



Smart environments, nanosensors & nanoreliability: *the use case of water quality monitoring*

Bérengère Lebental[^]

[^] Laboratoire de Physique des Interfaces et Couches Minces, Ecole Polytechnique, CNRS

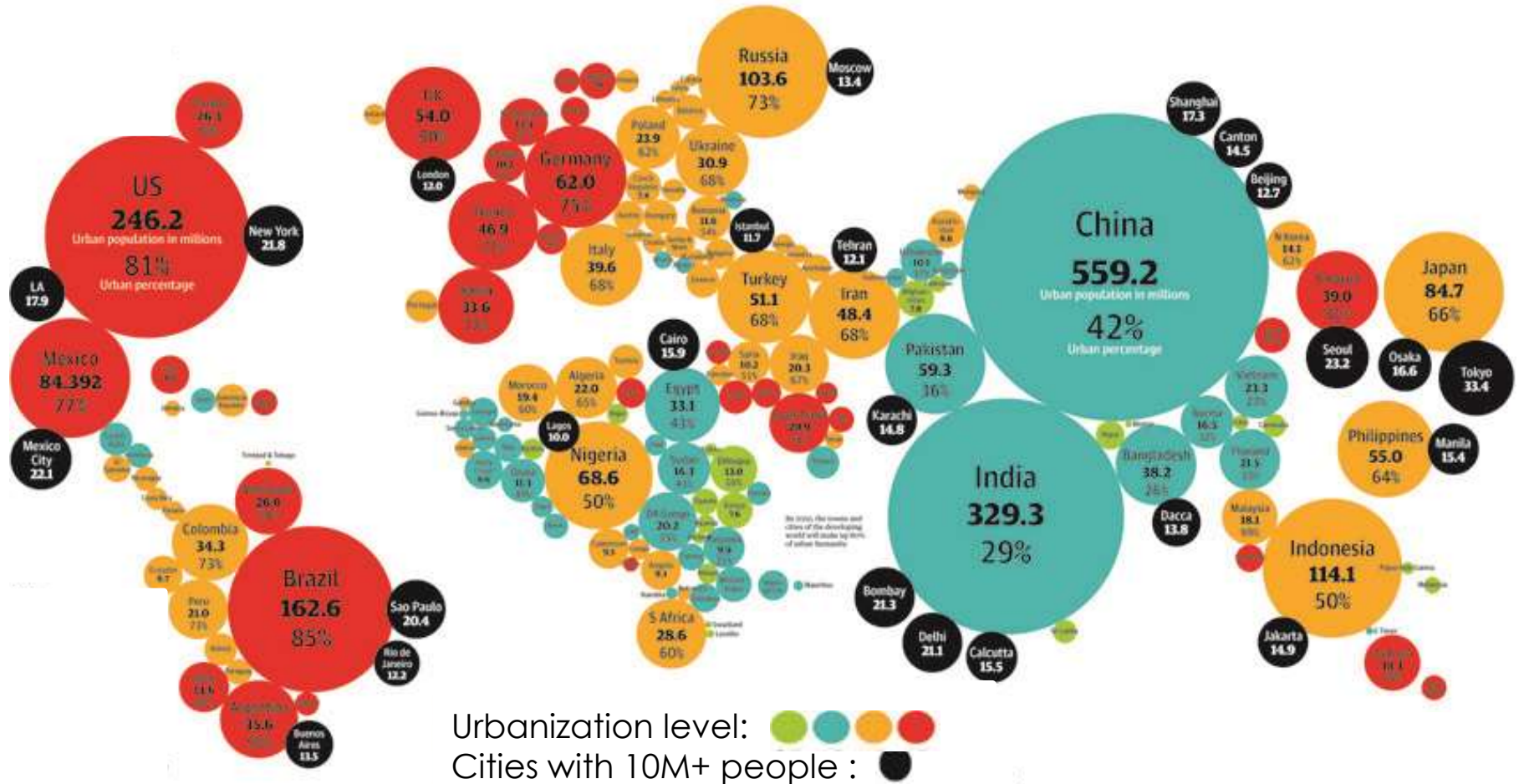
[^] IFSTTAR/COSYS/LISIS, Université Paris Est

University of Exeter, Center for Water Systems

November 30th, 2018



Urbanization...



World urban population:
3,307,950,000 – 53%

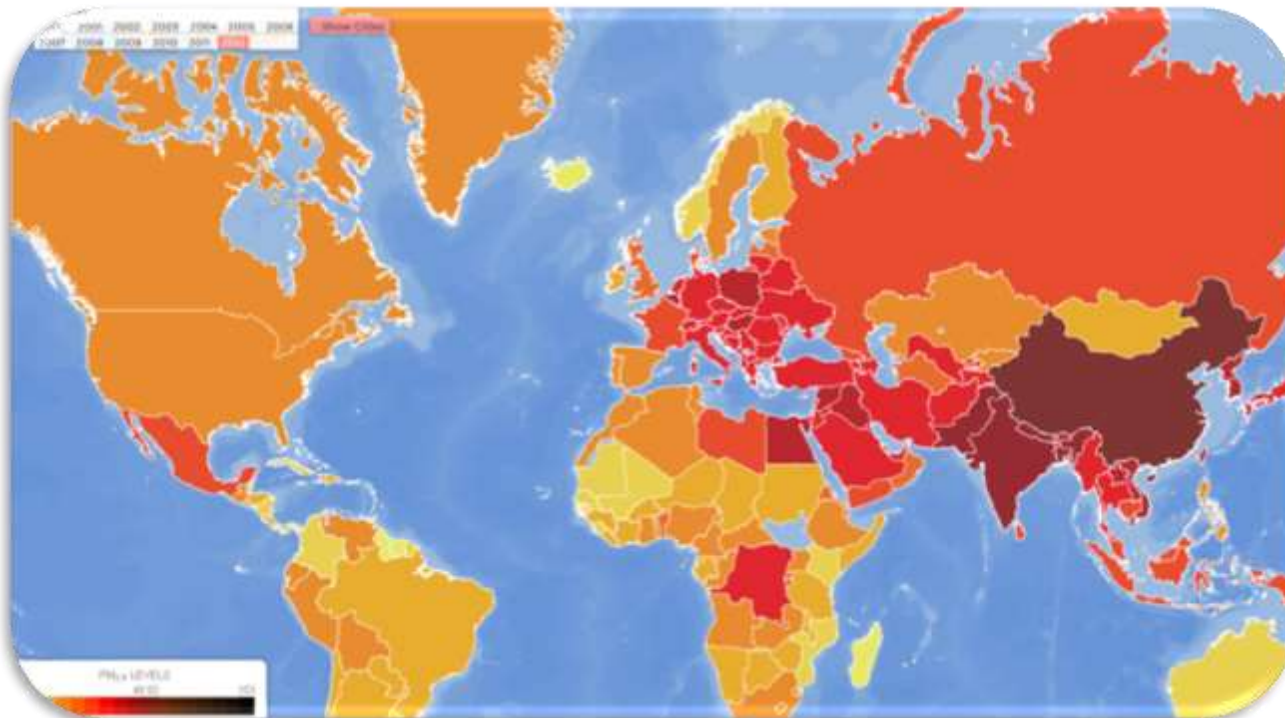
...weighs heavily on **people and planet**

350 000 death/yr

Attributed to air pollution in Europe

4000 Billions.kg/yr

waste



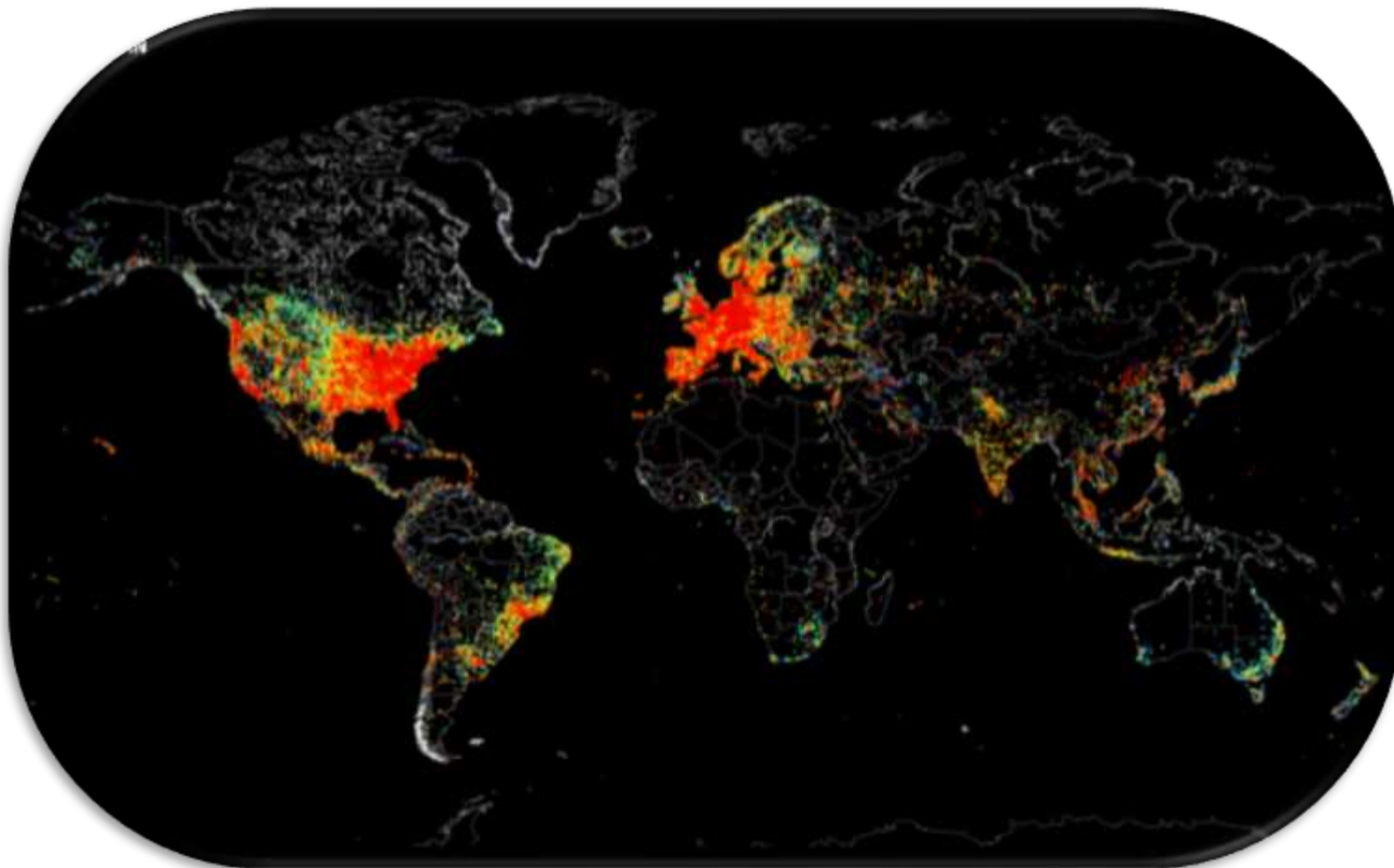
A situation worsening with **climate change**



A situation to which the **digital revolution contributes**

12.5 Billions
Connected devices

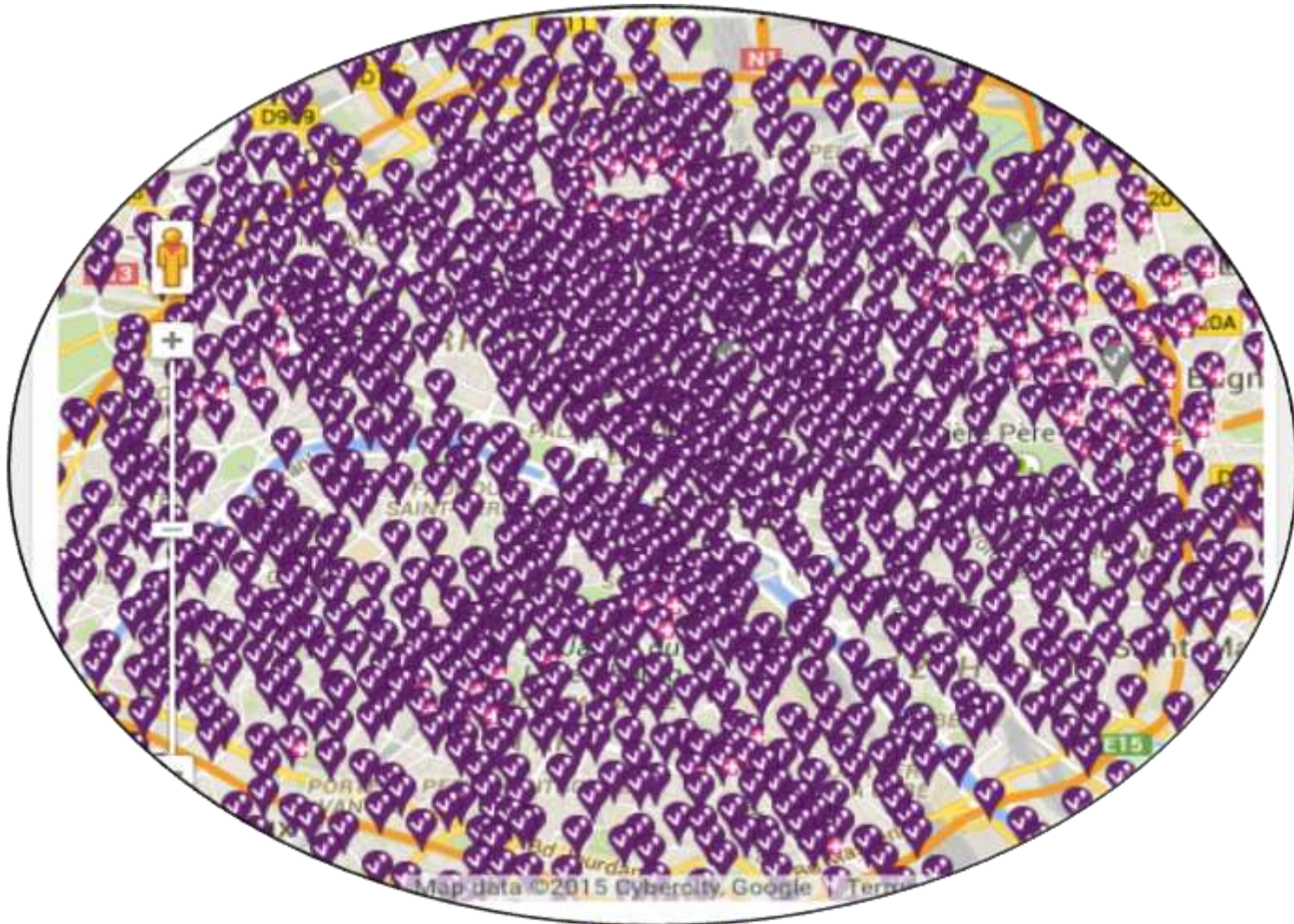
200Mto CO₂
Mobile communication



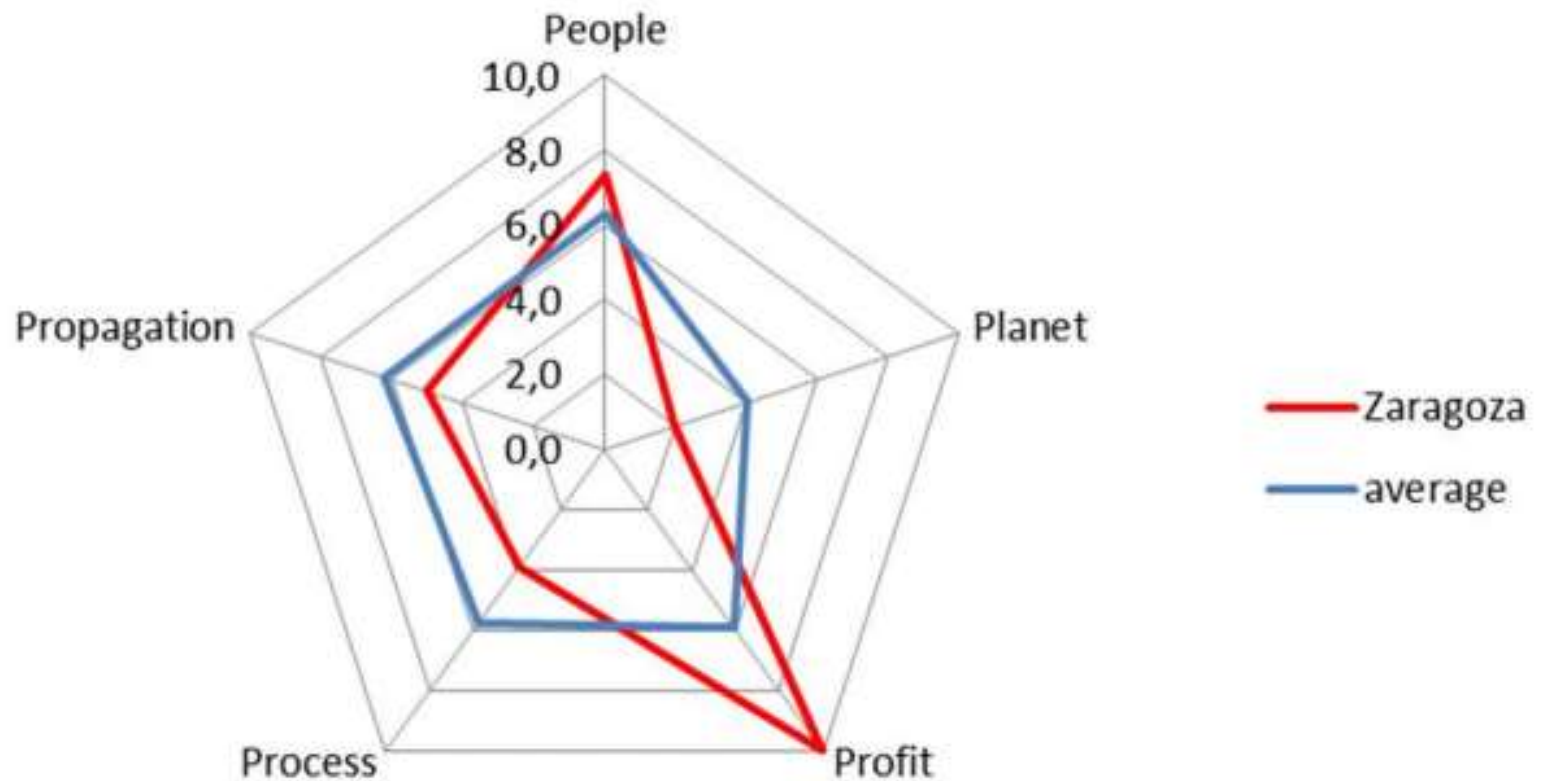


Can we exploit the digital revolution to
lower the impact of urbanization
& improve urban quality of life?

