

We have all the sub units.....Immune Response for Analytical Instruments?



Merging of Materials, Devices and Data

Data and Information; IOT

Major ICT companies, services, societal impact, economic opportunities

Devices and Platforms

Sensornets, Satellites, Citizen Science….

MATERIALS

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

Concluding Thoughts: Strategic Requirements

- Support BASIC research to maintain the flow of ideas through to future products and services
- Align APPLIED and BASIC research to create efficient pathways through TRLs to socio-economic impact
- Involve Social Science Researchers to define key societal issues and stimulate social engagement (citizen science)
- Create research instruments based on Public-Private partnerships
- Use ‘Challenges’ to focus efforts on solving particular issues (e.g. Alliance for Coastal Technologies ‘Nutrient Challenge’)
- ‘Moonshots’, ‘Mission’ based Initiatives (EU FET Programme ‘Flagships’, Lamy Report and FP9): €1billion budget; 10-years

Questions?