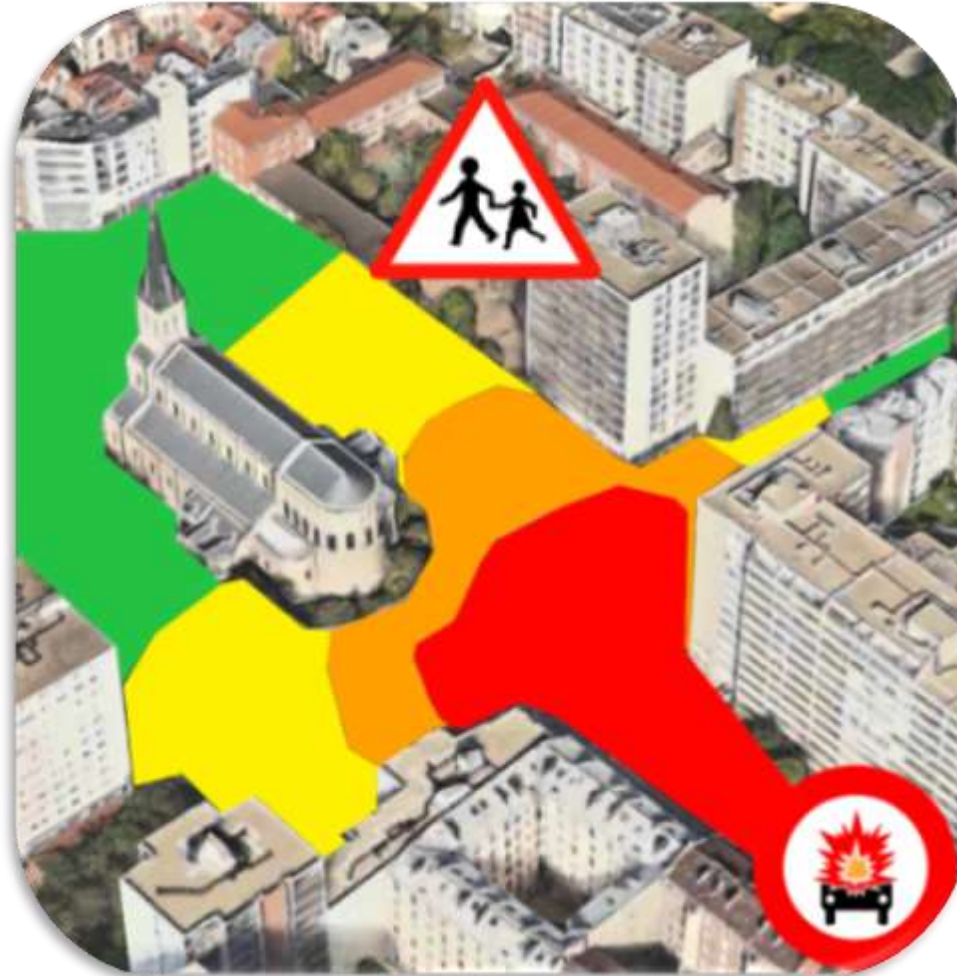
Ubiquitous data gathering via the Internet of Things



To enable **informed decision-making** **at the local scale**



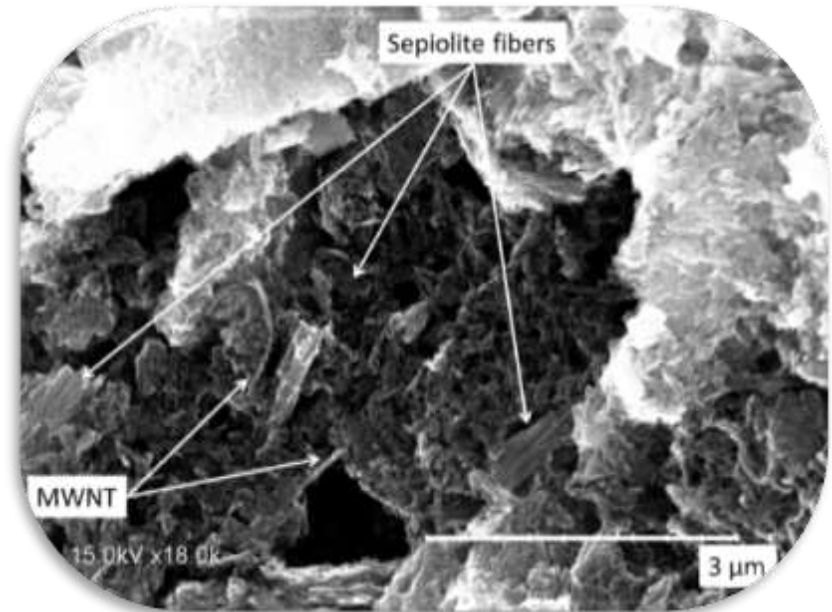
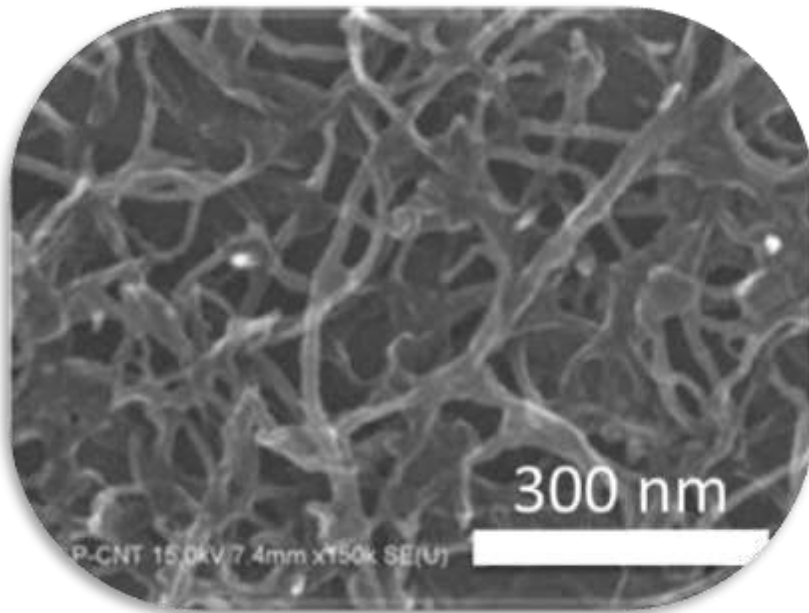
To enable **informed decision-making**
for the general public



A strong potential for nanotechnologies

High performances at low cost

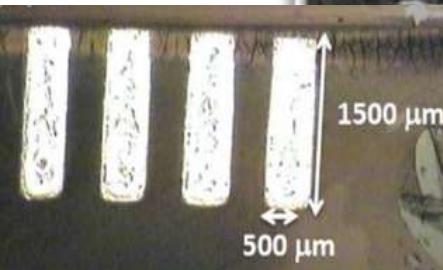
Small size with low power needs



Our vision is based on **nanosensors**



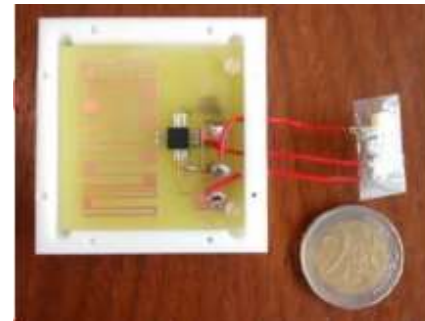
**Pollution
monitoring
Station with
GRAPHENE**



**Water quality
monitoring
station with
CARBON
NANOTUBES**



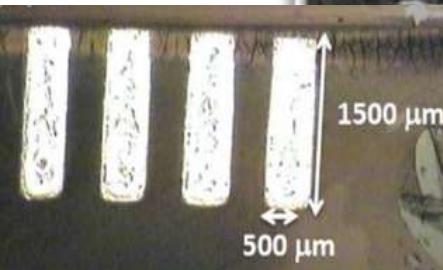
**Building and
road durability
monitoring with
CARBON
NANOTUBES**



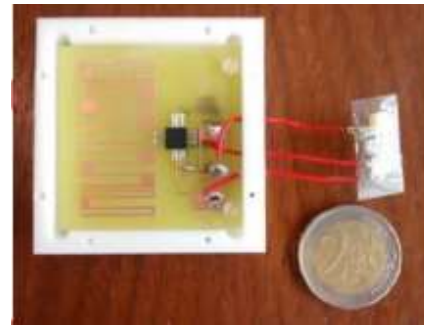
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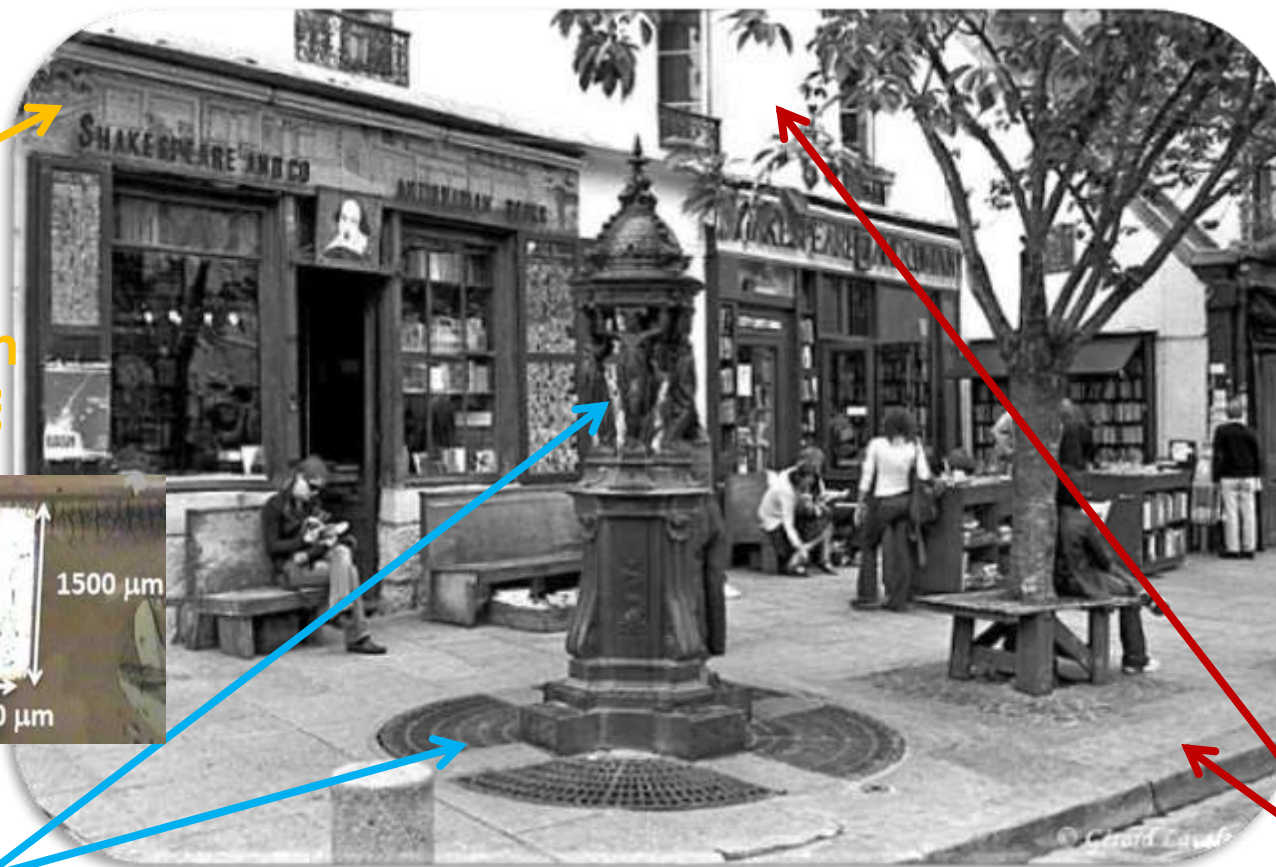
**Pollution
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**Building and
road durability
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Nanoreliability is our top challenge



Water network: 1 year



Car: 5 years



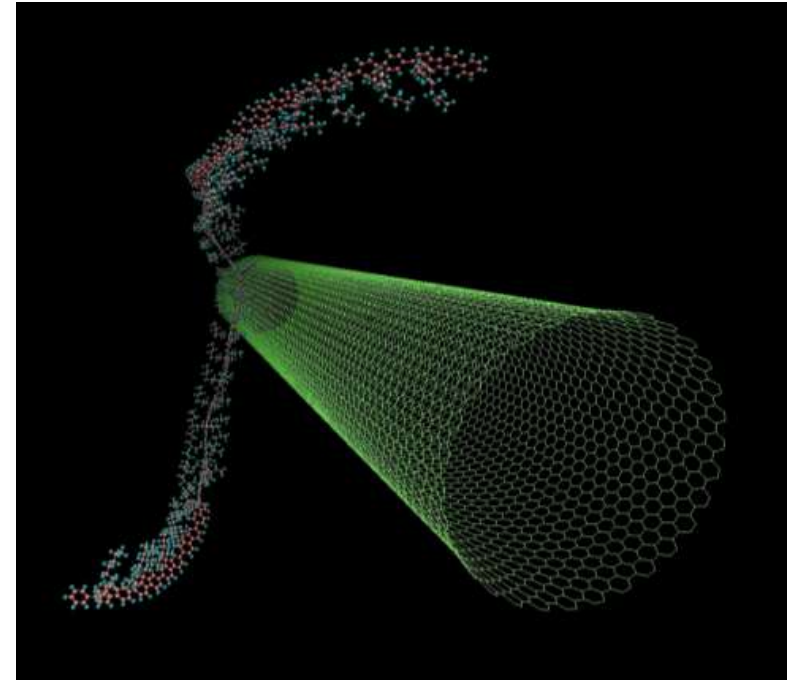
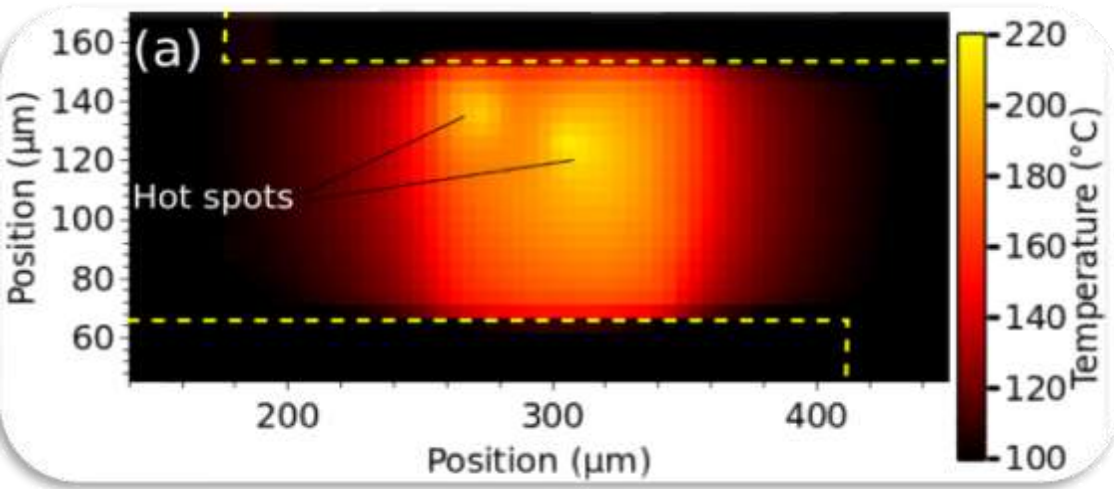
Bridge: 50 years



Addressed through **field deployments**...



And **nanoscale understanding** of ageing



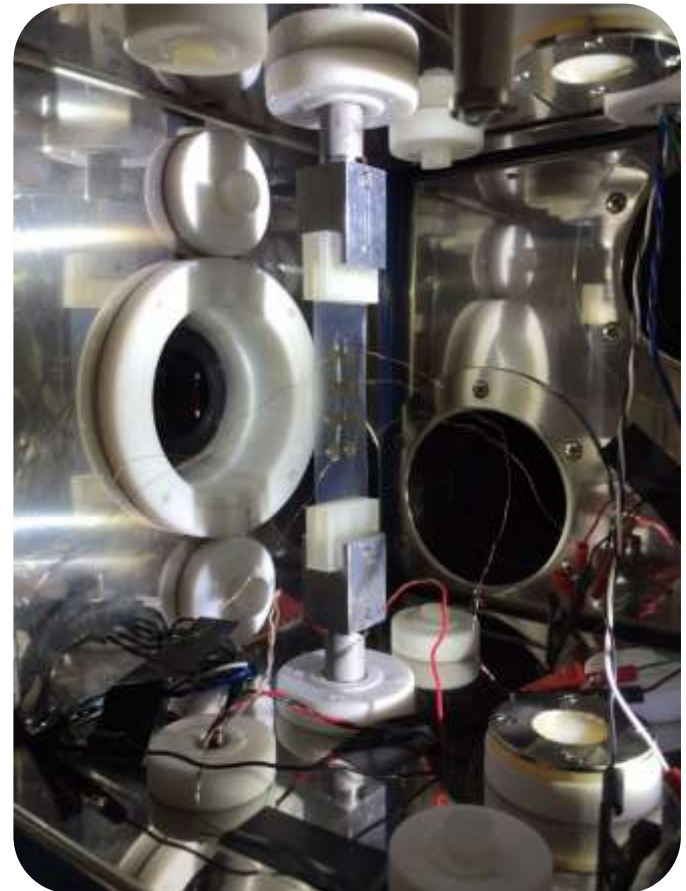
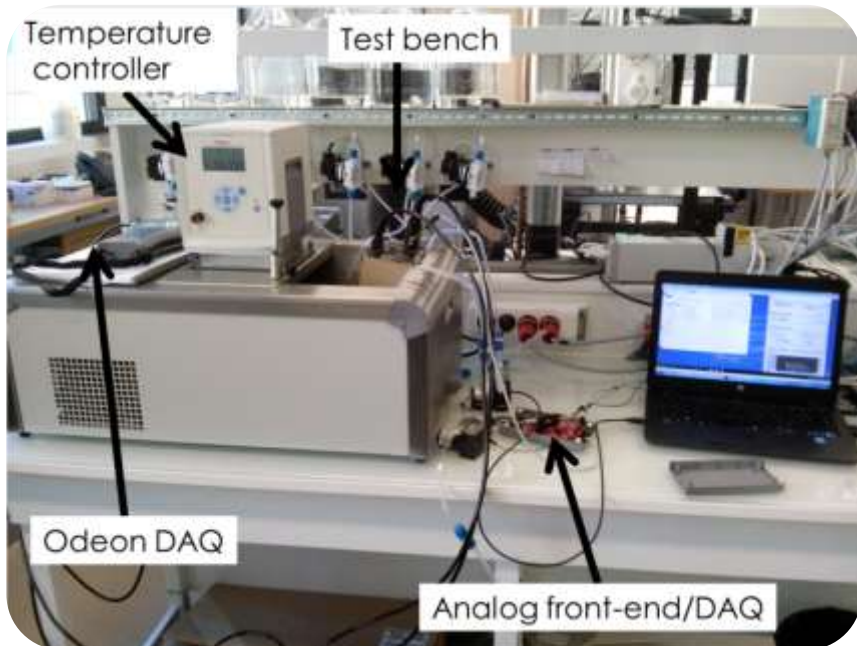
Supported by PLATINE platform

A pool of fabrication equipment compatible with low cost, wet processing of nanoparticles



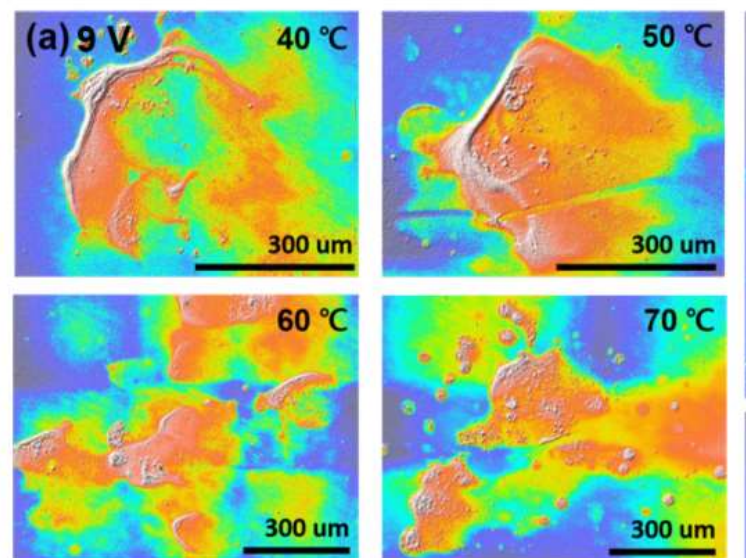
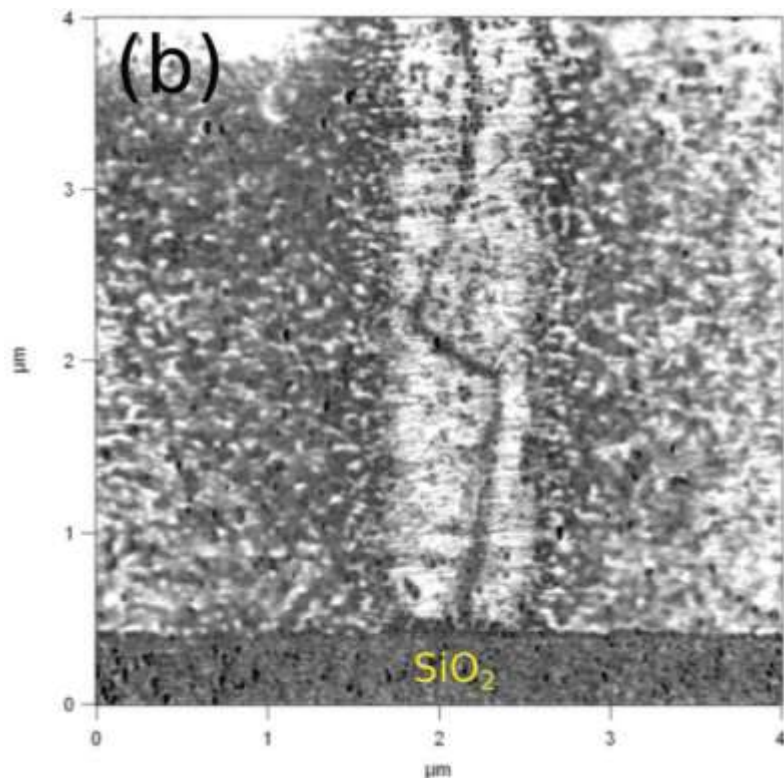
Supported by PLATINE platform

Custom-made, automated, multi-physics
in-situ characterization setups



Supported by PLATINE platform

High resolution and/or high throughput
equipment for advanced ex-situ characterizations



And a highly motivated team!

Researchers

L. Bodelot, B. Lebental,
G. Zucchi, Y. Bonnassieux



Platform engineers

B. Gusarov, J. Charliac,
J.F. Arruabarrena



Master students, PhDs, Post-docs

X. Wang, Q. Lin, R. Benda, C. Gookbin,
N. Massonnet





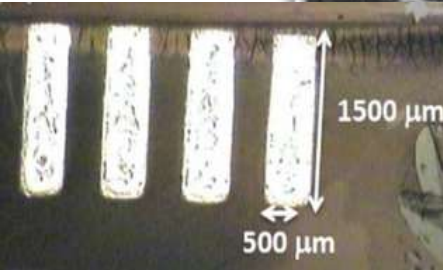
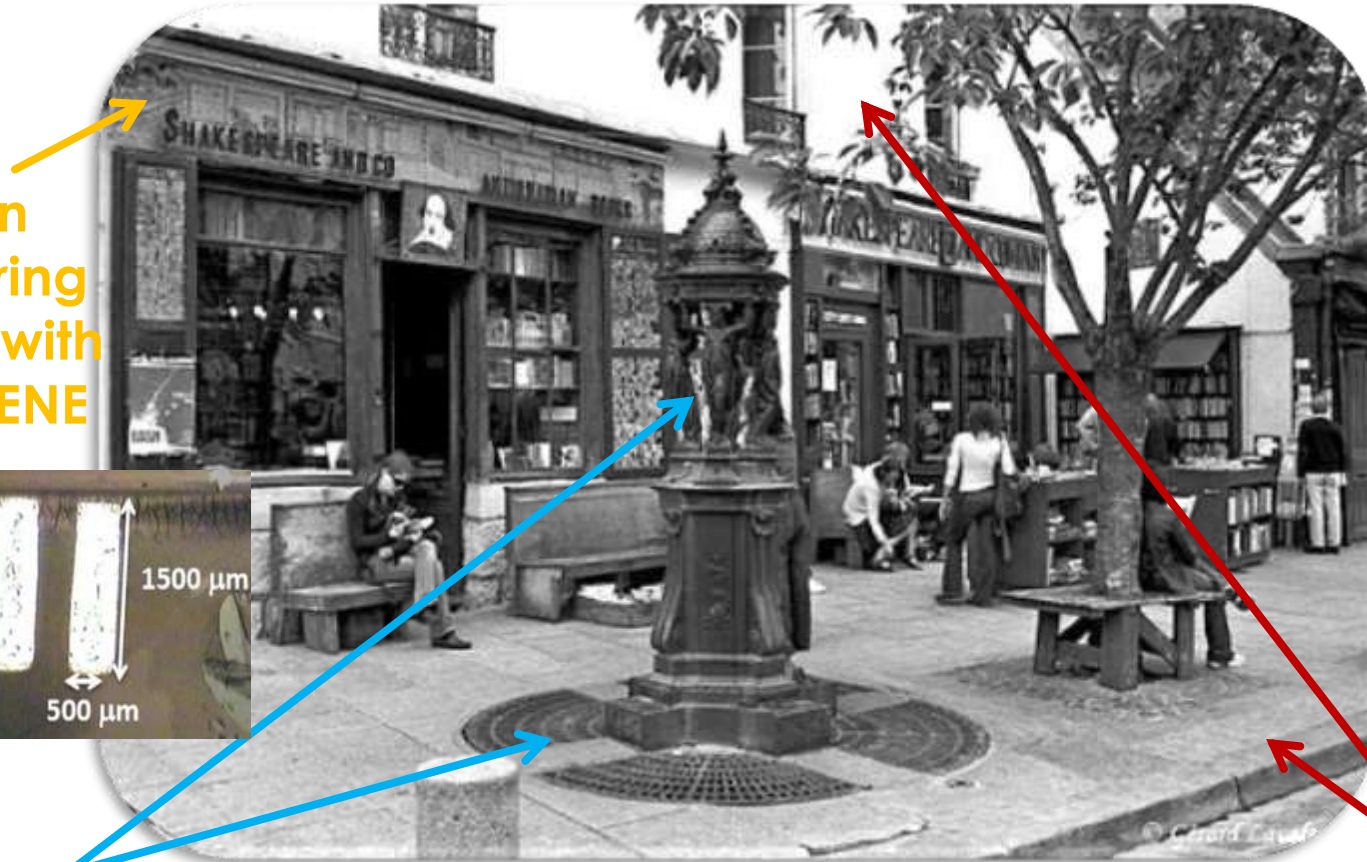
Sponsors



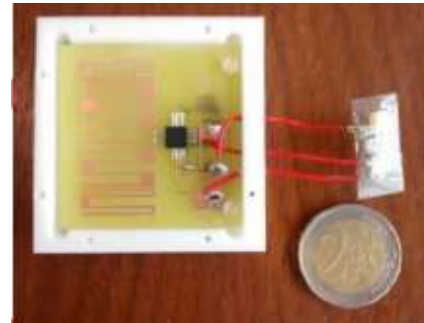
Summary: **a repertoire of nanosensors** applied to practical use cases



**Pollution
monitoring
Station with
GRAPHENE**

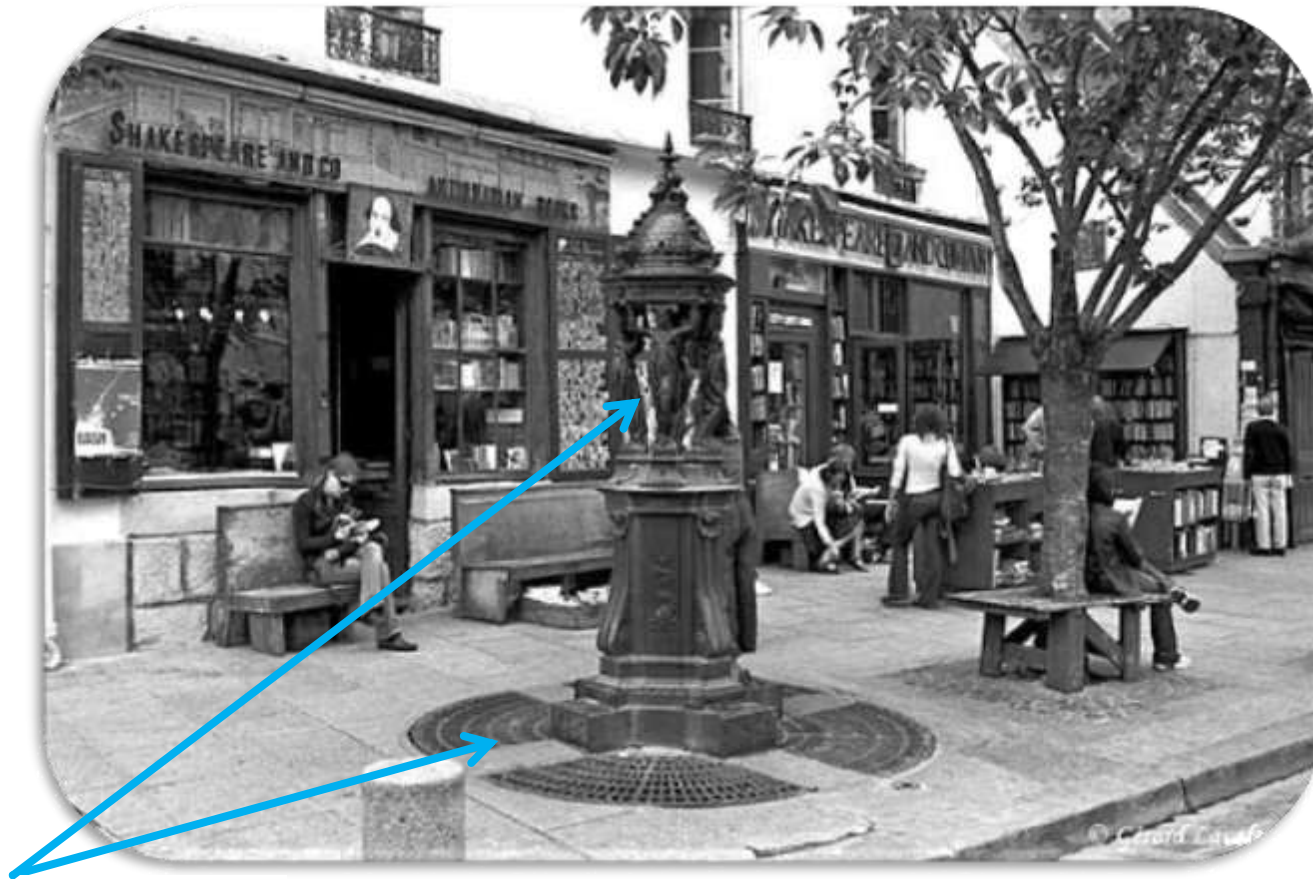


**Water quality
monitoring
station with
CARBON
NANOTUBES**



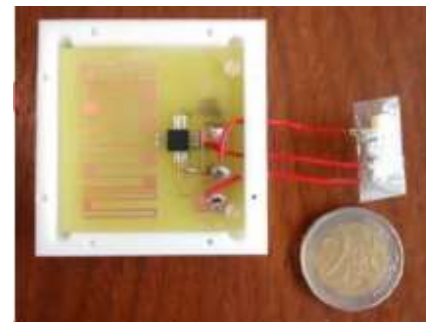
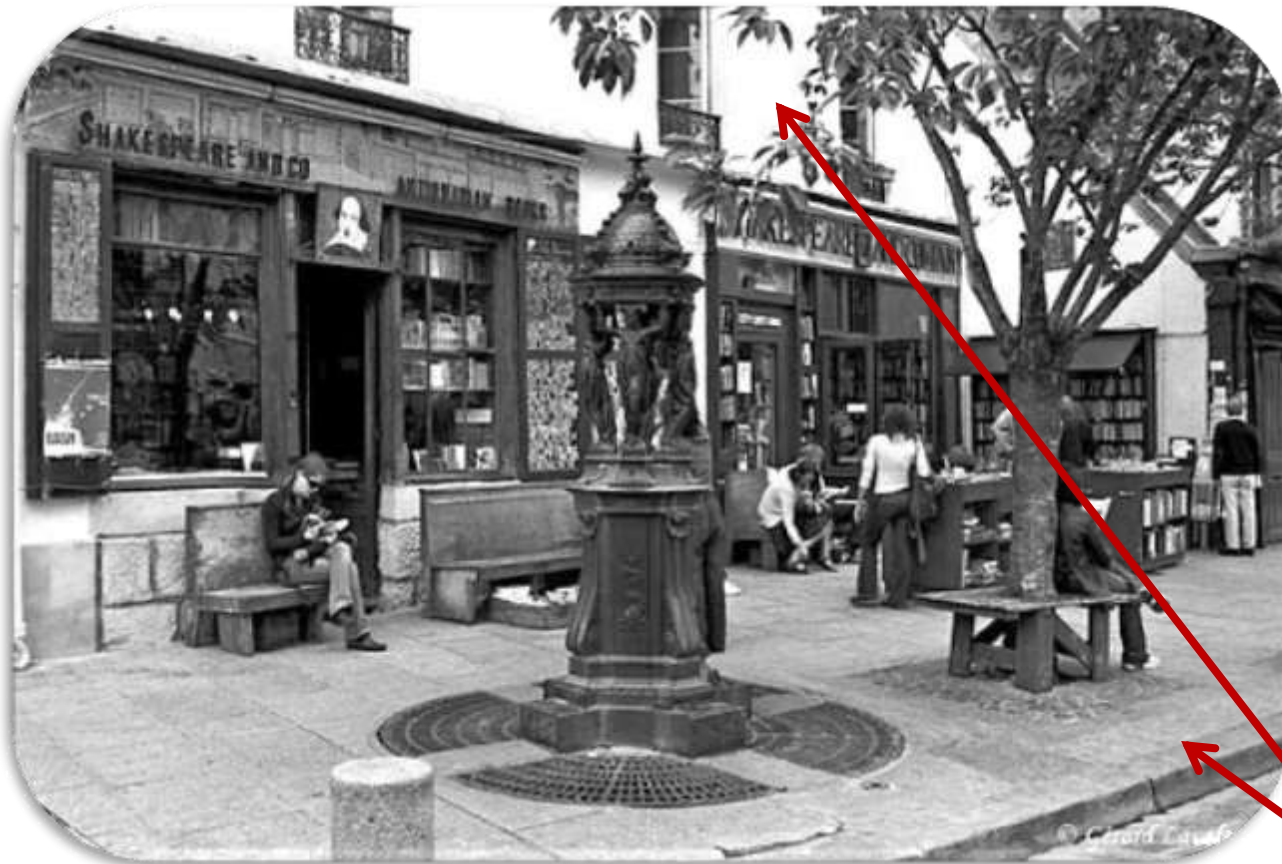
**Building and
road durability
monitoring with
CARBON
NANOTUBES**

Our main use case presently: **water quality monitoring!**



Water quality
monitoring
station with
**CARBON
NANOTUBES**

If time permits, I'll share about **our start up Altaroad!**



**Building and
road durability
monitoring with
CARBON
NANOTUBES**



ADAPTIVE MICROFLUIDIC - AND NANO - ENABLED SMART SYSTEMS FOR WATER QUALITY SENSING

PROTEUS

General overview
Focus on chemical sensing

Bérengère Lebental, Project coordinator

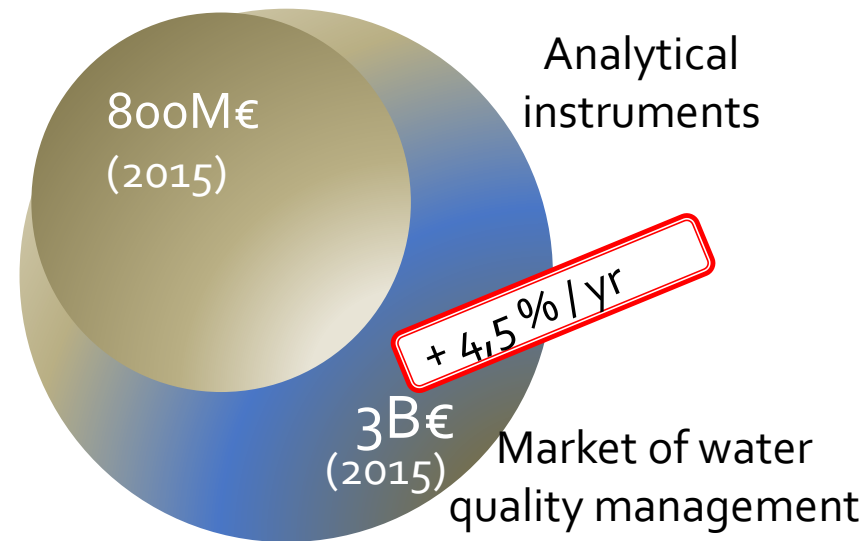
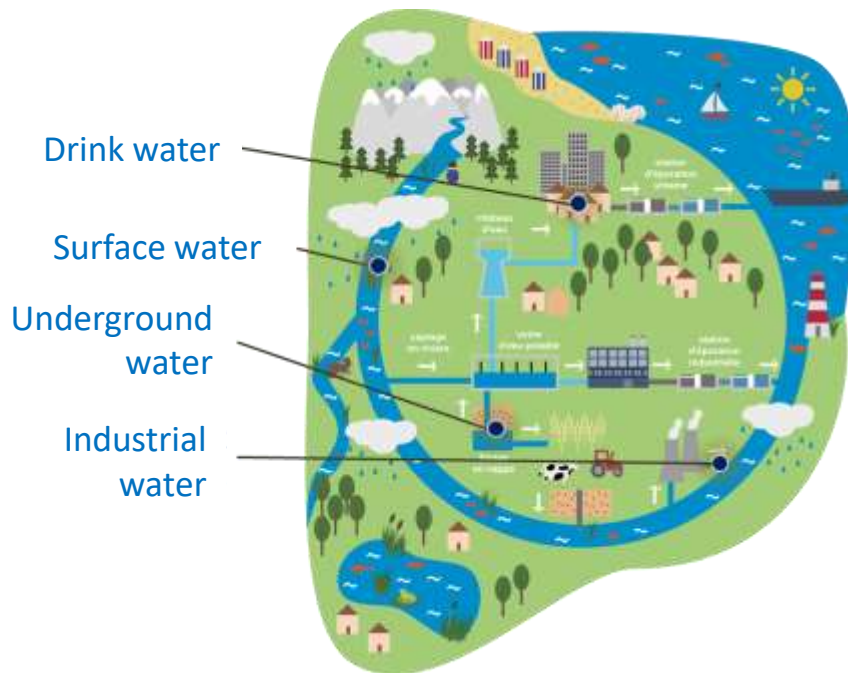


www.proteus-sensor.eu



Water monitoring challenges

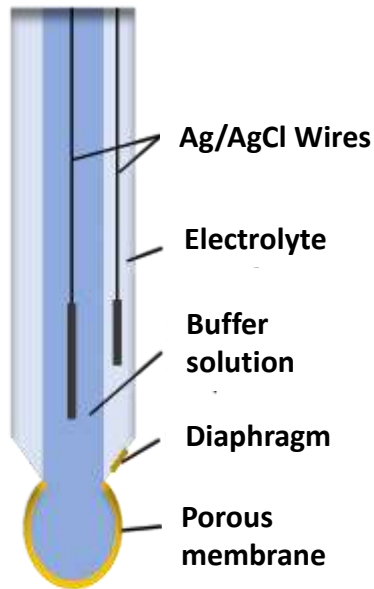
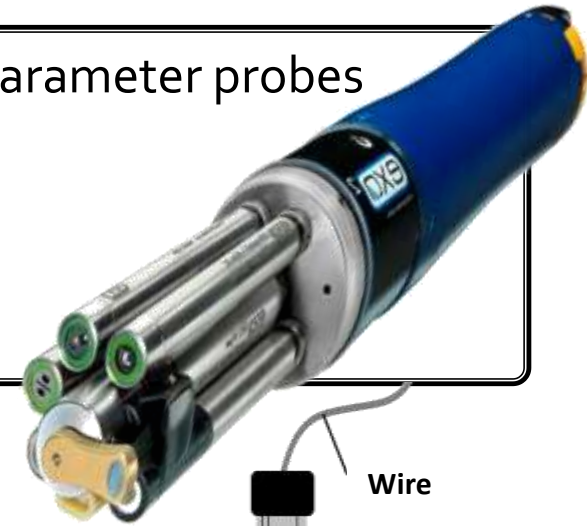
- ❖ Availability of clean (health-risk free) water (for drinking, reuse, aquaculture...)?
 - Half of the world population under water stress conditions
 - Ubiquitous industrial and agricultural contamination of water sources
- ❖ Consensus: heavily multiplexed water probes needed for massive deployment!



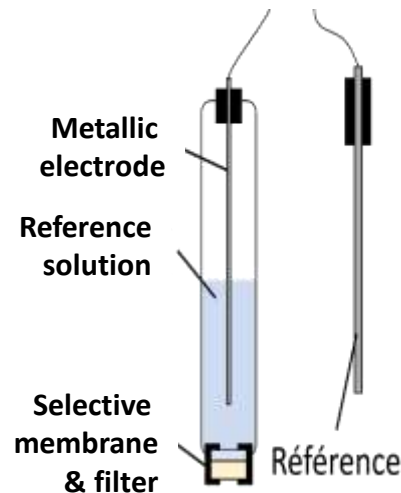
Commercial water quality sensing

Today's multiparameter probes = « assembly » of single-parameter probes

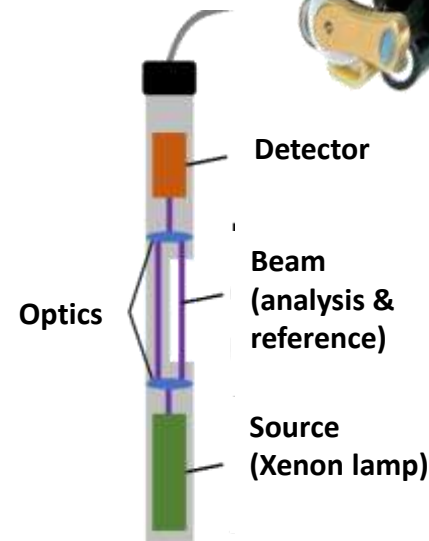
- **Bulky** and **not reconfigurable**
- **Not affordable** in large number (5 à 20 k€)
- **Power consumption** high
- **Maintenance and calibration** complex and frequent



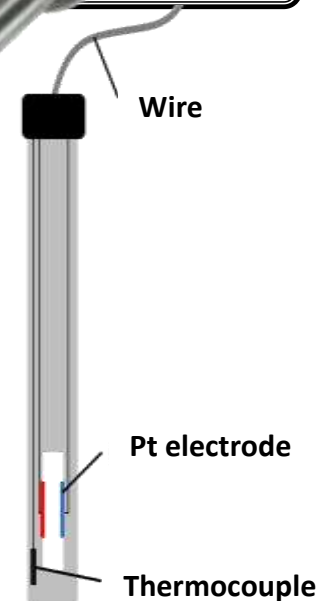
pH probe
PROTEUS



Analyte-selective
electrode



Optical probe
(UV-Vis)

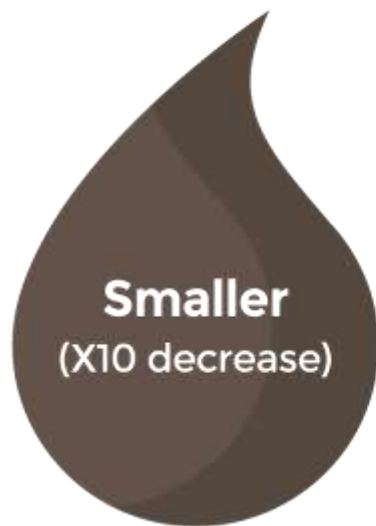


Conductivity
probe

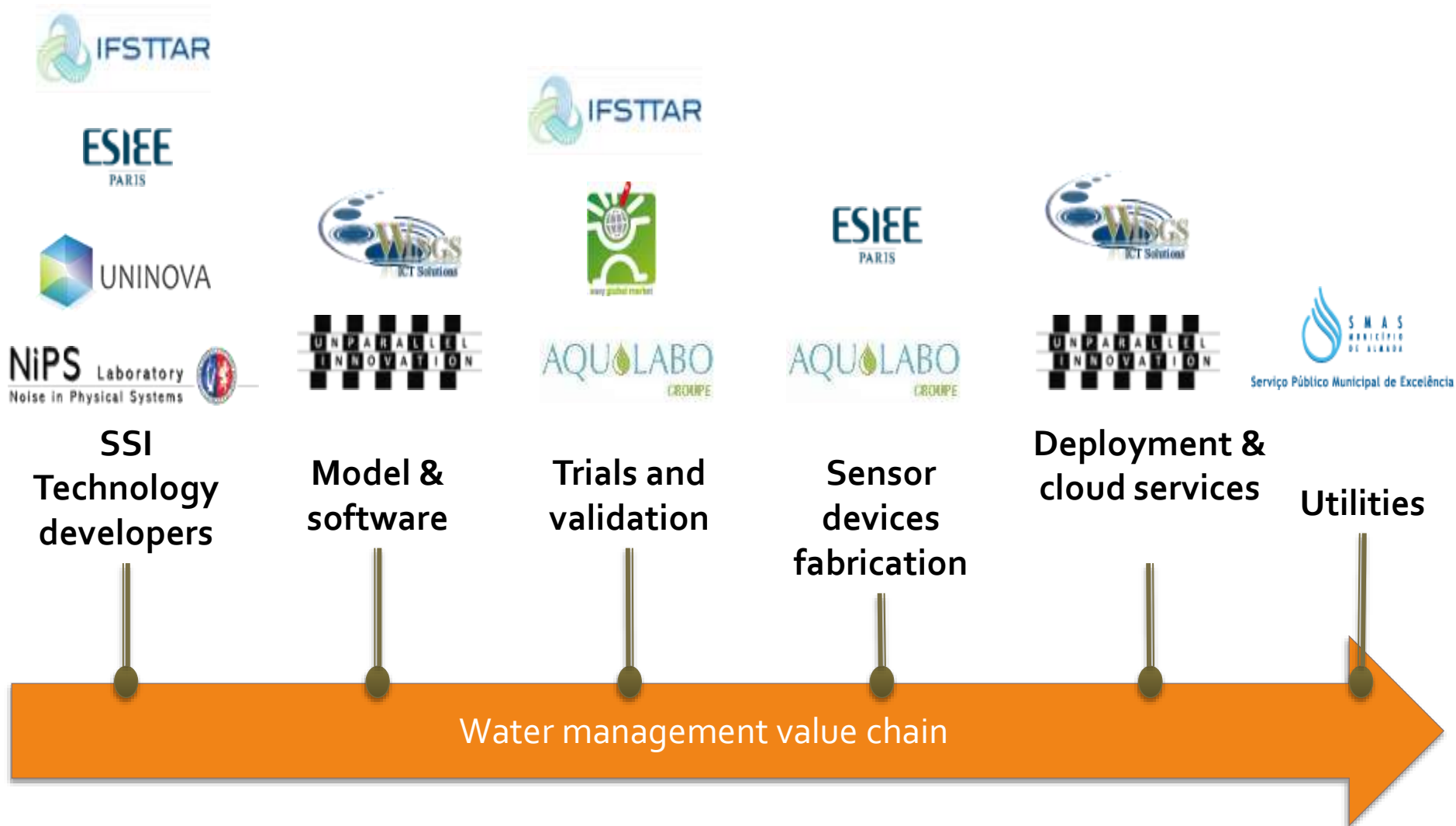


PROTEUS Objectives

Delivering an **autonomous,**
highly **multifunctional MEMS- and nano-enabled**
sensor node for **adaptive and cognitive**
drink & waste water quality monitoring.

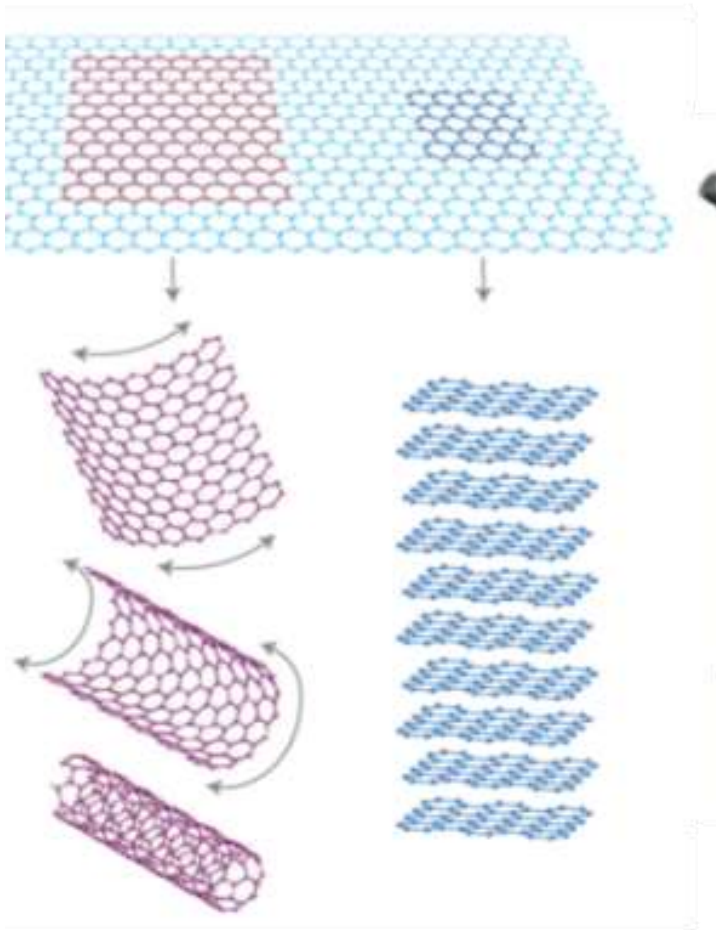


Proteus consortium



Nanocarbon for multiparameter chemical sensing?

Graphene



Nanotube

Graphite

Today's carbon hype: 2 recent Nobel prizes

Electron mobility:
>100 x silicon

Mechanical properties:
Young's modulus: 5 x steel

Thermal conductivity:
>5x copper

Applications:

- Beyond-Moore electronics
- Energy applications
- Filler in nanocomposites
- Drug delivery and therapy



Nanocarbon sensors in brief

W H A T ?	<u>Gas sensors:</u> Vapor water (relative humidity), Atmospheric gas Dangerous gas (civil or defense) Volatile Organic Compounds	<u>Electronics devices</u>	H O W ?
	<u>Chemical sensing:</u> pH, chlorine, heavy metals	<u>Electrodes for electrochemistry</u>	
	<u>Biological sensing:</u> biomarkers in saliva or blood	<u>Electromechanical devices</u>	
	<u>Other:</u> Strain, flow, thermal	<u>Optical devices and spectroscopy</u>	

Potential for high sensitivity:
high surface over volume ratio
high adsorption capability



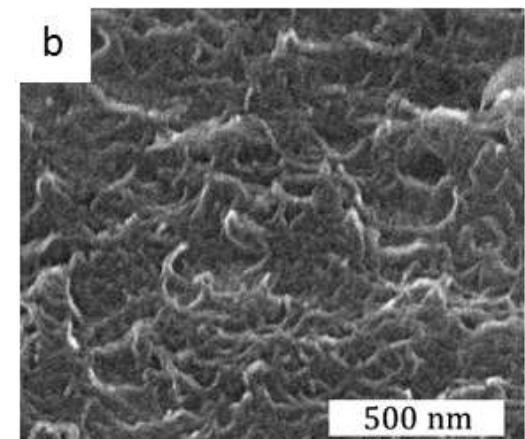
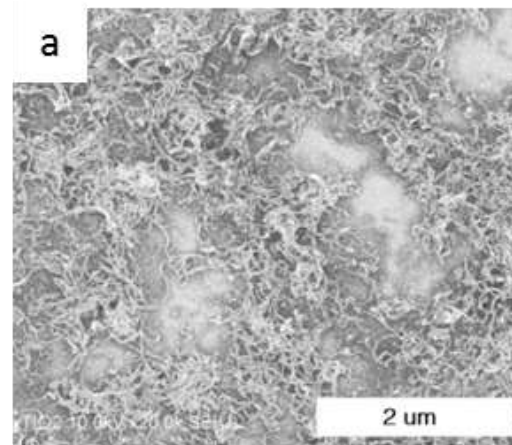
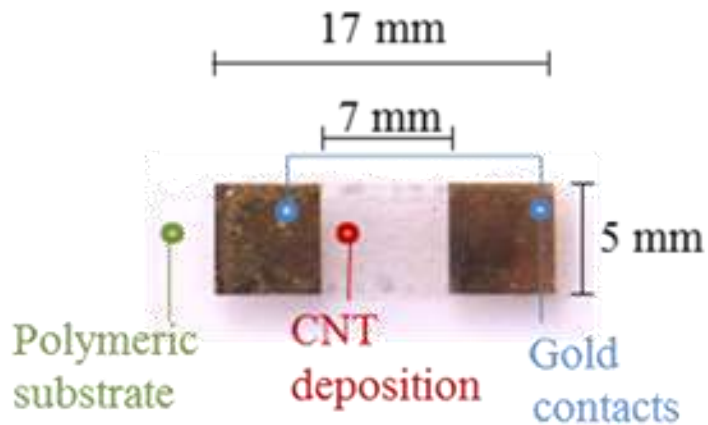
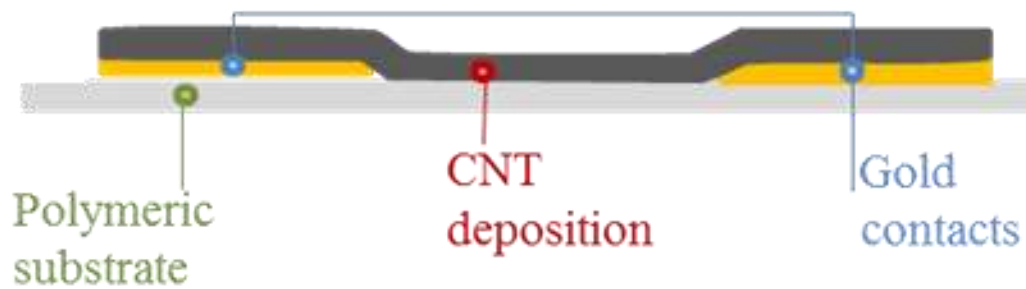
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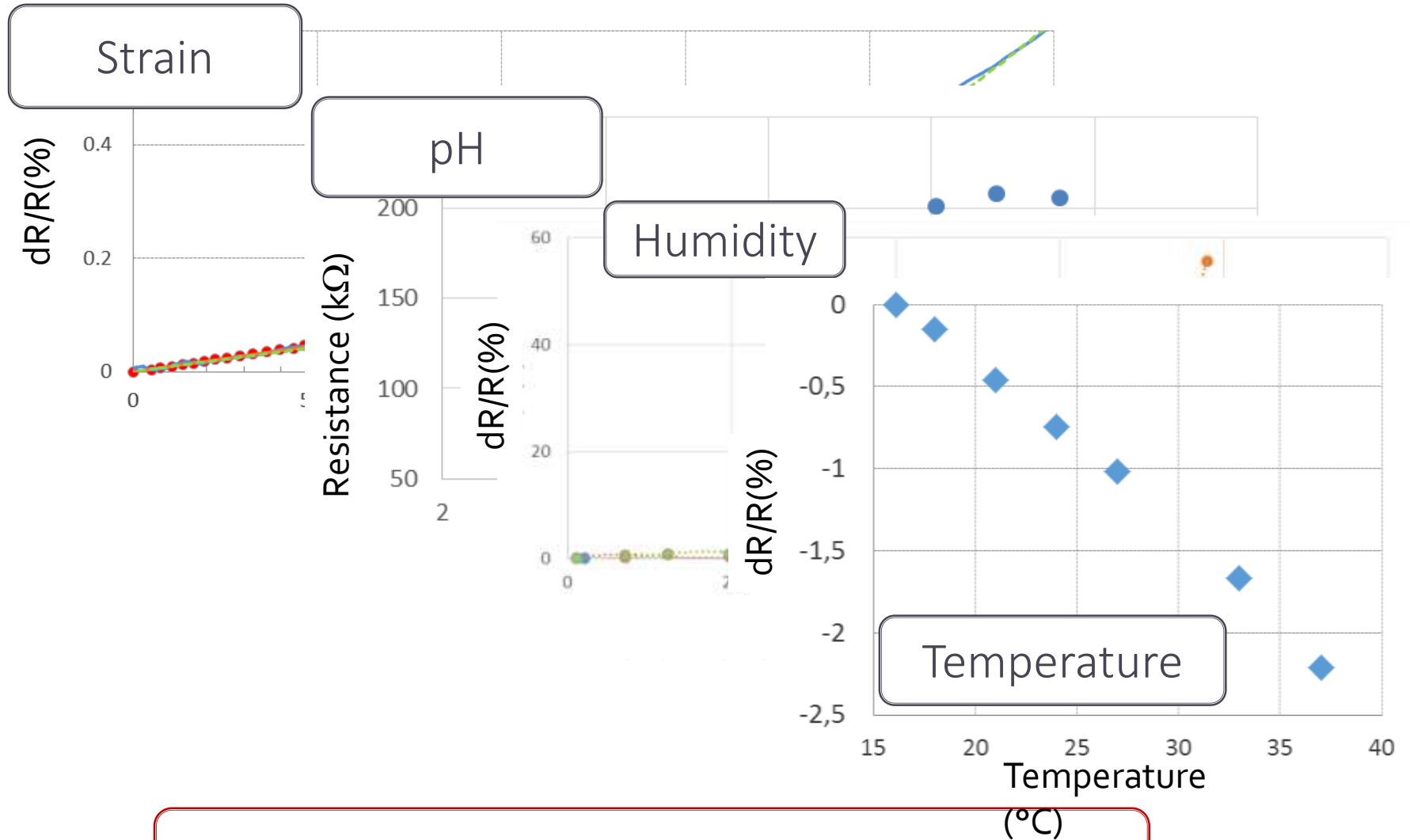
Potential for high sensitivity:
high surface over volume ratio
high adsorption capability

Carbon nanotube sensors in brief

Typical architecture: Inkjet printed, random network of multi-walled carbon nanotubes on polymer or silicon



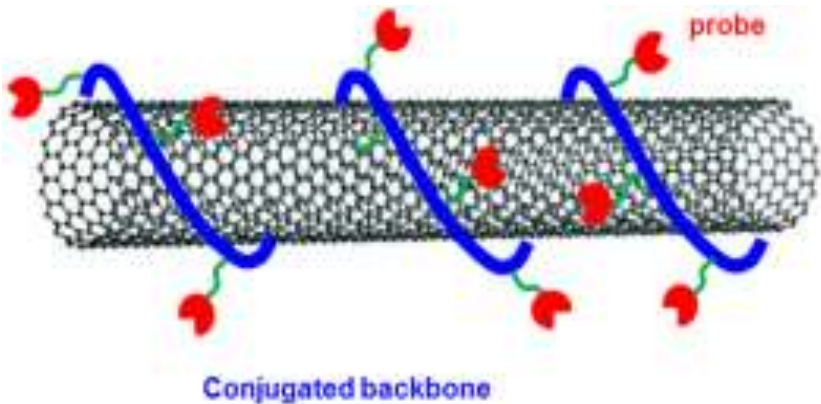
Carbon nanotube sensors: multifunctionality!



What about selectivity in sensing?

Our strategy for carbon nanotube sensing

Selectivity in chemical sensing : functionalization

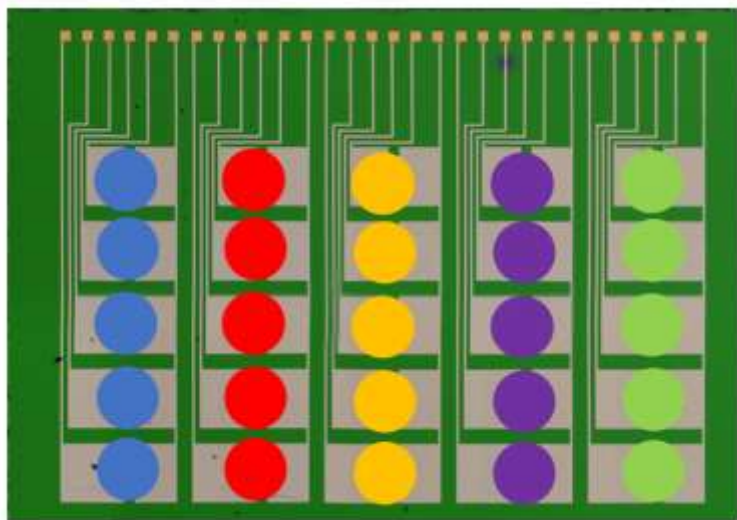


1 Chemical Function \rightarrow 1 Target Analyte

Big and Small Molecules

Covalent or Non-covalent

Multiparameter chemical sensing: sensor array



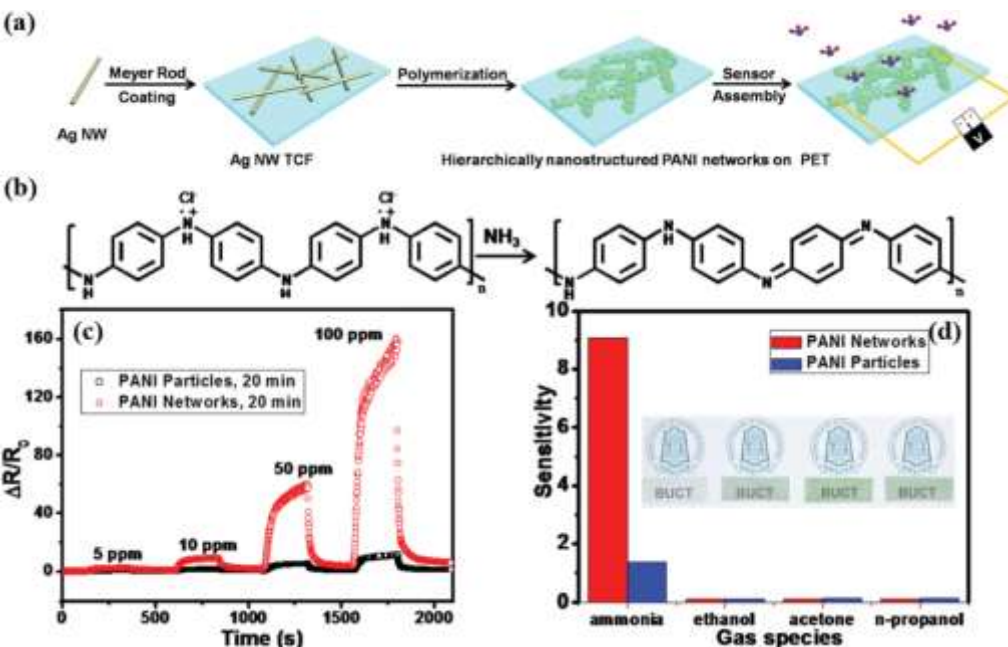
1 (small) chip or die or patch or tag...

X by Y Grid of (CNT) sensors

X functions to target X analytes

Y sensors by function for redundancy

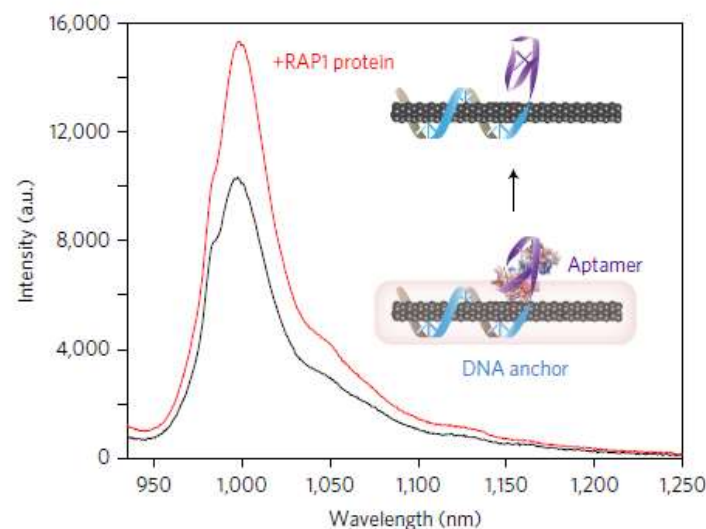
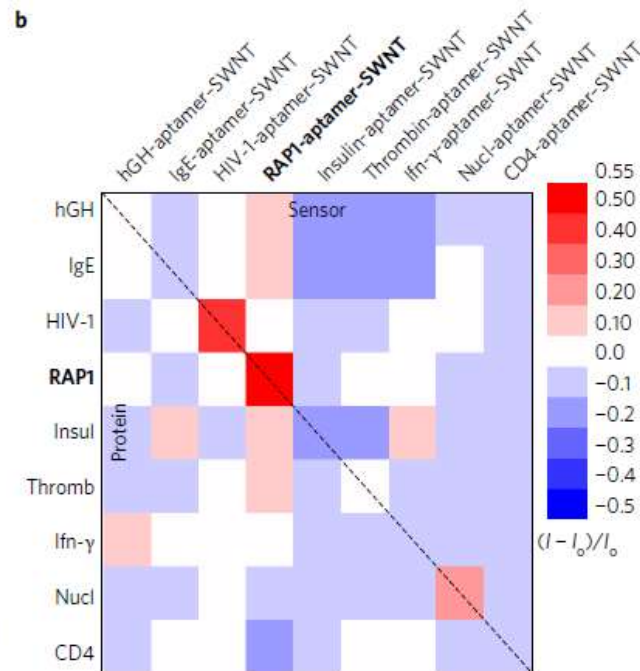
Functionalized carbon nanotubes sensor array for air quality and biological monitoring



Popular application of CNT

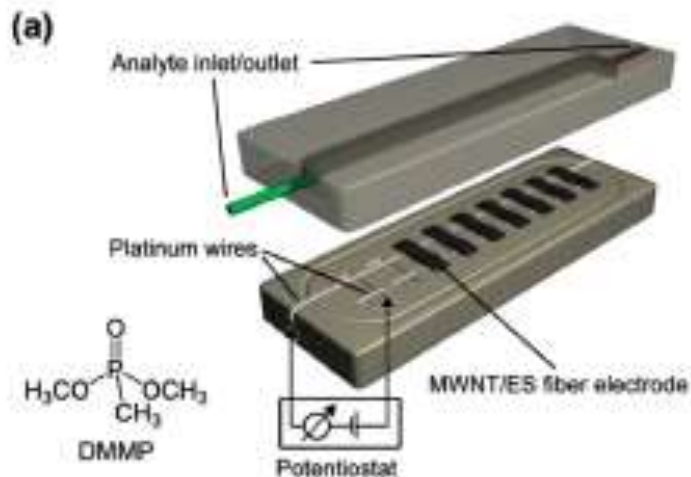
- Since 2003
- Mostly gas & biological
- What about water?

Nat Nano 2017, vol. 12, 368–377



small 2016, 12, No. 28, 3748–37!

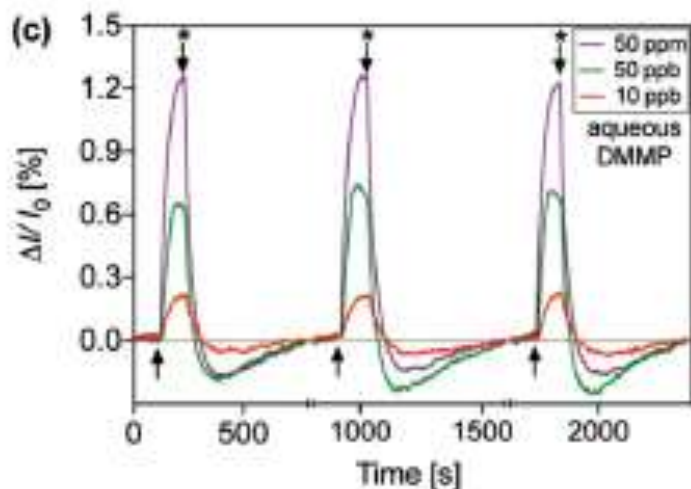
Functionalized carbon nanotubes sensor array for water quality monitoring?



CNT-based **electronic tongue**:

- pH, chlorine, nitrates, metals...
- **Mostly mono or bi-parameter**
- Very little electronic devices
- Very little deployment report

➔ Toward a **systematic multiparameter approach** to CNT e-tongue including **end-to-end integration**



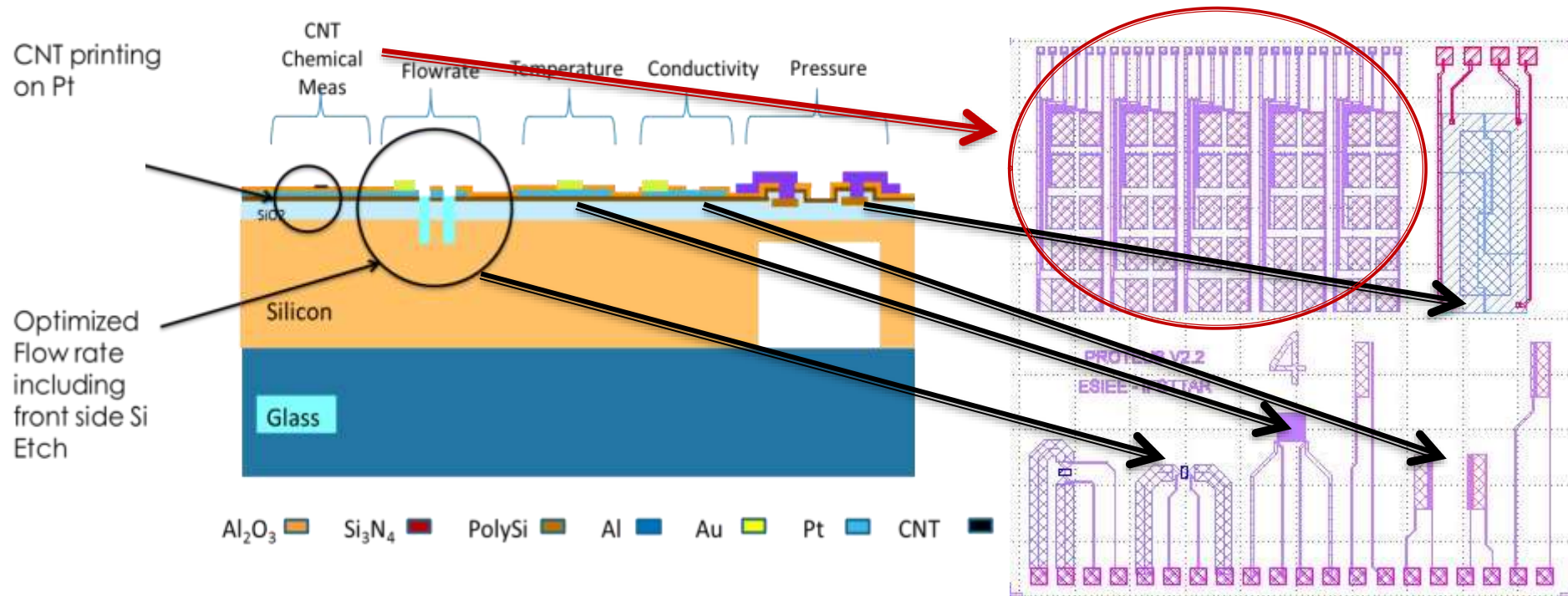
Adv Func Mat 2014, vol. 24, 492–502

Multiplexing: heterointegration of CNT sensor array on a MEMS platform

9 Physical and Chemical Sensors - on a Single 1 cm² Si Chip – up to 31 Devices

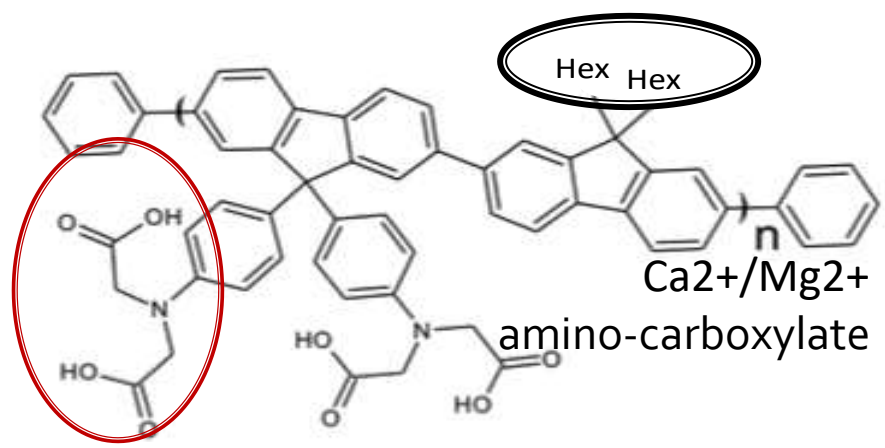
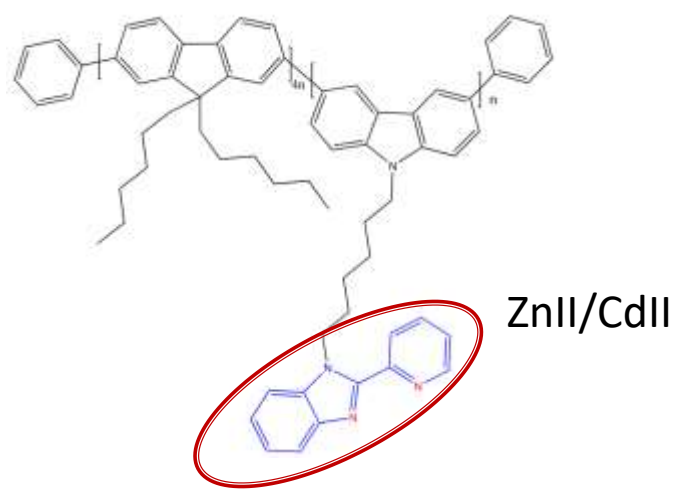
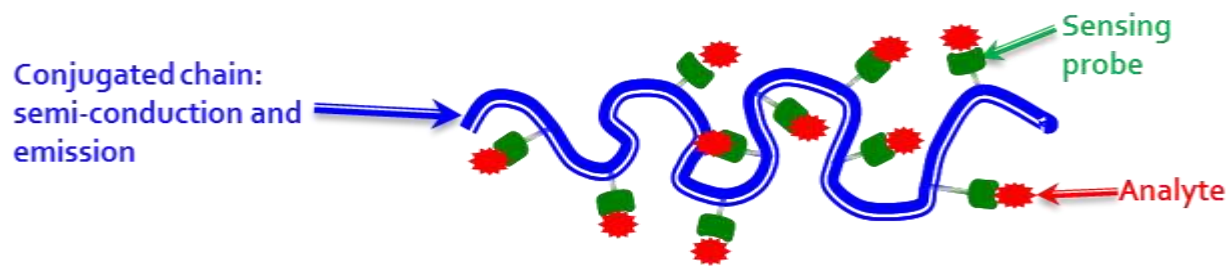
MEMS sensors : temperature, conductivity, pressure, **flow rate**

CNT sensors: pH, chlorine, **chloride**, **nitrate**, **calcium**





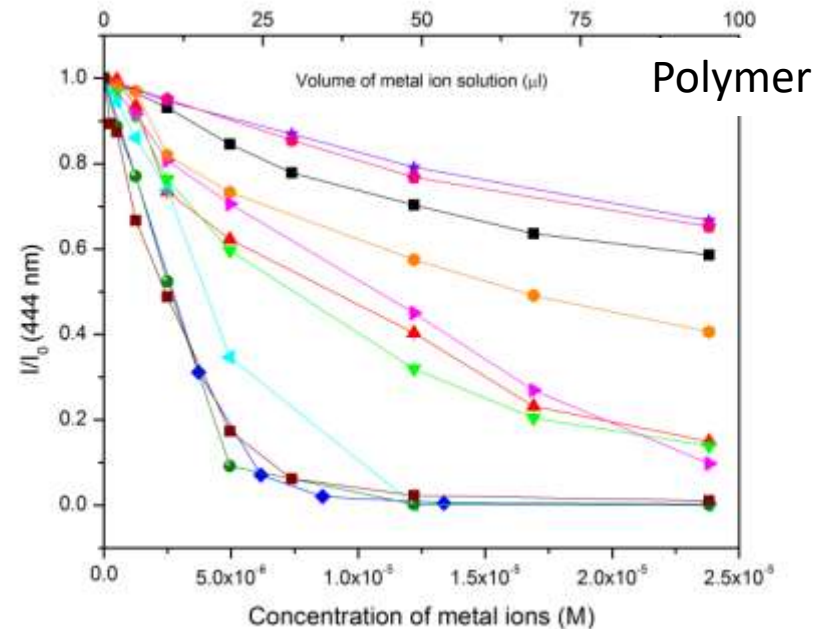
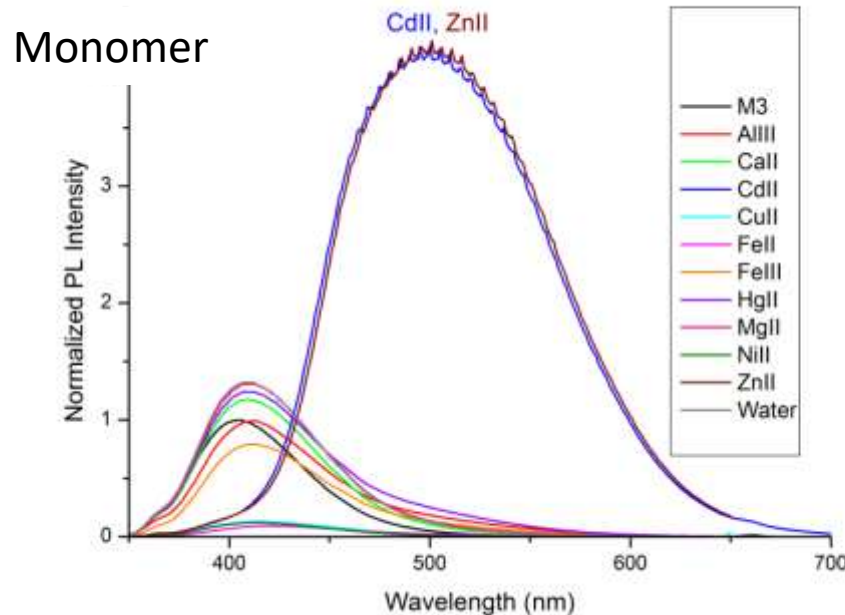
Functionalization: Our patented set of **tunable** conjugated polymers (FR1753131)



Validation of polymer design: polymer alone

Optical sensing with polymer alone

Photoluminescence quenching – New Photoluminescence peak

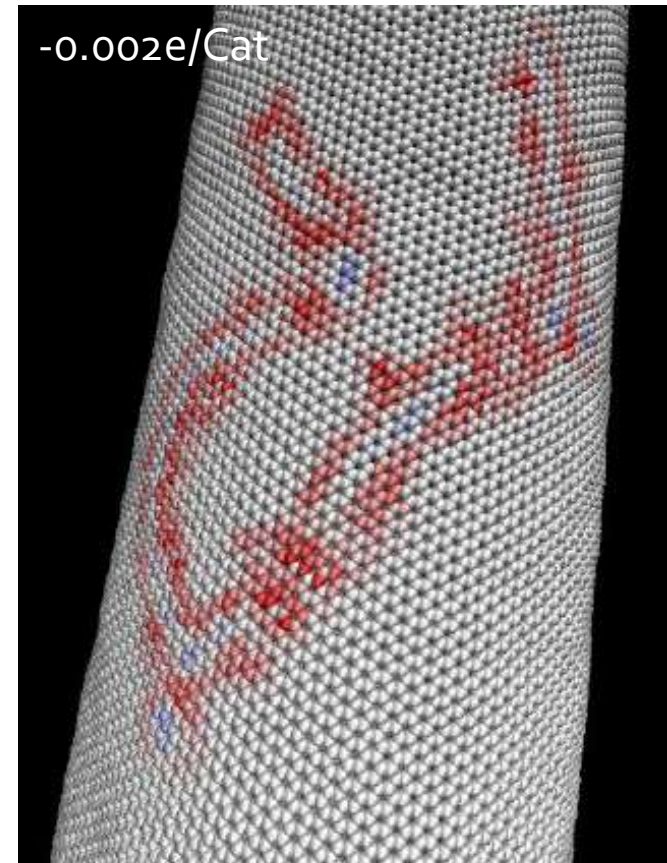
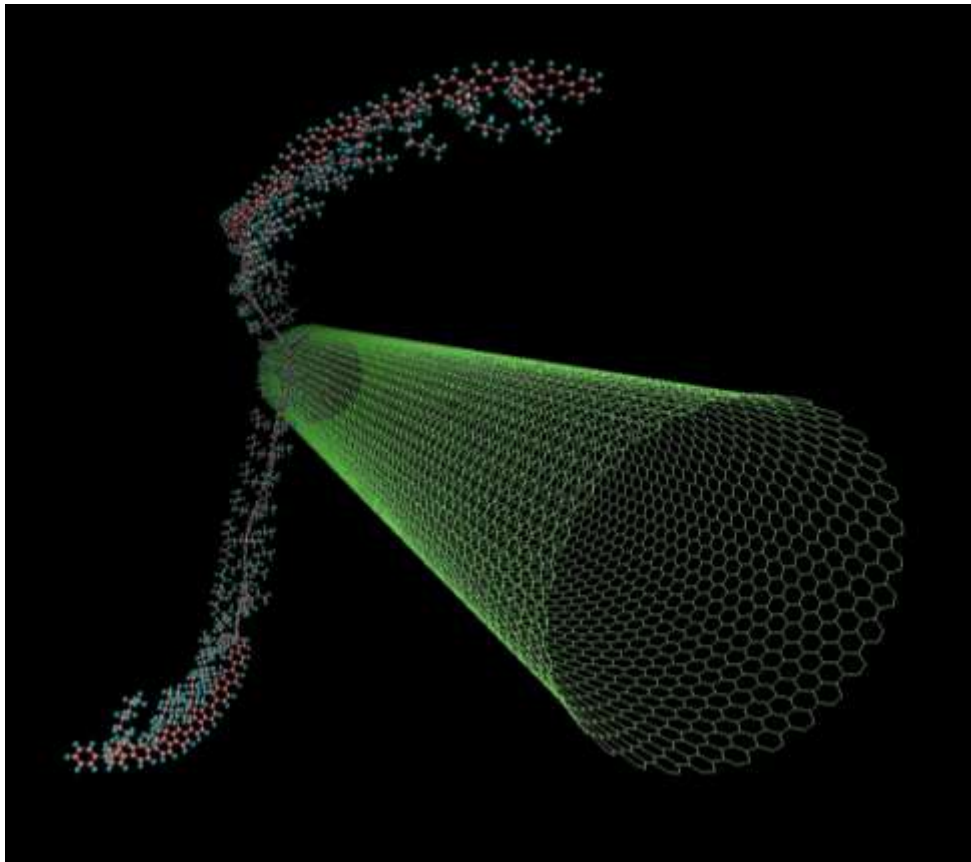


Validation of polymer design: polymer + CNT

Molecular dynamics simulations:

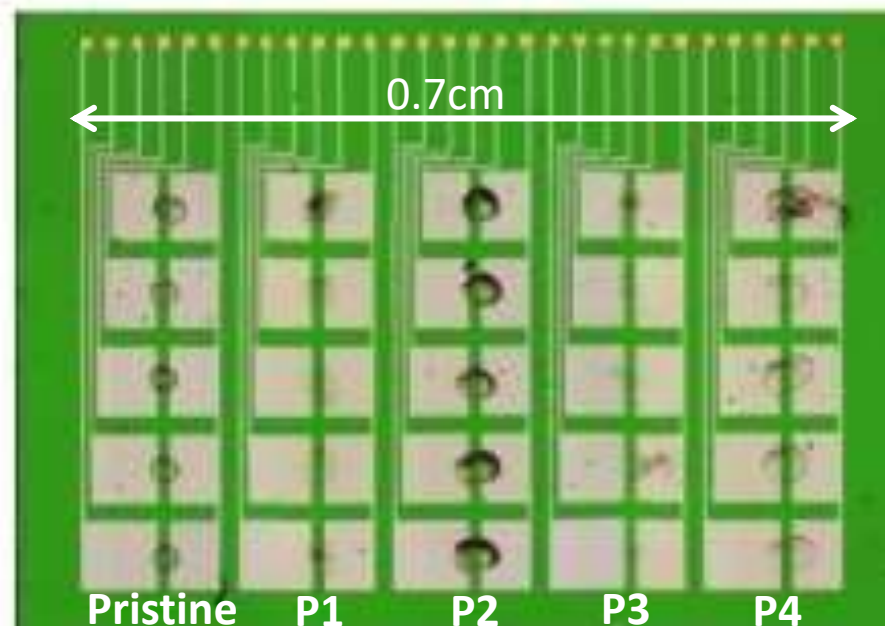
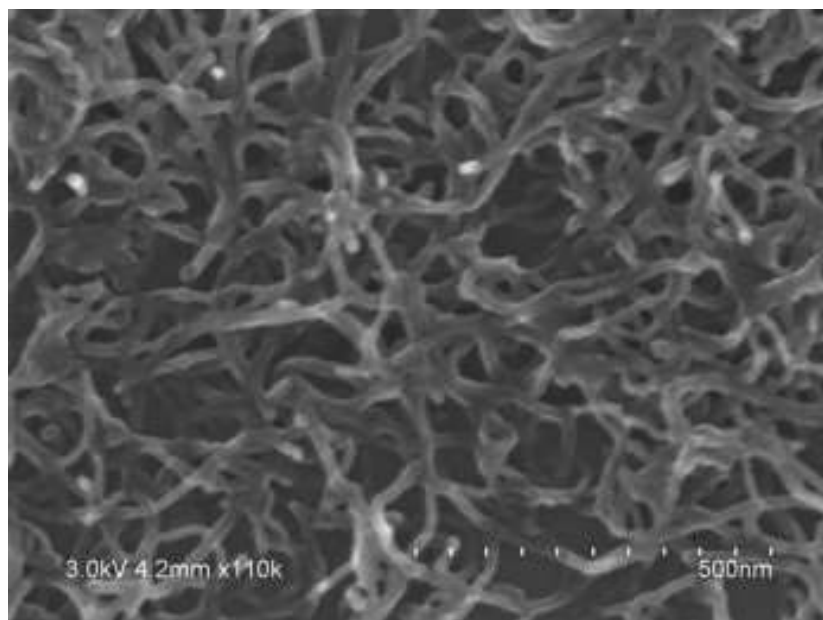
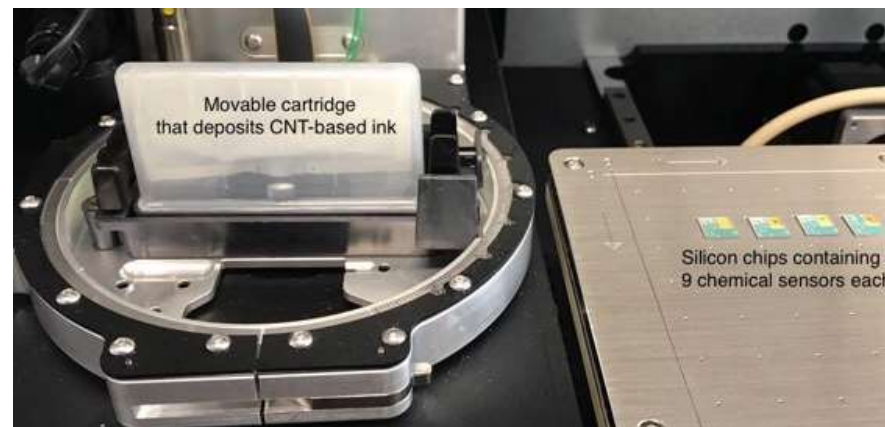
To study functionalization morphology

To prove **charge transfer between polymer and CNT**



CNT sensor array : device fabrication

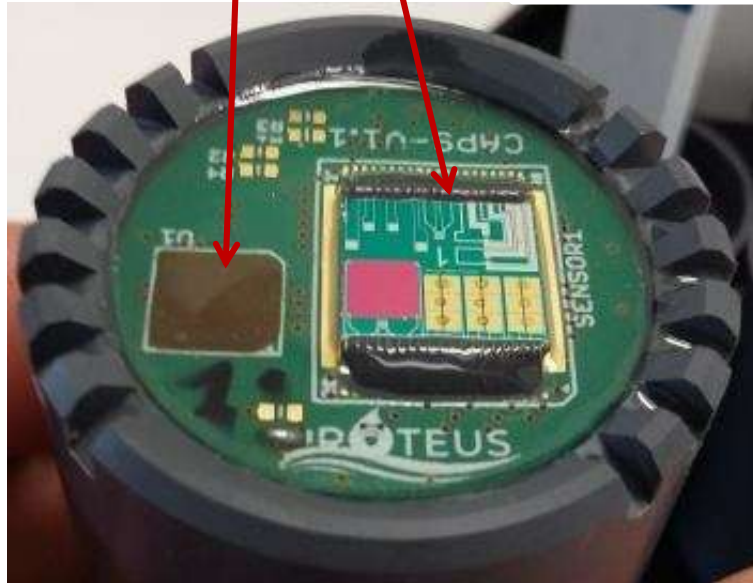
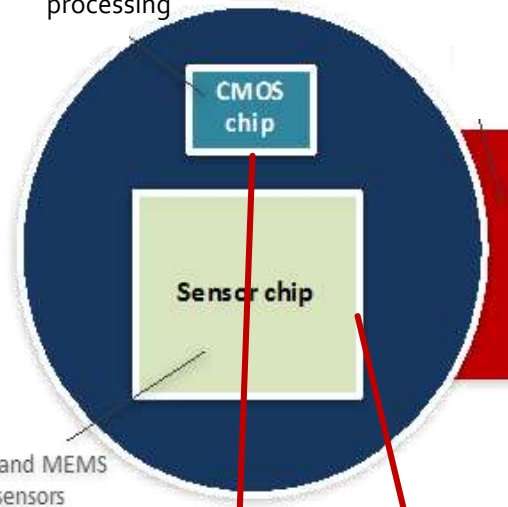
- ❖ CNT & polymers processed into inks and ink-jet printed in small series



From multiparameter sensor chip to IOT node

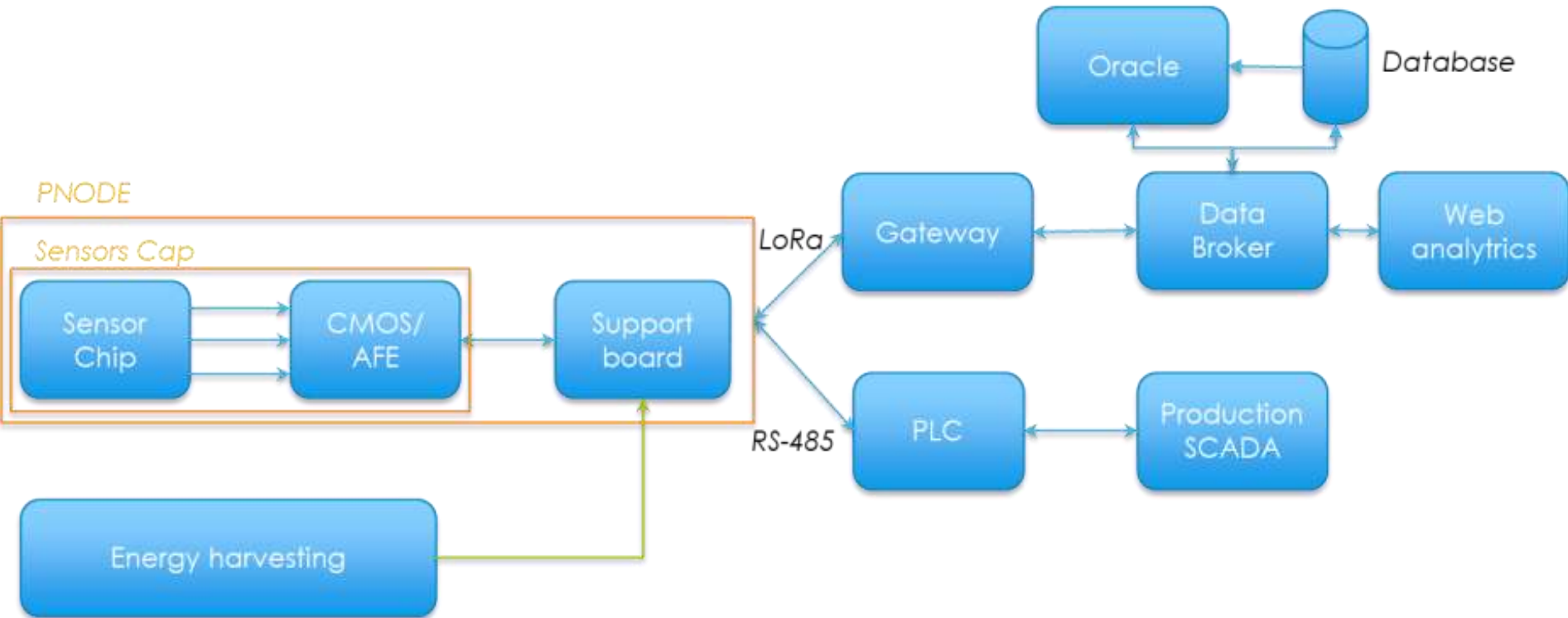


Analog front end
Part of digital
processing

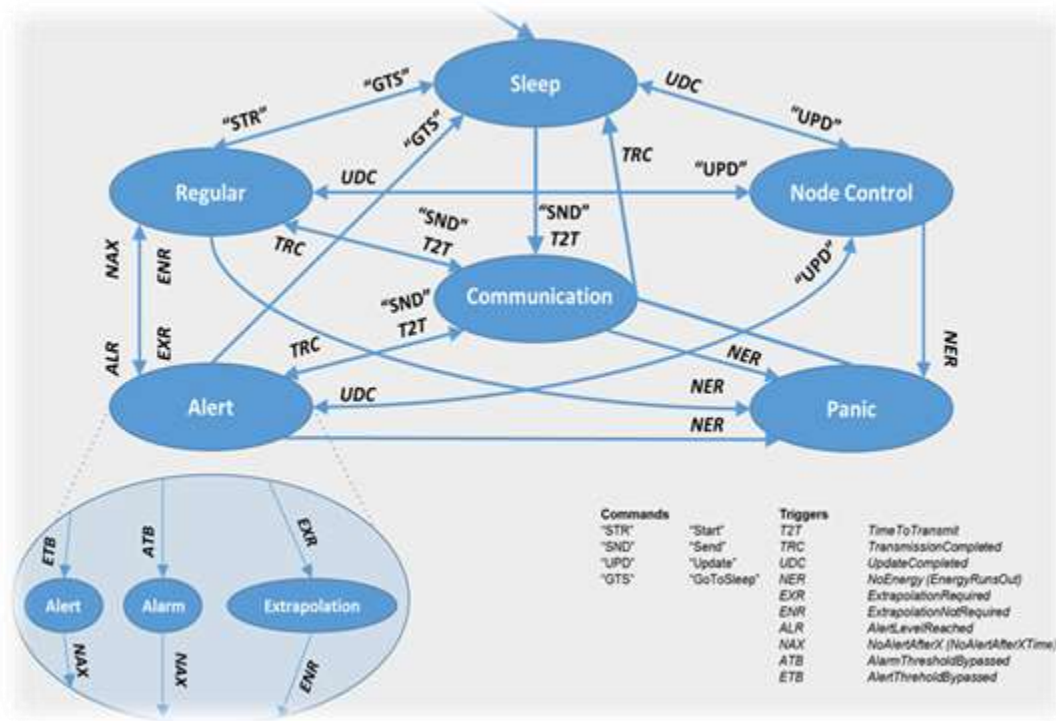


10x decrease in size
25x decrease in cost
within 3-5 years

From IoT node to IoT system: supporting legacy systems and cloud supervision

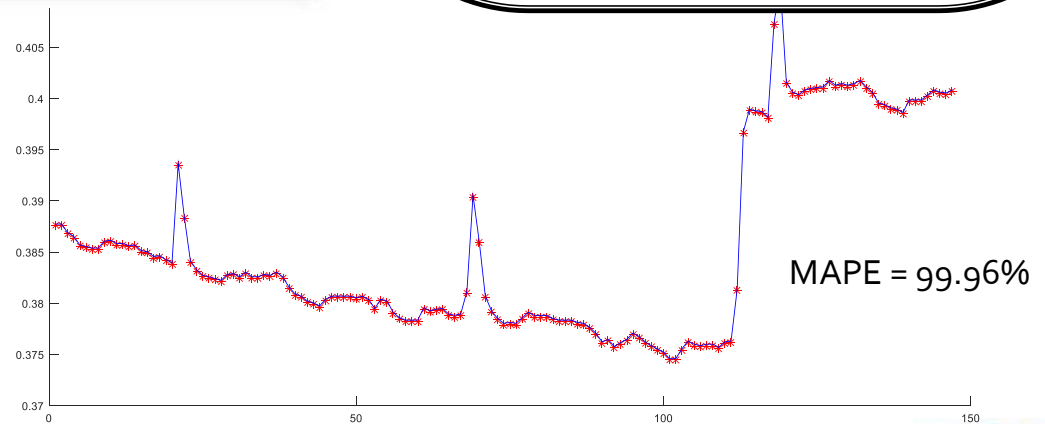


A reconfigurable IoT node: reaction and prediction

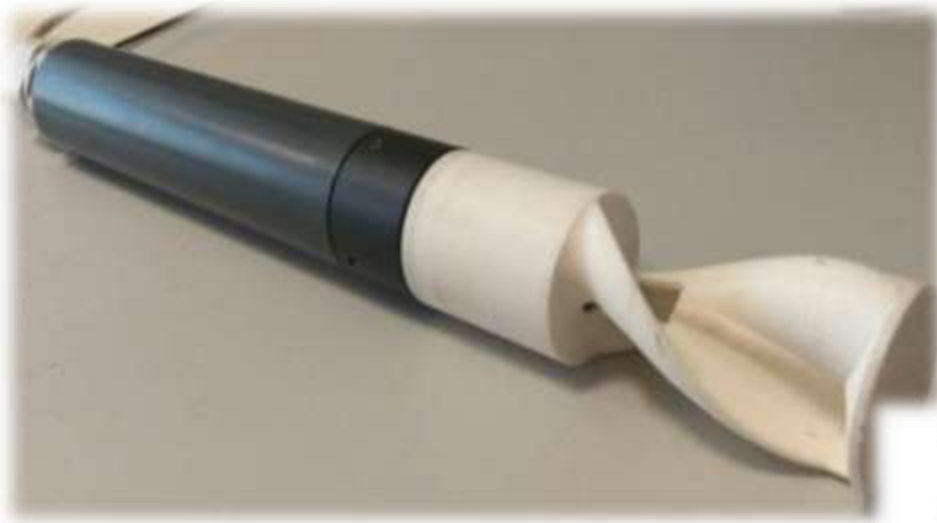


Reactive and predictive operational software:

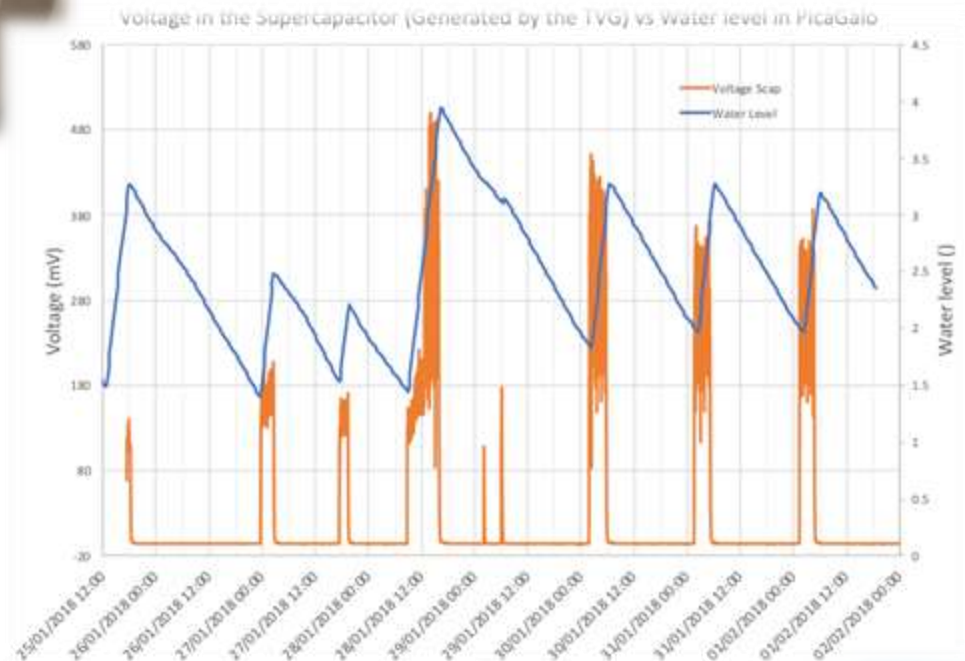
- In-node recognition of use-case specific scenarios
- Adaptation of node operation (sensing, communication, processing...)
- In-node and in-cloud prediction of events



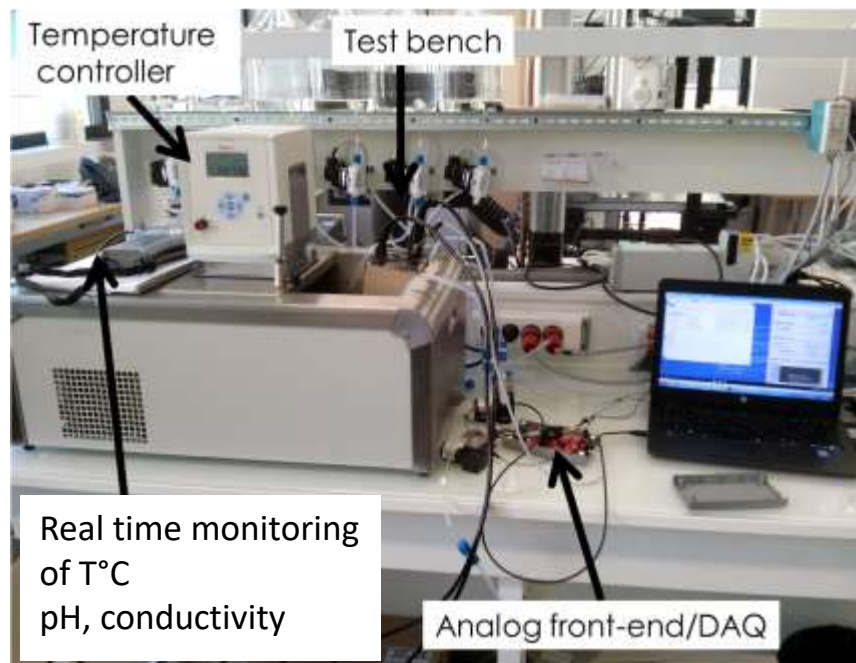
An autonomous sensor node thanks to reactive & cognitive capabilities



**Innovative micro-turbine
design tested in field condition**



Understanding sensitivity in the lab



End user requirements:

pH: 6 to 8

Chlorine: 0 to 5 mg/L (0.05 to 5ppm)

Chloride: 0 to 250mg/L (10 to 250ppm)

Calcium: 0 to 200mg/L (10 to 200ppm)

Nitrate: 0 to 100mg/L (10 to 100ppm)

Pre-industrial sensor batch:

12 nodes tested

108 devices

Development of semi-automated testbench

for extensive characterization
device resistance vs concentrations

Understanding sensitivity in the lab

Caps #	type of function	Index of device	pH	total chlorine	chloride	nitrates	calcium
13	P2 polymer	CNT1-R1	-18%	-20%	no	no	16%
	P2 polymer	CNT1-R2	no	-25%	-7%	no	9%
	P2 polymer	CNT1_R3	no	-25%	-12%	no	14%
	CF-OX	CNT2_R1	-20%	-28%	no	no	no
	CF-OX	CNT3_R1	-24%	-23%	no	-10%	22%
	pristine	CNT2_R2	-19%	-18%	no	no	18%
	pristine	CNT3_R2	no	-20%	no	no	11%
	FF-UR	CNT2_R3	-22%	-22%	no	no	15%
	FF-UR	CNT3_R3	-16%	-29%	-24%	no	no

-5 analytes monitored with single probe and 2x-redundancy
 -Differentiated selectivities with polymers
 -New sensors in CNT state of the art!

Detection thresholds

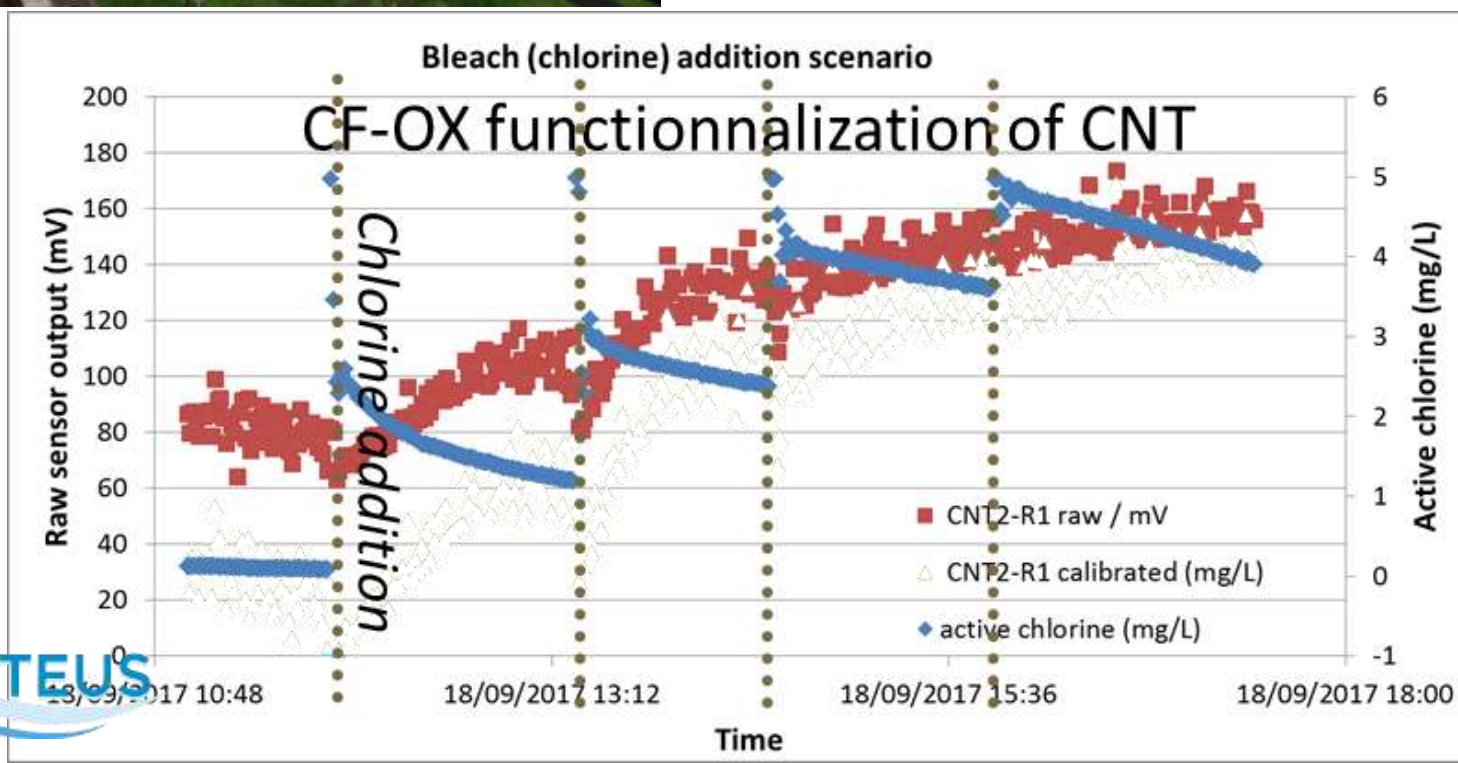
- pH: 0.05 pH unit
- HOCl/OCl⁻: 0.05mg/L
- NO₃⁻: 0.7mg/L
- Ca²⁺: 8mg/L
- Cl⁻: 20mg/L

Field response: event detection



Deployment in realist (Sense-City) and real (Almada network) locations

- Detection of chlorine and chloride
- Real time (<15min)
- Operational for (at least) a week

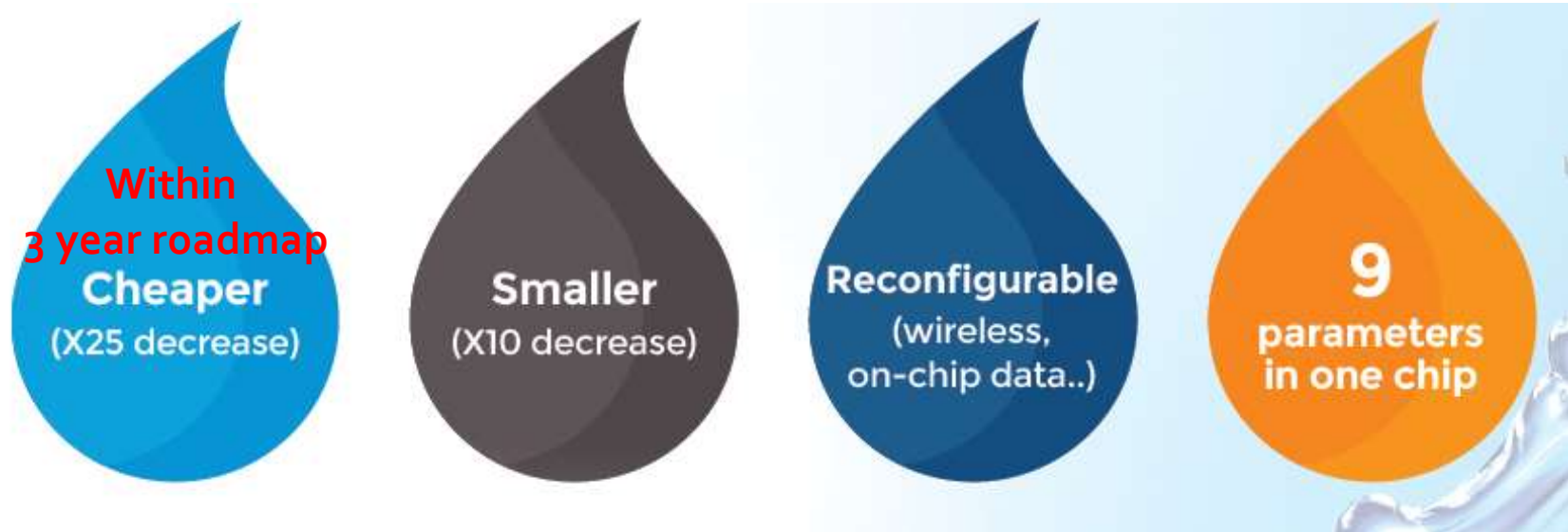


Conclusions and prospects



9 devices, 5 analytes CNT-based e-tongue atop 4-sensor MEMS chip

- ❖ Drastic progress compared to commercial & research SOTA, at high TRL



➔ **Start'up Sens'hydre** funded from January 2019!

➔ **EU-India project LOTUS** starting February 2019



LOW-cost innovative Technology for water quality monitoring and water resources management for Urban and rural water Systems in India



Team NACRE (IFSTTAR-Ecole Polytechnique-CNRS)

Researchers

L. Bodelot, B. Lebental, G. Zucchi

Platform engineers

B. Gusarov, J. Charliac, J.F. Arruabarrena,
I. Florea, E. Merliot

Master students, PhDs, Post-docs

Y. Wang, R. Benda, C. Gookbin, N. Massonnet, I. Fomicheva, L. Loisel, K. Ramachandran, M. Godumala, A. Gutierrez, Y. Zhang

ESIEE

T. Bourouina, F. Marty, F. Shaun

UNINOVA

J. Oliveira

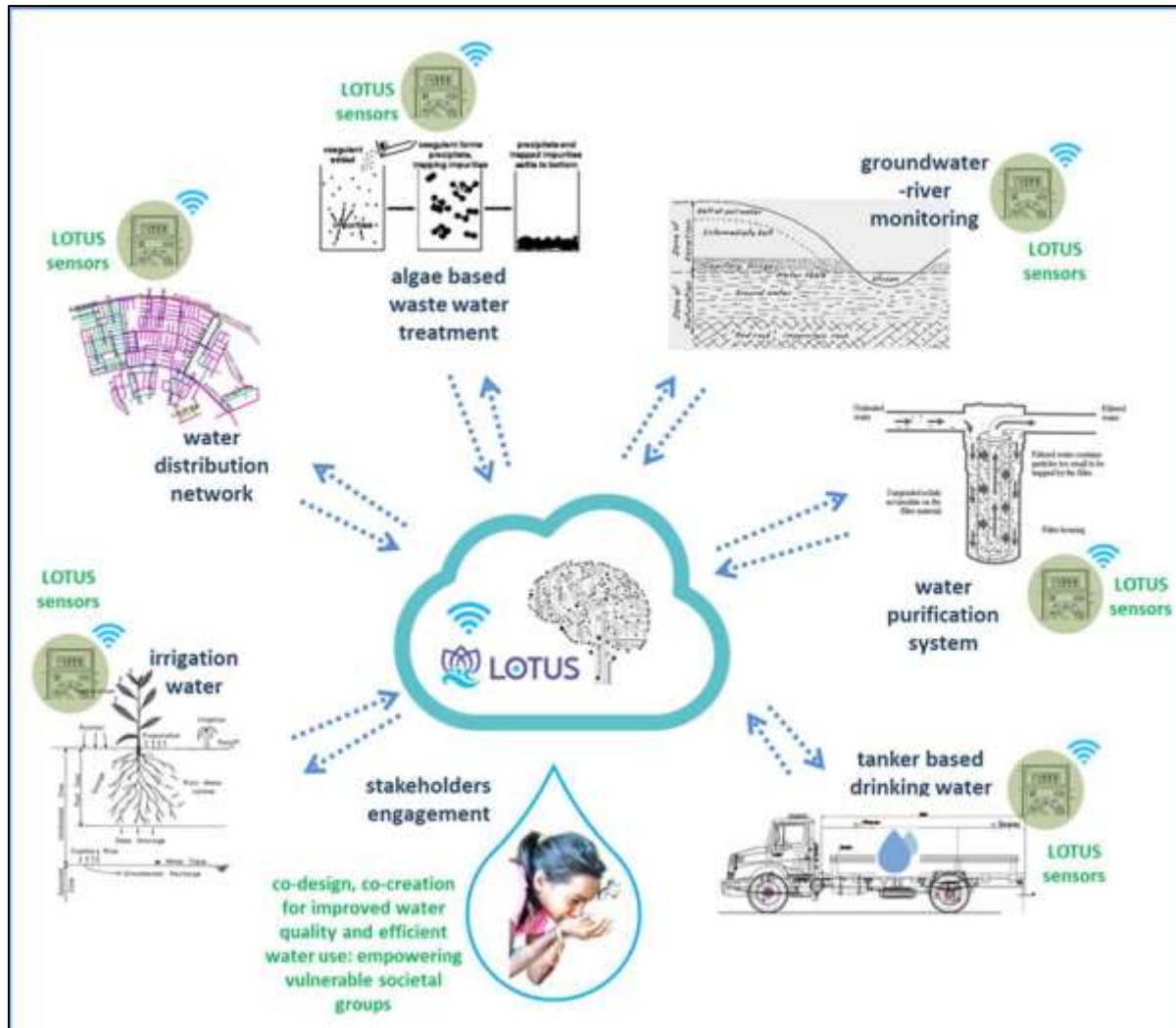
Aqualabo

F. Bellouard

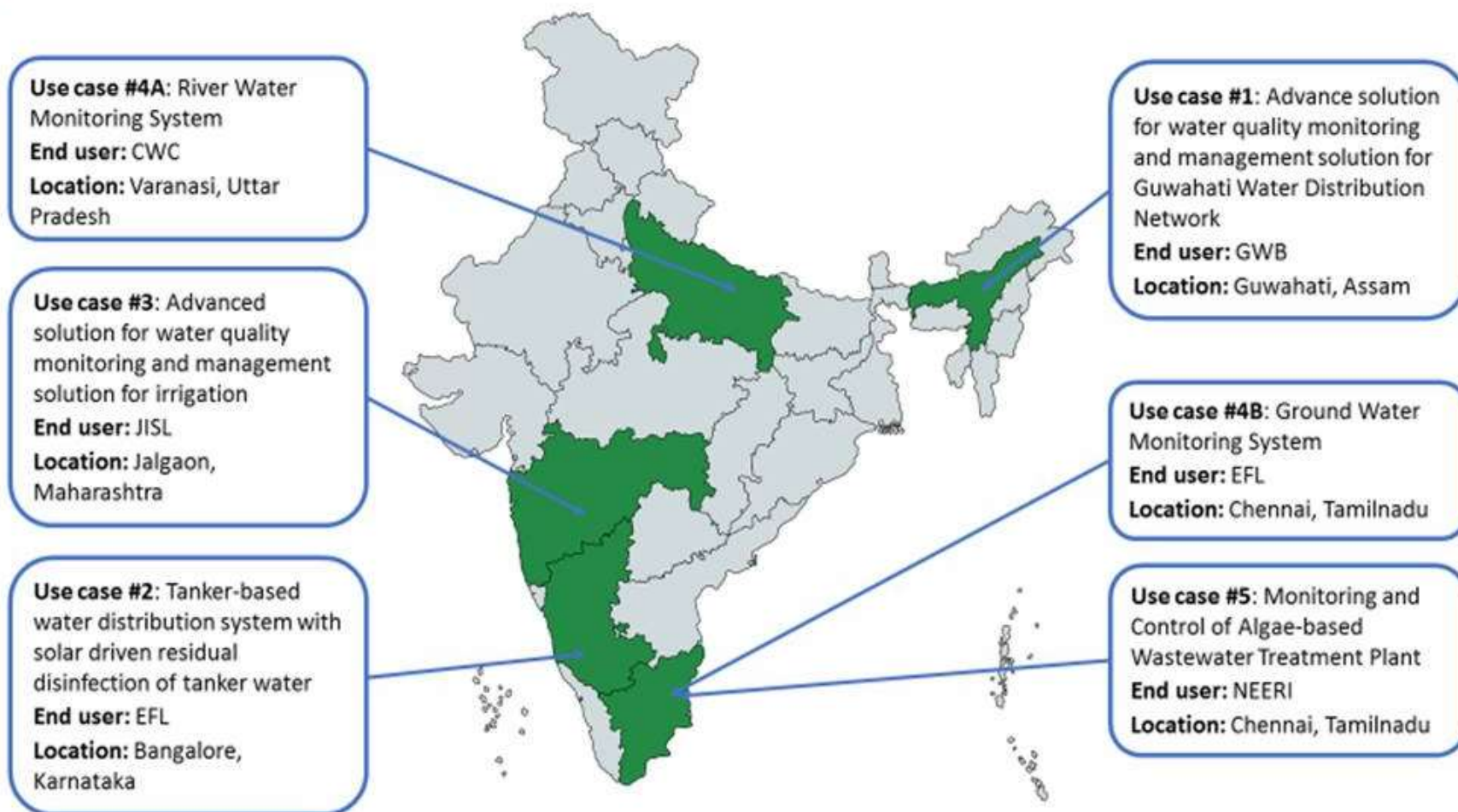
Unparallel

B. Almeida, M. Costa

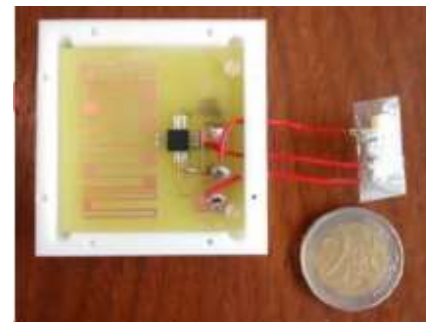
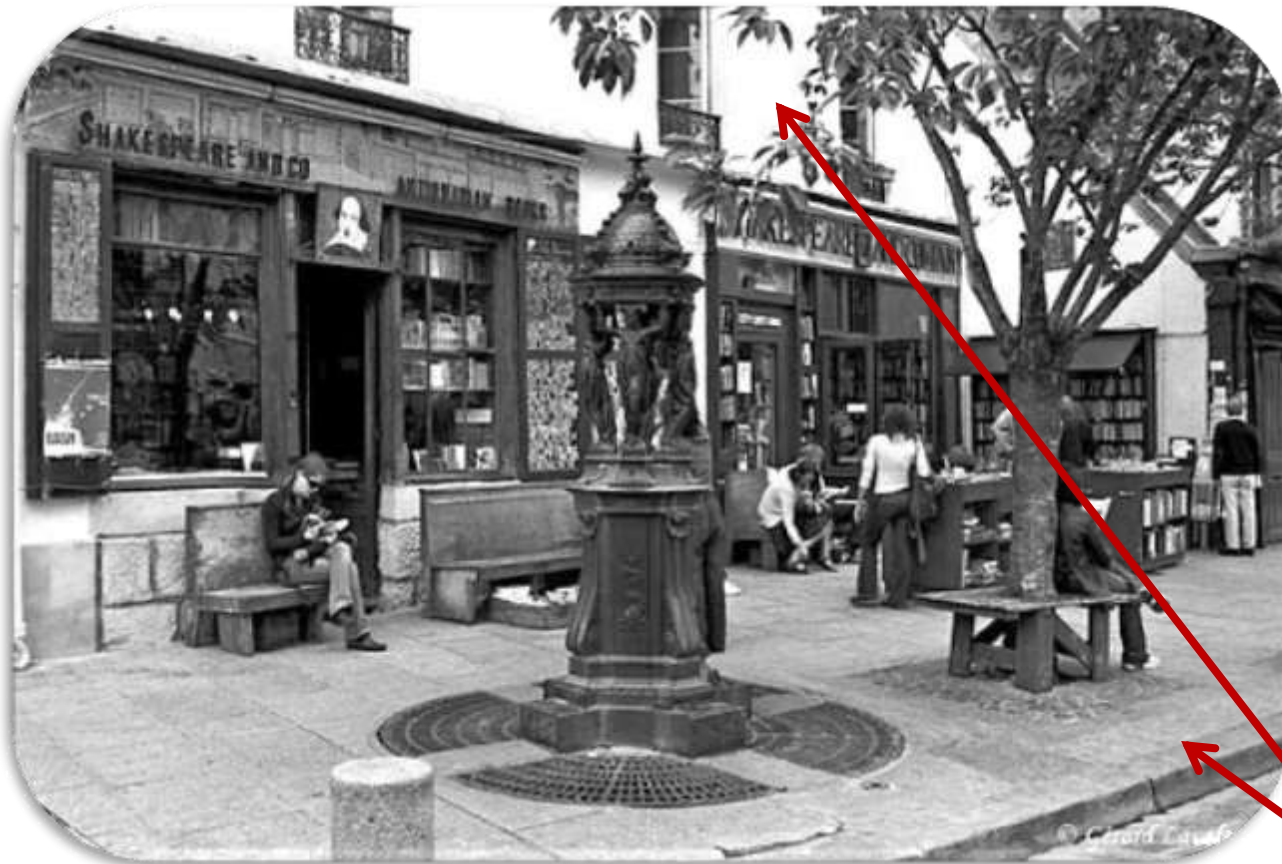
Insight into upcoming LOTUS



Insight into upcoming LOTUS



If time permits, I'll share about **our start up Altaroad!**



**Building and
road durability
monitoring with
CARBON
NANOTUBES**



Enabling the next generation of roads
Project presentation – October 2018

“Grand Prix” of the I-LAB BPI competition for innovative, deep-tech startups
with the support of:



The **road network** is the most critical infrastructure in any country. How can we maintain and upgrade it?



What if the road could talk ?

+10%
trucks traffic

Flat tires
please check
your tires at
the next
opportunity

4 years
before
repairing this
road section

Warning!
Countersense
driving

ALTAROAD enables a **new generation** of connected roads

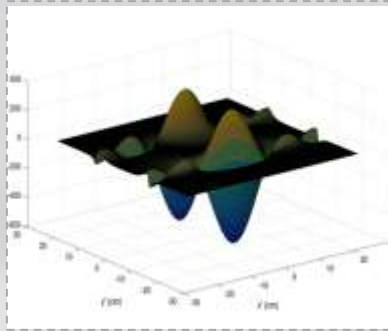


Freight traffic optimization

Repairs at the right place and at the right time

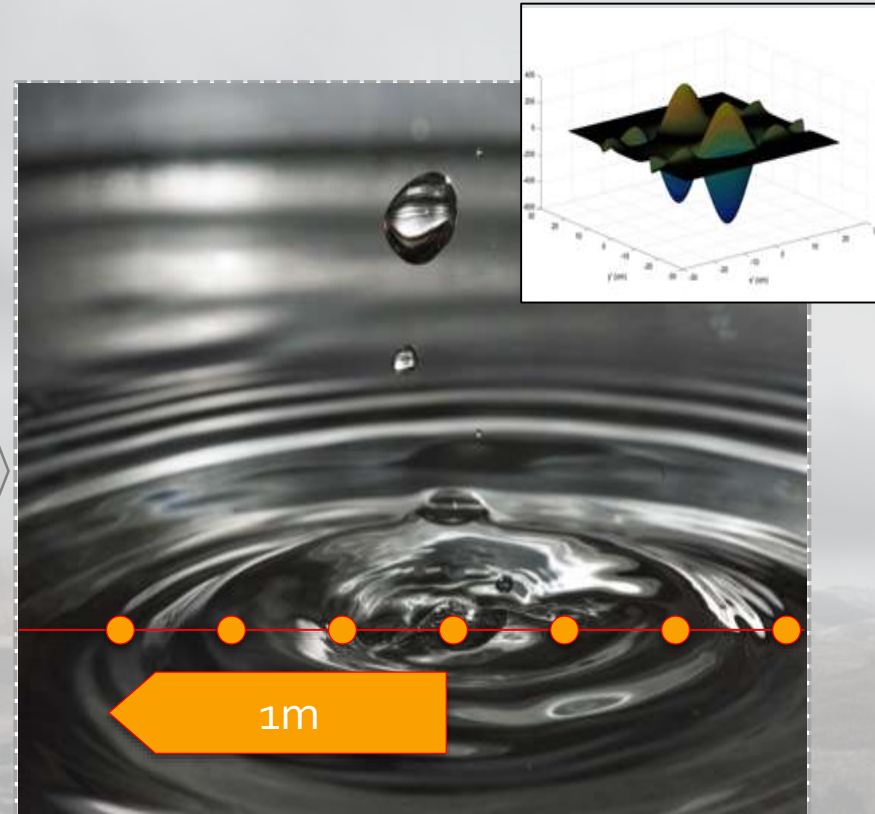
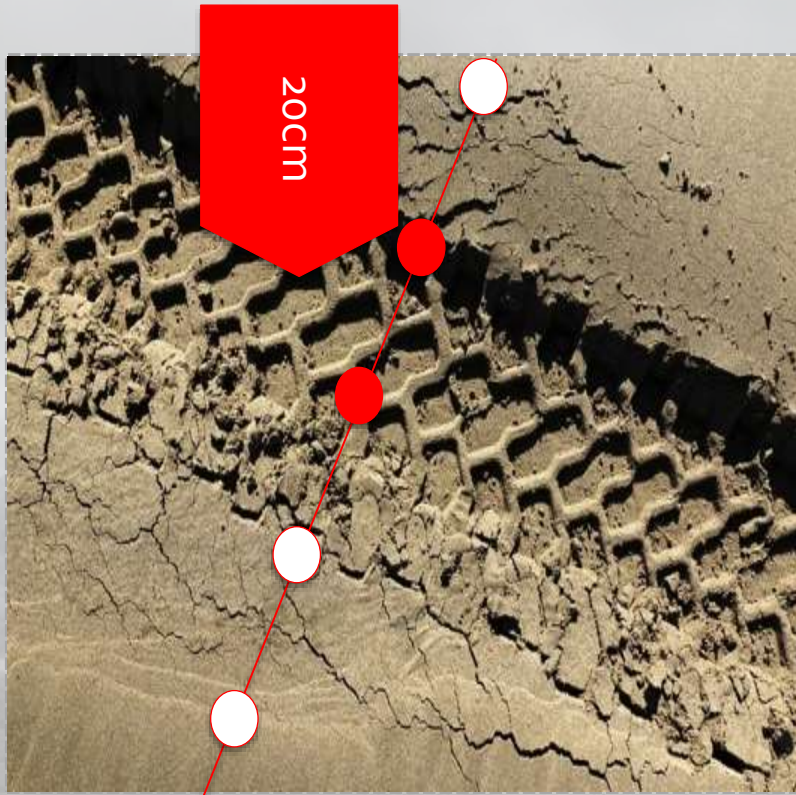
Autonomous vehicles safety feedback

ALTAROAD has developed **patented industrial IoT** devices.



Invisible built in solution

Our devices look at the signal **propagating along the road surface.**



ALTAROAD in the news



Generating data for smart cities, transportation and logistics providers

ALTAROAD in a 90-seconds video

<https://www.youtube.com/watch?v=y5aA23nKog8>

<https://www.dailymotion.com/video/x6noipo>

Cécile VILLETTE

06 80 32 93 26

cecile.villette@ALTAROAD.com

BPI FRANCE, Grand prix du concours i-LAB 2018 des startups DeepTech

<https://www.bpifrance.fr/A-la-une/Actualites/Concours-i-Lab-le-palmars-2018-41254>

USINE DIGITALE, Les capteurs d'ALTAROAD rendent la route intelligente

<https://www.usine-digitale.fr/article/les-capteurs-d-ALTAROAD-rendent-la-route-intelligente.N726164>

BATIACTU - ALTAROAD, les capteurs français qui rendent la route intelligente

<https://www.batiactu.com/edito/ALTAROAD-capteurs-francais-qui-rendent-route-intelligente-52630.php>

MILKSHAKE VALLEY - ALTAROAD optimise le transport et la logistique grâce aux datas de la route

<http://milkshakevalley.com/ALTAROAD-optimise-transport-logistique-datas-route/>

With the support of:

