WWSC → WWSC 2.0

Electric, electronic and digital cellulose and paper
Lab. of Organic Electronics @ LiU

Magnus Berggren

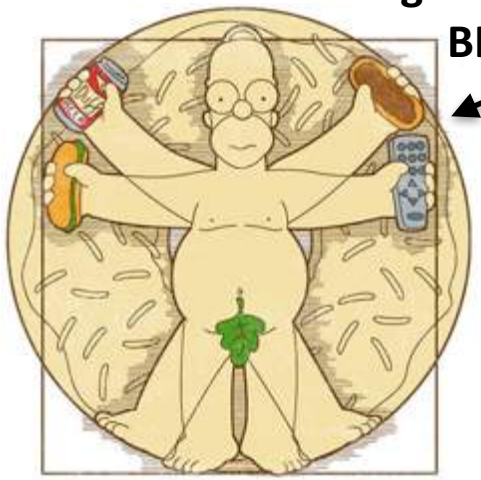
LINKÖPINGS UNIVERSITET

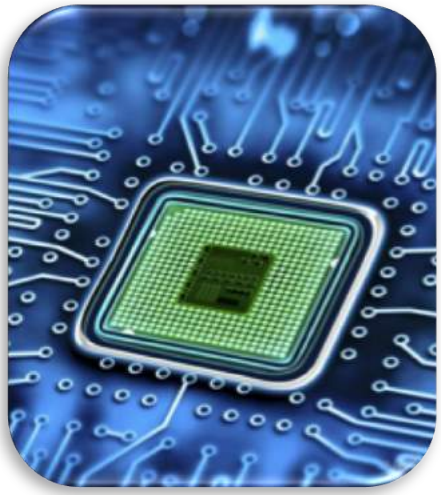
Outline

- Intro, LOE@LiU and RISE Acreo
- Printed Electronics, Bioelectronics and BioComLab
- Power Papers
- e-Plants
- Outlook

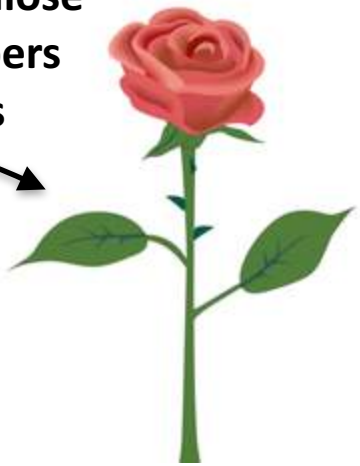
Our vision
Materials and signals in electronics, animals and plants

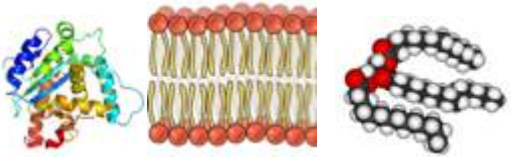
Artificial Nervous Systems
Organic Bioelectronics
BIOCOM Lab



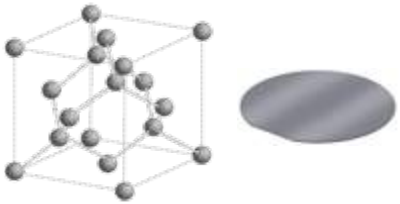


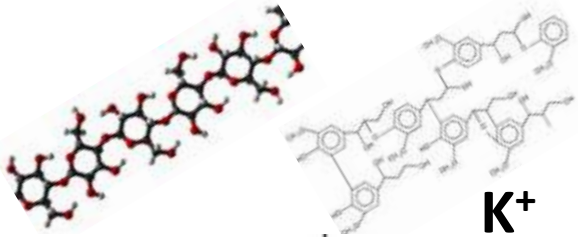
WWSC 2.0
Digital Cellulose
Power Papers
***e*-Plants**

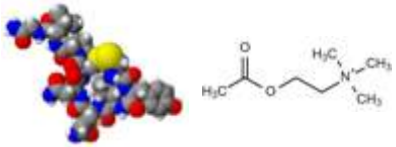




Si

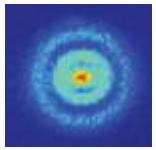


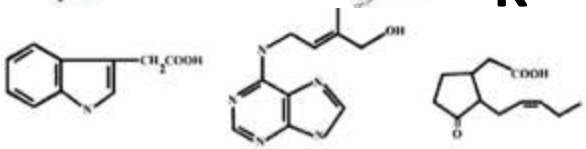




K^+

$e^- : \lambda = p/h$





K^+

Laboratory of Organic Electronics

RI SE acreo

- Laboratory Director – Magnus Berggren
- Organic Bioelectronics – Daniel Simon
- Organic Energy Material – Xavier Crispin
- Printed Electronics – Isak Engquist
- Modelling and Theory – Igor Zozoulenko
- Organic Nanocrystals – Eric Glowacki
- Organic Nanoelectronics – Simone Fabiano
- Organic Photonics – Magnus Jonsson
- Electronic Plants – Eleni Stavrinidou

- Printed Electronics – Göran Gustafsson
- Printed Electronics Arena – Tommy Höglund

Linköping University
Campus Norrköping, Sweden

The Täppan Clean Room, LiU, Campus Norrköping

Printed Electronics Arena, LiU, Campus Norrköping
Swedish Research Laboratory for Printed Electronics (KAW)

PEA
Printed Electronics Arena


Printing, patterning, coating and lamination

Smart packages


Ink development

Selected by the European Commission as a mKPL Demonstrator


Printing processes


Electrochromic displays


Collaborations


Body area network


Electronic skin patches

Spinning out companies


in vivo electronics

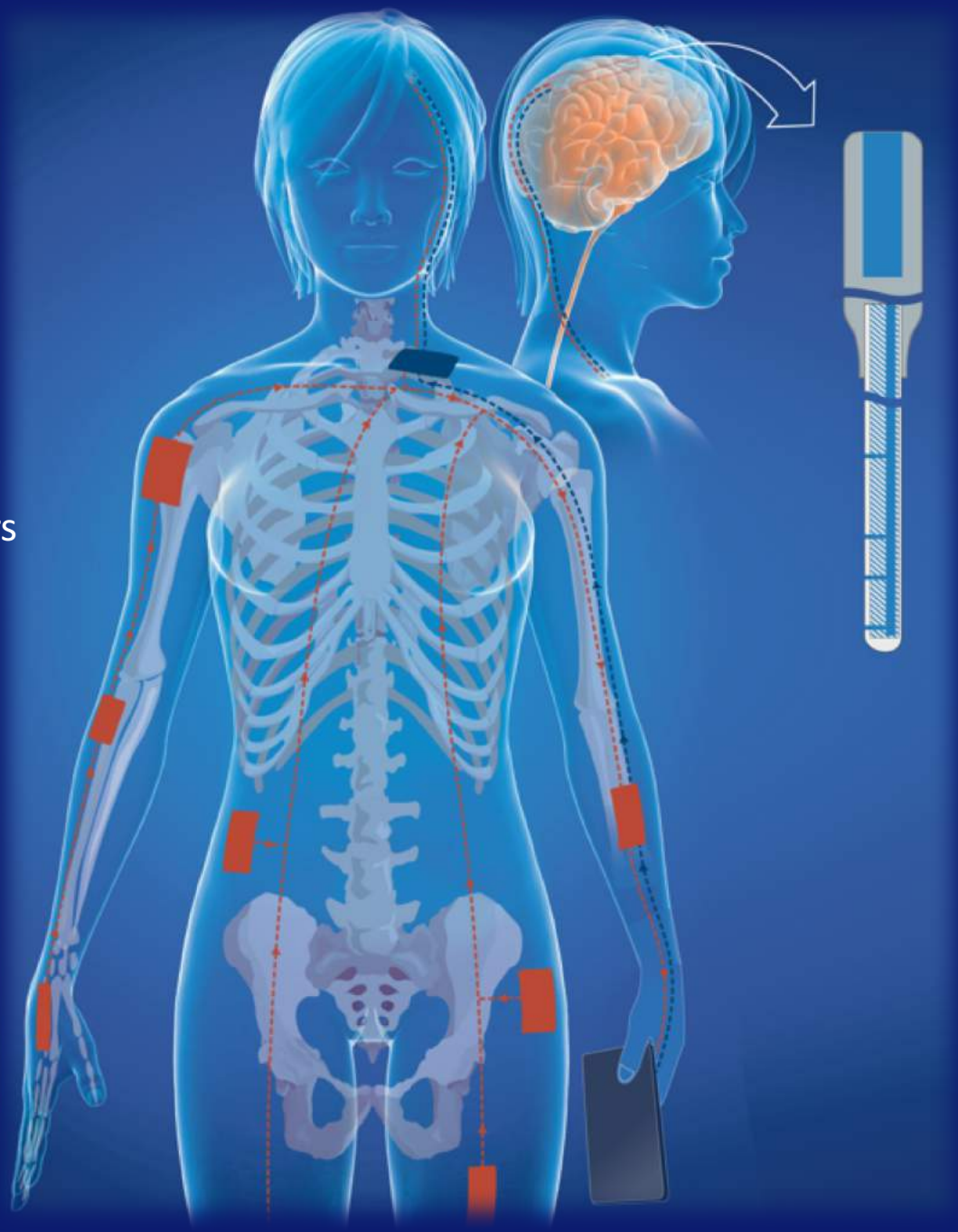
biocomlab.se

Neurological diseases
(8% of global population)

- Skin Patches
  Printed Organic Electronics on
  Paper and Foils
  Organic Electrochemical Transistors

- Organic Electronic Ion Pump
  Neurotransmitters
  Chemical circuits

- Body Area Network
  Capacitive Coupling
  13.56 MHz



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Printed electronics
Skin patches and packages
for medical applications
Sensing and Recording
Printed Organic Electronics

Sensor Labels

Printed Organic Electronics and Si-chips manufactured on labels, skin patches and packages

Conducting polymer

Printing machines for electronic papers (DP Patterning)

Displays printed on paper (ThinFilm)

Electronic sensors on medical packages (Doctors without borders)

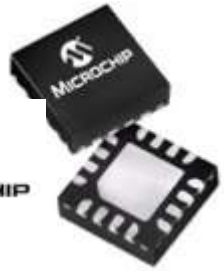
Electronic labels (Invisense)

e-Band aids (Absorbest)

Electronic skin patches for diagnostics and monitoring

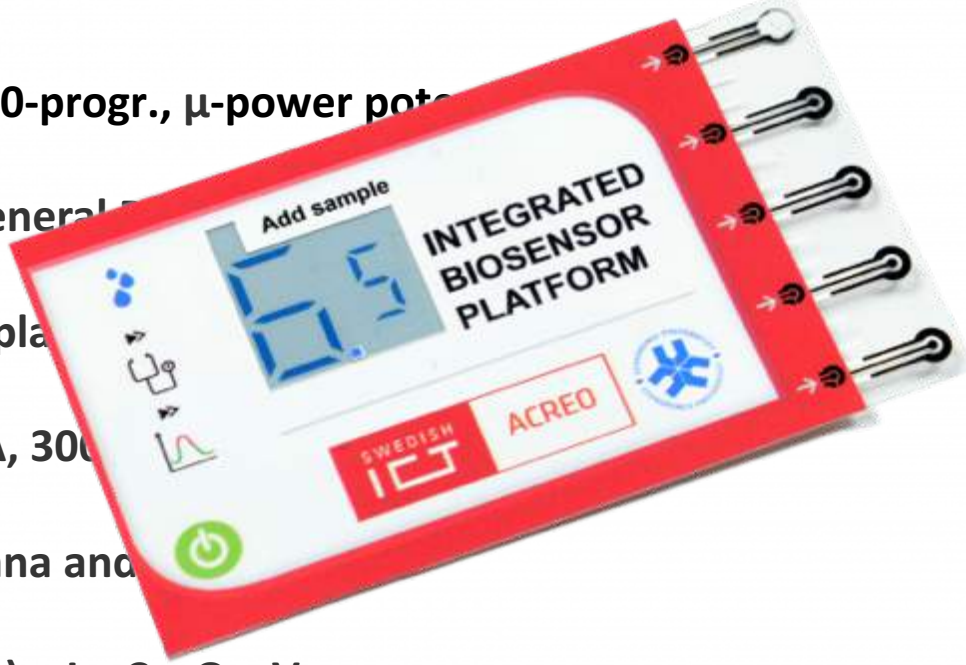
Printed Sensor Labels

TEXAS INSTRUMENTS



MICROCHIP

- **Si-chip 1: LMP91000-progr., µ-power pot**
- **Si-chip 2: 20-Pin Genera**
- **Electrochromic Displa**
- **Battery (3 V, 10 mA, 30**
- **Push button, antenna and**
- **Sensors (e.g. OECTs): ΔI, ΔC, ΔΩ, ΔV (Glucose, T, UV, RH, Biomolecules)**



Printed Sensor Labels

Swedish Research Laboratory for Printed Electronics

Dry Phase Patterning
metal foils, antennas

R2R label printer
displays and circuits

Slot die coater
Photovoltaics

ATMA OE MF66
Aut. sheet based screen printer

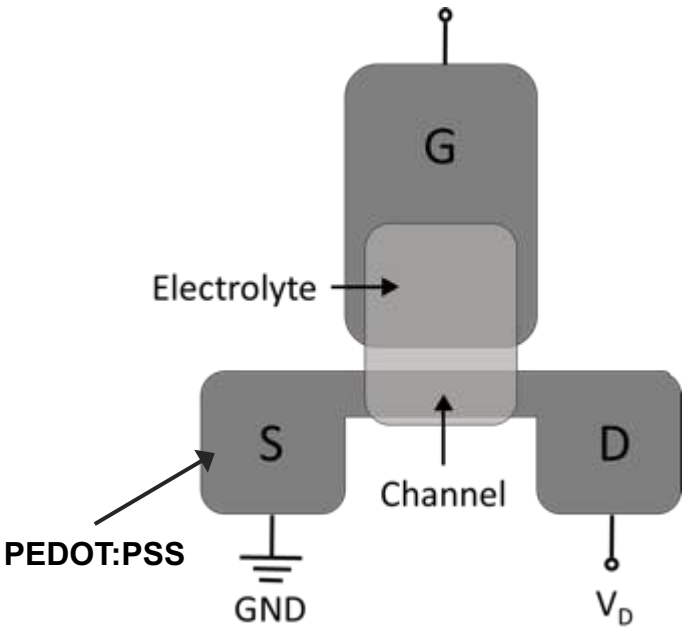
Laser ablation

Screen-printer

Ceradrop Inkjet, aerosoljet
Novacentrix Xwnon flash

Besi Datacon Flip chip
Bonder - Pick and place

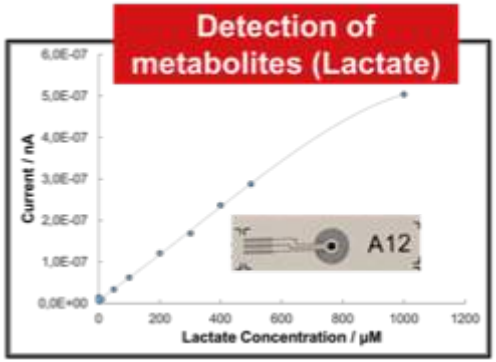
Screen-printed Organic Electrochemical Transistor (OECT)



Bio RAPID

Electronic labels

Screen-printed OEC Transistors and Electrodes

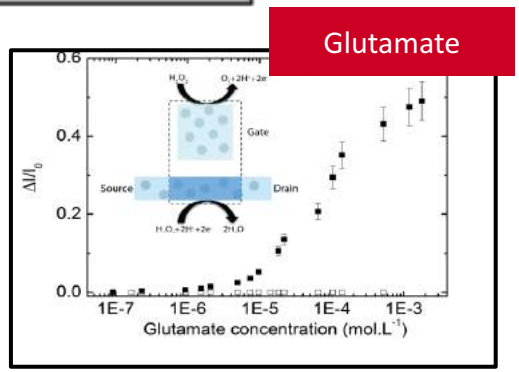


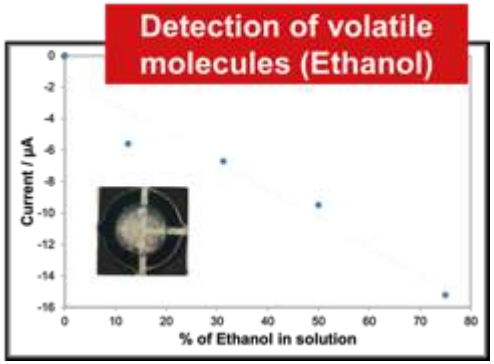
Metabolites (glucose[1], sucrose, lactate)

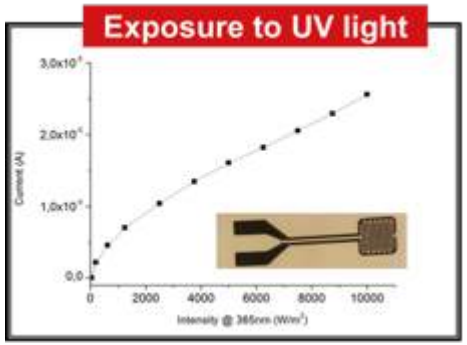
Neurotransmitters (ACh, Glutamate[3])

Phys./Chem. parameters (T, RH, UV[2])

Volatile molecules (ethanol)







[1]**ECS Journal of Solid State Science and Technology**, 4 (10) S3001-S3005 (2015)

[2]**Flexible and Printed Electronics**, 1, 4, 044003 (2016)

[3]**Advanced Materials**, 26, 32, 5658-5664 (2014)

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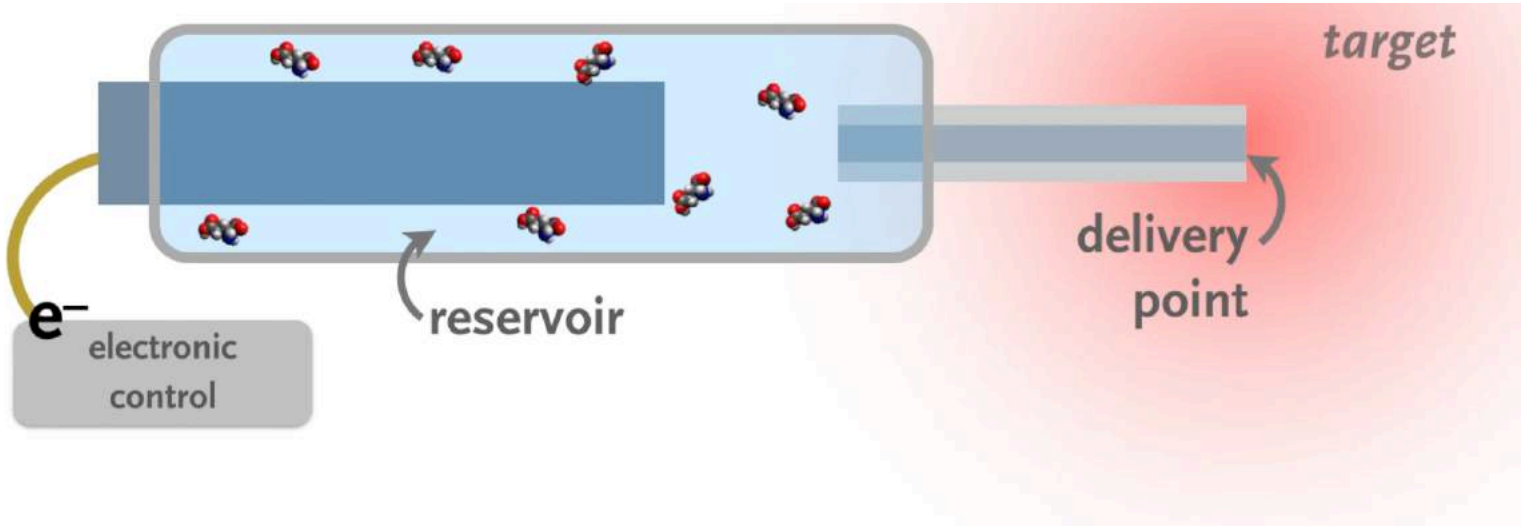
Organic Electronic Ion Pumps

in vivo delivery of neurotransmitters

Organic Electronic Ion Pump (OEIP)

Electronic delivery of neurotransmitters (ACh, GABA, …)



Organic Electronics for Precise Delivery of Neurotransmitters to Modulate Mammalian Sensory Function
D. T. Simon, S. Kurup, K. C. Larsson, K. Tybrandt, M. Goiny, E. W. H. Jager, M. Berggren, B. Canlon and A. Richter-Dahlfors
Nature Materials *8*, 742-746 (2009).

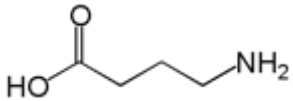
Electronic Control of Ca2+ Signalling in Neuronal Cells using an Organic Electronic Ion Pump
J. Isaksson, P. Kjäll, D. Nilsson, N. Robinson, M. Berggren and A. Richter-Dahlfors
Nature Materials, 2007, 6(9), 673-679.

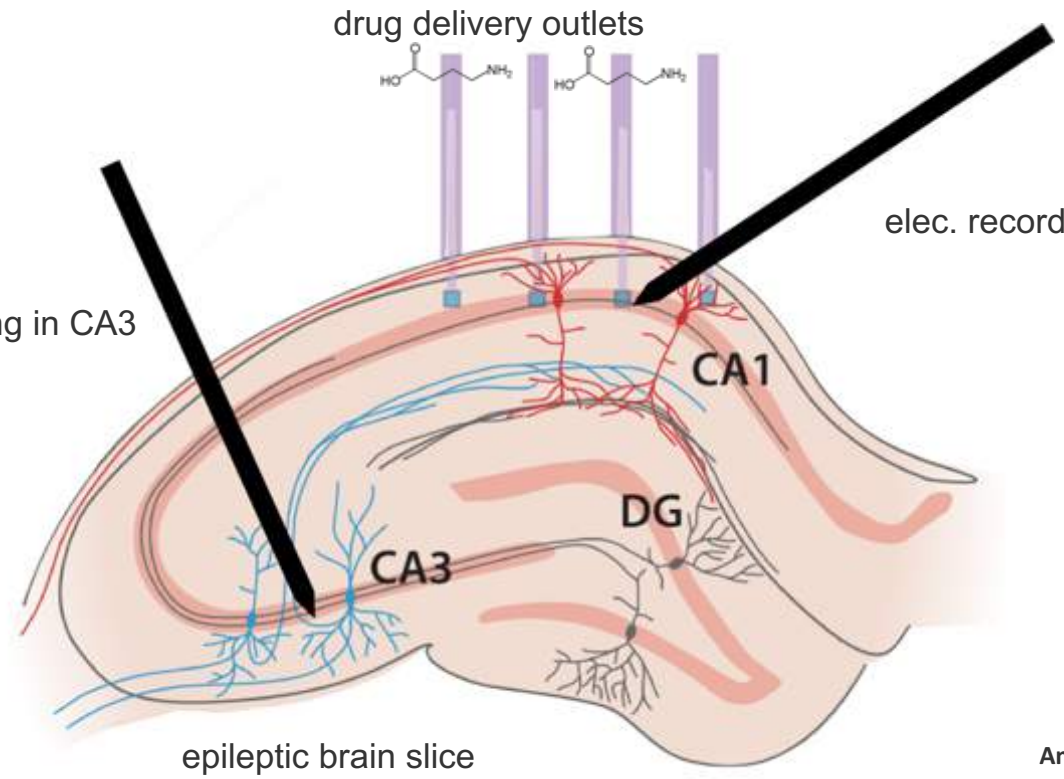
Organic Electronic Ion Pump (OEIP)

Electronic termination of epileptic seizure (GABA)

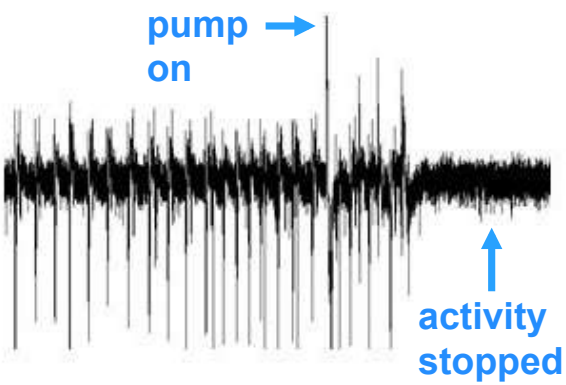
MINES Saint-Étienne

Aix*Marseille université





- **epilepsy model**
- **delivery of anti-seizure compounds**
- **simultaneous electrical recording of seizure activity**



Amanda Jonsson

Theresia Arbring Sjöström

Daniel Simon

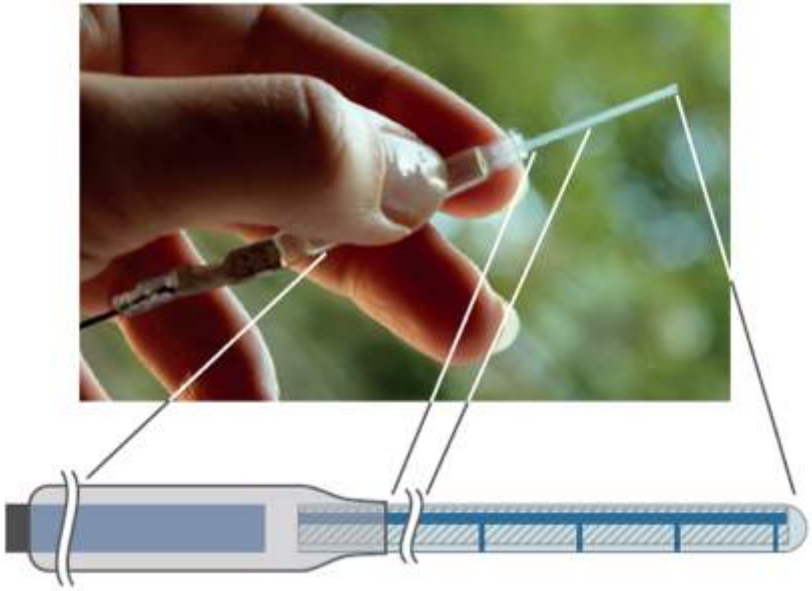
Controlling Epileptiform Activity with Organic Electronic Ion Pumps
Adam Williamson, Jonathan Rivnay, Loïg Kergoat, Amanda Jonsson, Sahika Inal, Ilke Uguz, Marc Ferro, Anton Ivanov, Theresia Arbring Sjöström, Daniel T. Simon, Magnus Berggren, George G. Malliaras, and Christophe Bernard
Advanced Materials vol. 27, 20, May 27, 2015

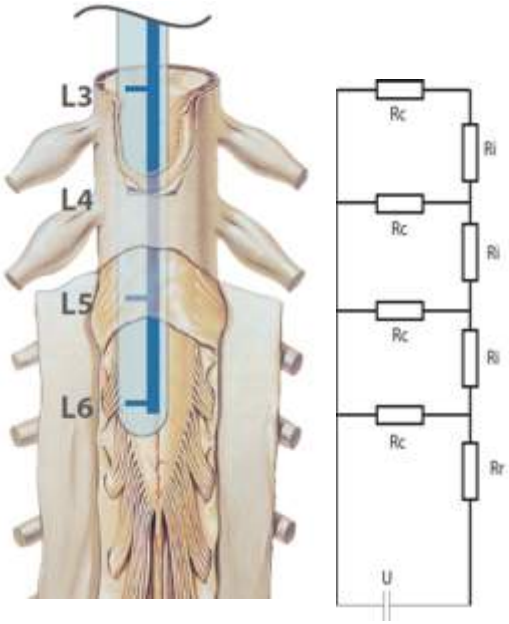
Organic Electronic Ion Pump (OEIP)

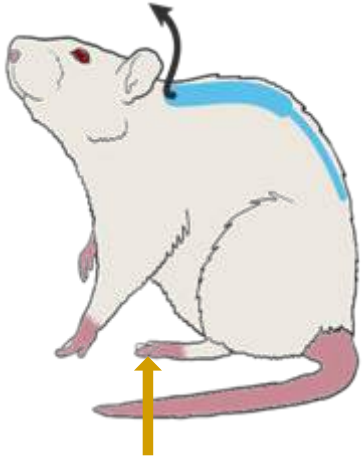
Electronic pain relief and spinal cord repair (GABA)

Amanda Jonsson

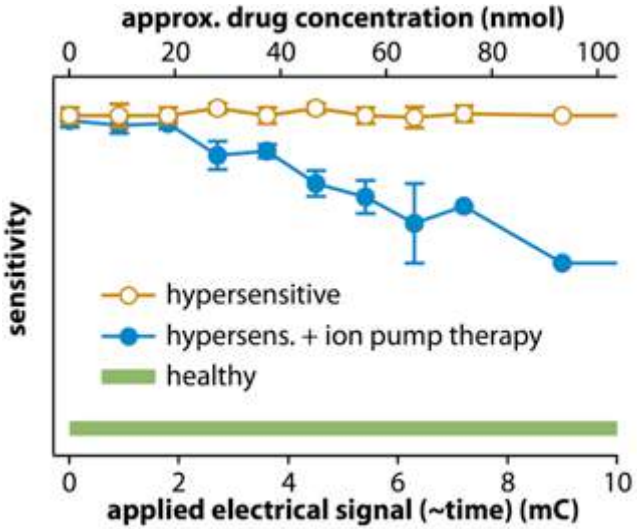
Karolinska Institutet







induced hypersensitivity



Therapy using implanted organic bioelectronics
Science *Advances*, 08 May Vol. 1, no. 4, e1500039, 2015

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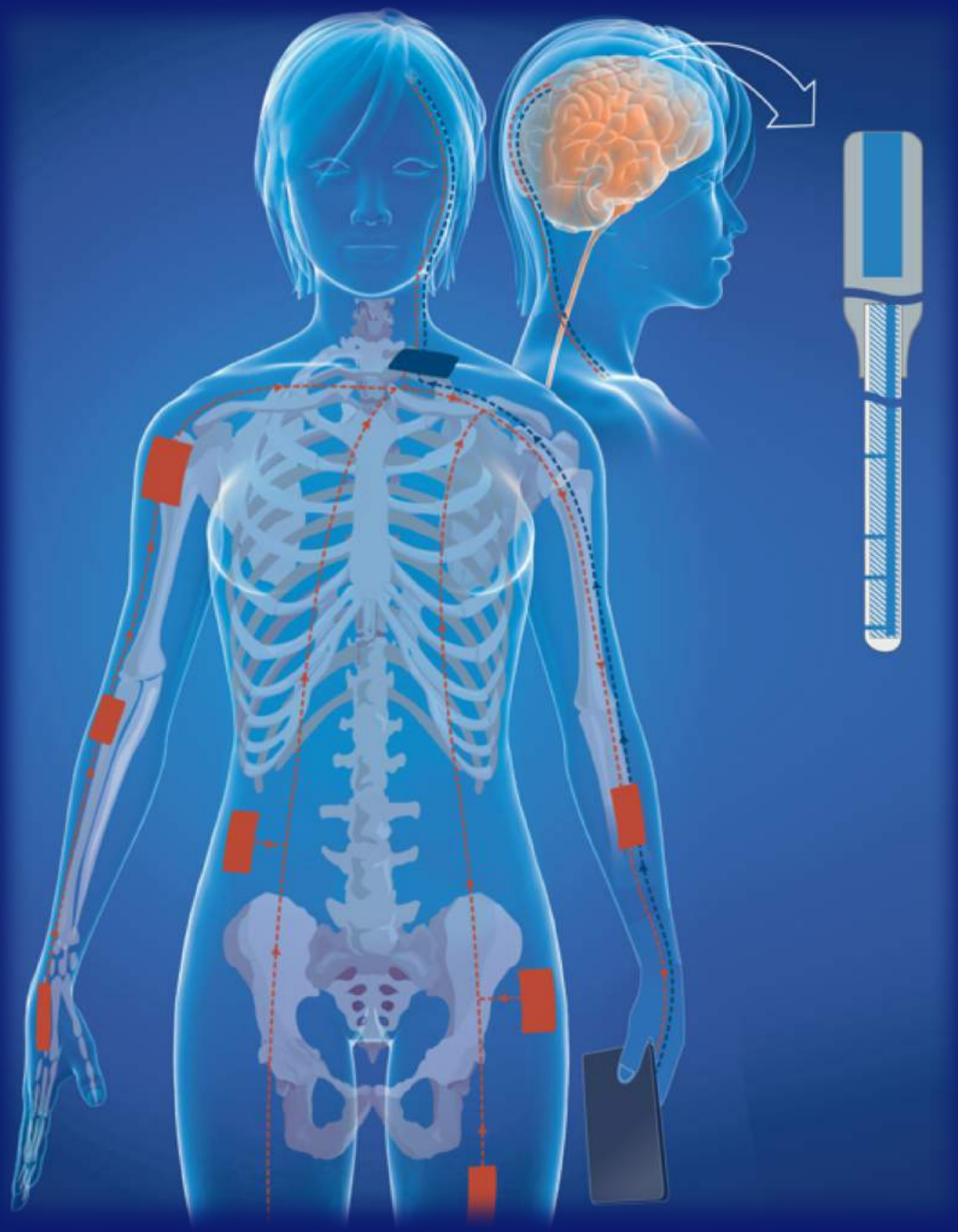
Neurological diseases
(8% of global population)

- Body Area Network
  Capacitive Coupling
  13.56 MHz

ERICSSON

“Printegrated” communication unit for capacitive-coupled BAN



Assoc. Professor Daniel Simon

Organic Bioelectronics

Theresia Arbring Sjöström | Astrid Armgarth | Chiara Diacci | Erik Gabrielsson | Roger Gabrielsson | Marie Jakesova | Pelle Jansson | Josefin Nissa | David Poxson | Maria Seitanidou | Klas Tybrandt

BIOCOM LAB

BiocomLab

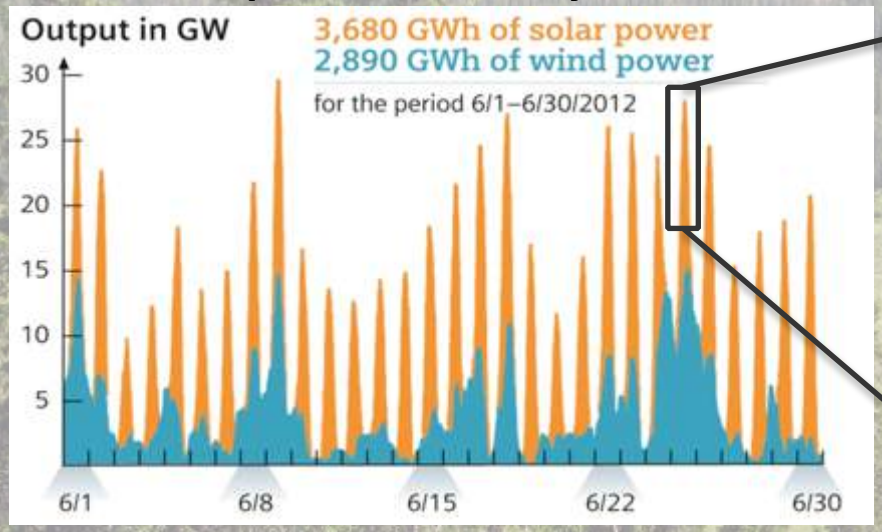
- Skin Patches
- Organic Electronic Ion Pump
- Body Area Network

Power Papers and 0D+1D+2D=3D

Our society is lacking green and cost-effective storage of electrical energy. Therefore, production of electricity must at all time match the demand, which gives
poor utilization of capacity.
Since 2015,
electricity from renewable sources is cheaper than from fossil fuels.
Green, large-scale and cost-effective storage of electricity is a prerequisite for the transition to a society free from fossil energy

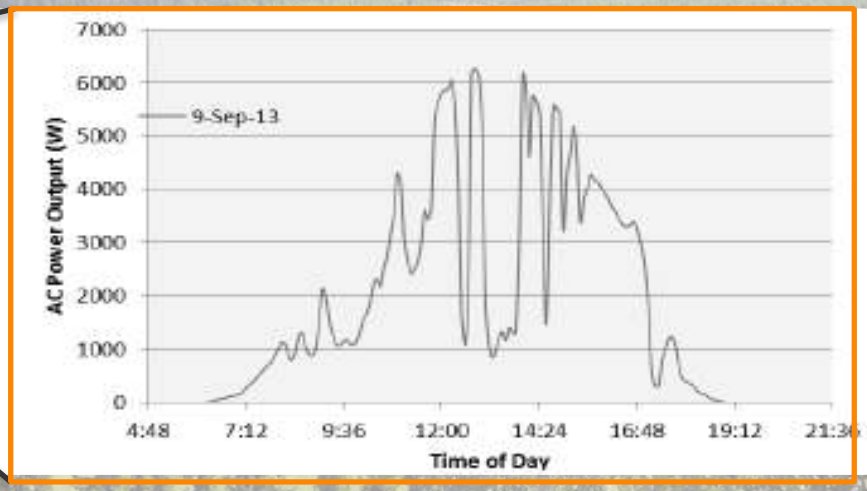
Power Papers and 0D+1D+2D=3D

Power output in Germany



Source: Physik konkret (18, 2013), Konrad Kleinknecht, Helmut Alt

Local Power output in Munich



Power Papers - Supercapacitors and batteries from nano-structured/fibrillar cellulose

- [illegible]
- [illegible]
- [illegible]

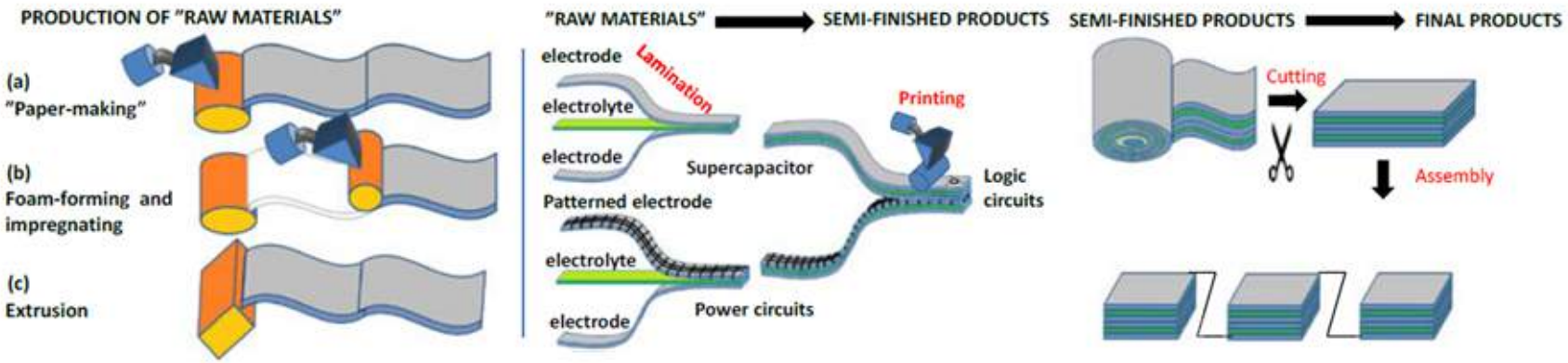
lectronic plastics

rom the forest

An organic mixed ion–electron conductor for power electronics
Abdellah Malti, Jesper Edberg, Hjalmar Granberg, Zia Ullah Khan, Jens W Andreasen, Xianjie Liu, Dan Zhao, Hao Zhang, Yulong Yao, Joseph W Brill, Isak Engquist, Mats Fahlman, Lars Wågberg, Xavier Crispin, Magnus Berggren, Advanced science, vol. 3, (2) 2016

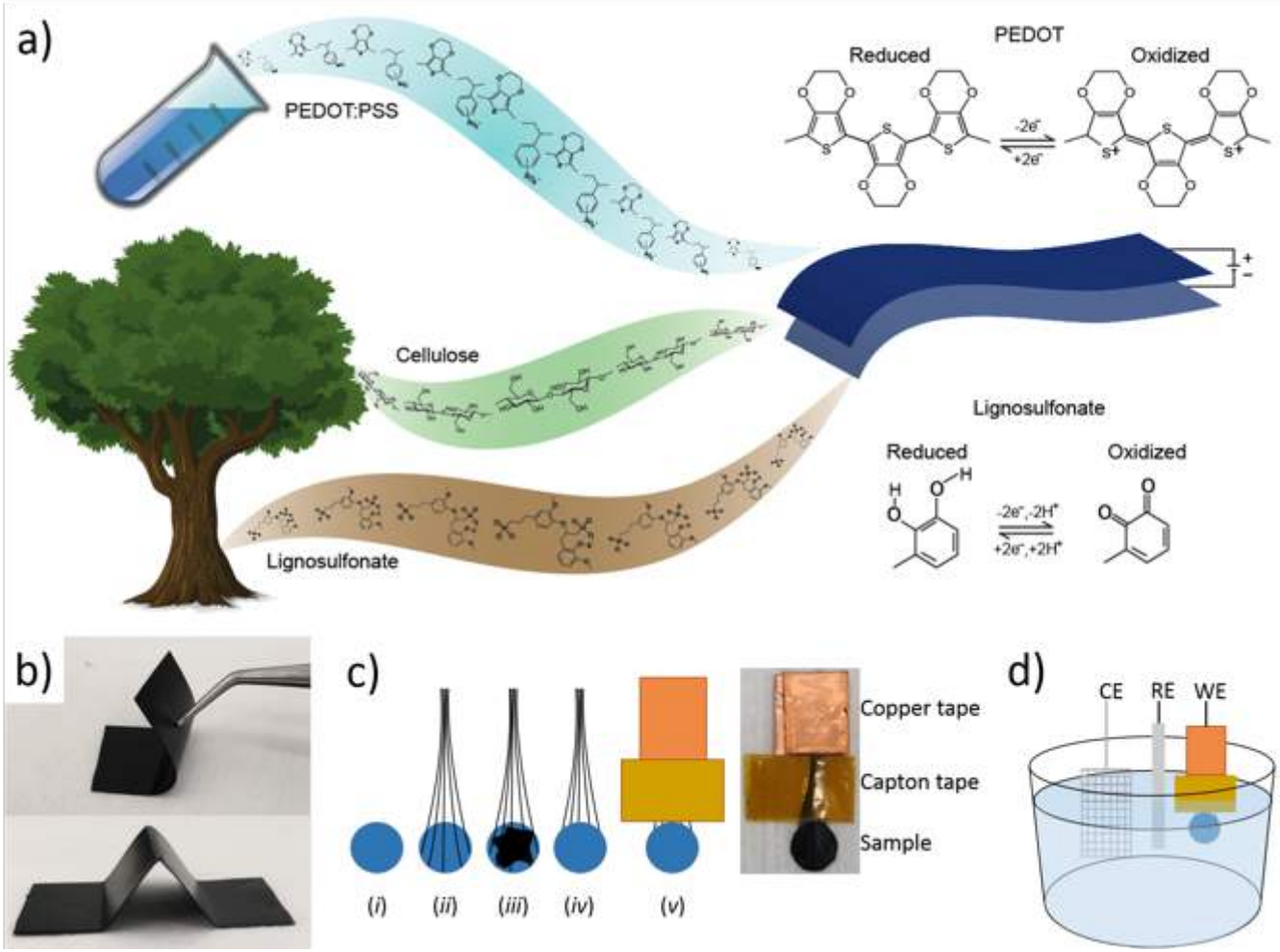
Power Papers and 0D+1D+2D=3D

Specifications ➔ Material formulations ➔ Production ➔ Test and Prototypes

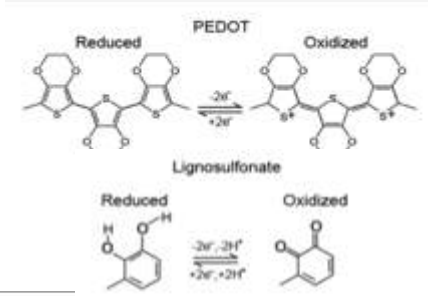


Power Papers and 0D+1D+2D=3D

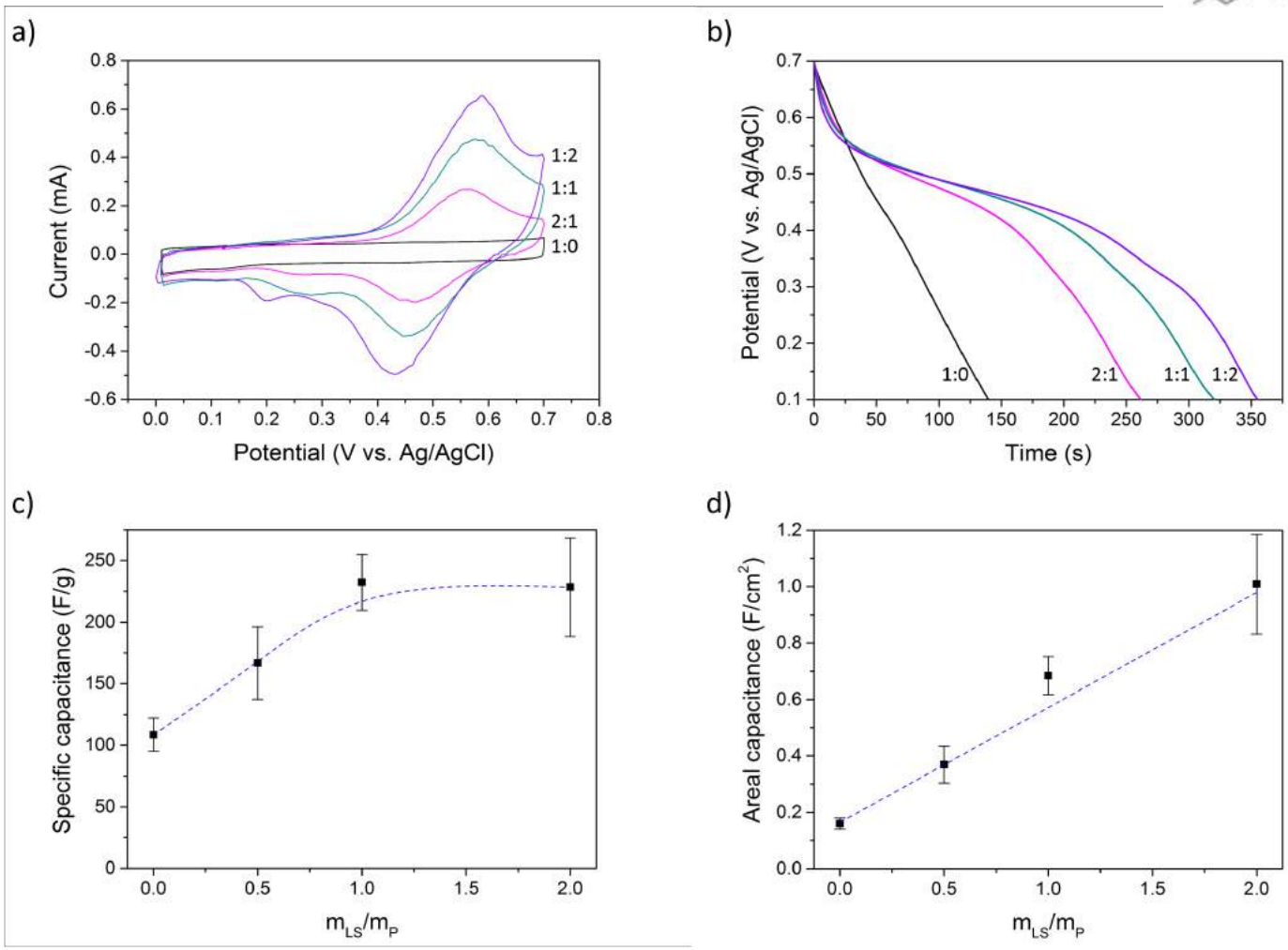
Boosting the capacitance with Lignosulfonates



Recent progress



Boosting the capacitance with Lignosulfonates



Boosting the Capacity of All-Organic Paper Supercapacitors Using Wood DerivativesJ Edberg, O Inganäs, I Engquist, M Berggren - Journal of Materials Chemistry A, 2017

Power Papers - Large scale storage of electricity

Assoc. Professor Isak Engquist

Printed Electronics

Marzieh Zabihipour | Jesper Edberg | Dagmawi Belaineh Yilma | Pawel Woijcik | Mehmet Girayhan Say

Peter Andersson Ersman, Göran Gustafsson, Roman Lassnig

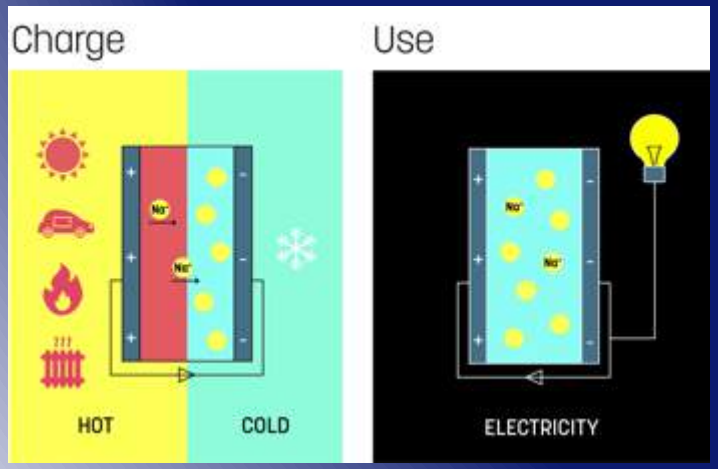
- Printed electronic systems integrated with Si-chips
- (Nano-)cellulose based energy storage systems
  - Batteries
  - Supercapacitors
- Energy scavenger systems
  - Electrochemical
  - Microwaves

Professor Xavier Crispin

Organic Energy Materials

- Optical, thermal, dielectric properties and charge transport properties of organic electronic materials are characterized
- Devices include diodes, transistors, thermoelectric generators, physical and chemical sensors, fuel cells, supercapacitors and batteries.
- Many devices are includes composites with (nano)cellulose

Ionic thermoelectric generator

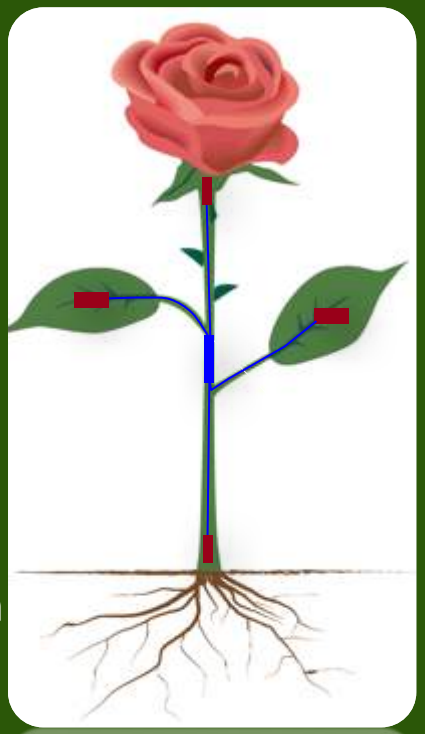


LIGNA ENERGY

Disruptive energy storage technology from the forest

e-Plants

Devices and circuits manufactured inside plants
Plant area networks
Analogue and digital circuits in plants

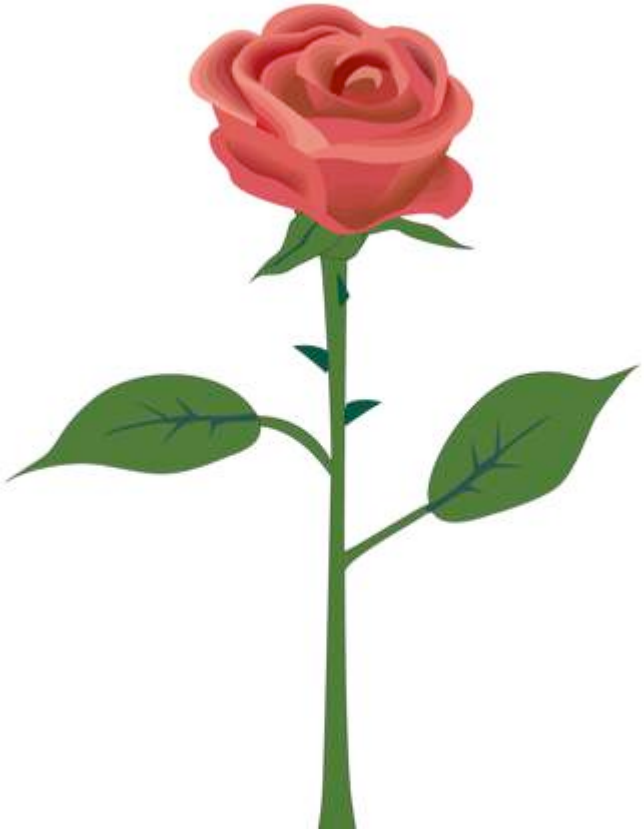


- phytohormones, physical and chemical parameters
- phloem (unidirectional) and xylem (up) vascular system
- growth (gene expression), physiology and defence mechanisms (pathogens

Add an “artificial neuronal system” and circuit technology to improve plant functionality and to derive novel green technology

Plants

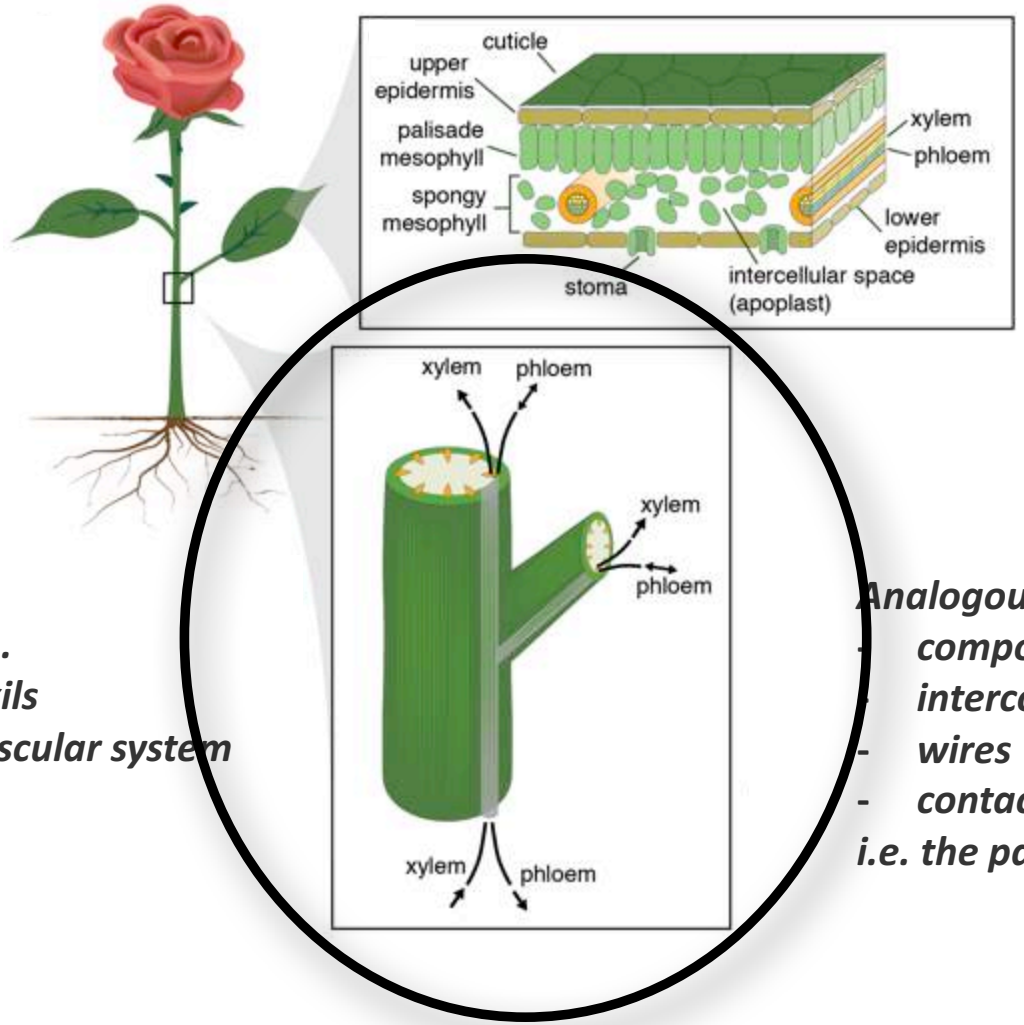
e.g. Rosa floribunda



Science Advances; DOI: 10.1126/sciadv.1501136

Plants

e.g. Rosa floribunda



A plant is composed of

- *leaves, petals, roots, ..*
- *branches, petioles, axils*
- *phloem and xylem vascular system*
- *stoma and root hairs*

Analogous to

- *components*
- *interconnects*
- *wires*
- *contacts*

i.e. the parts of circuits

Our vision

Using the chemical signals, tissue constructs, vascular system and overall shape of gymnosperms and angiosperms as the integral part and template to manufacture organic bioelectronics, *in vivo*.

Science Advances; DOI: 10.1126/sciadv.1501136

Conducting wires in the vascular tissue

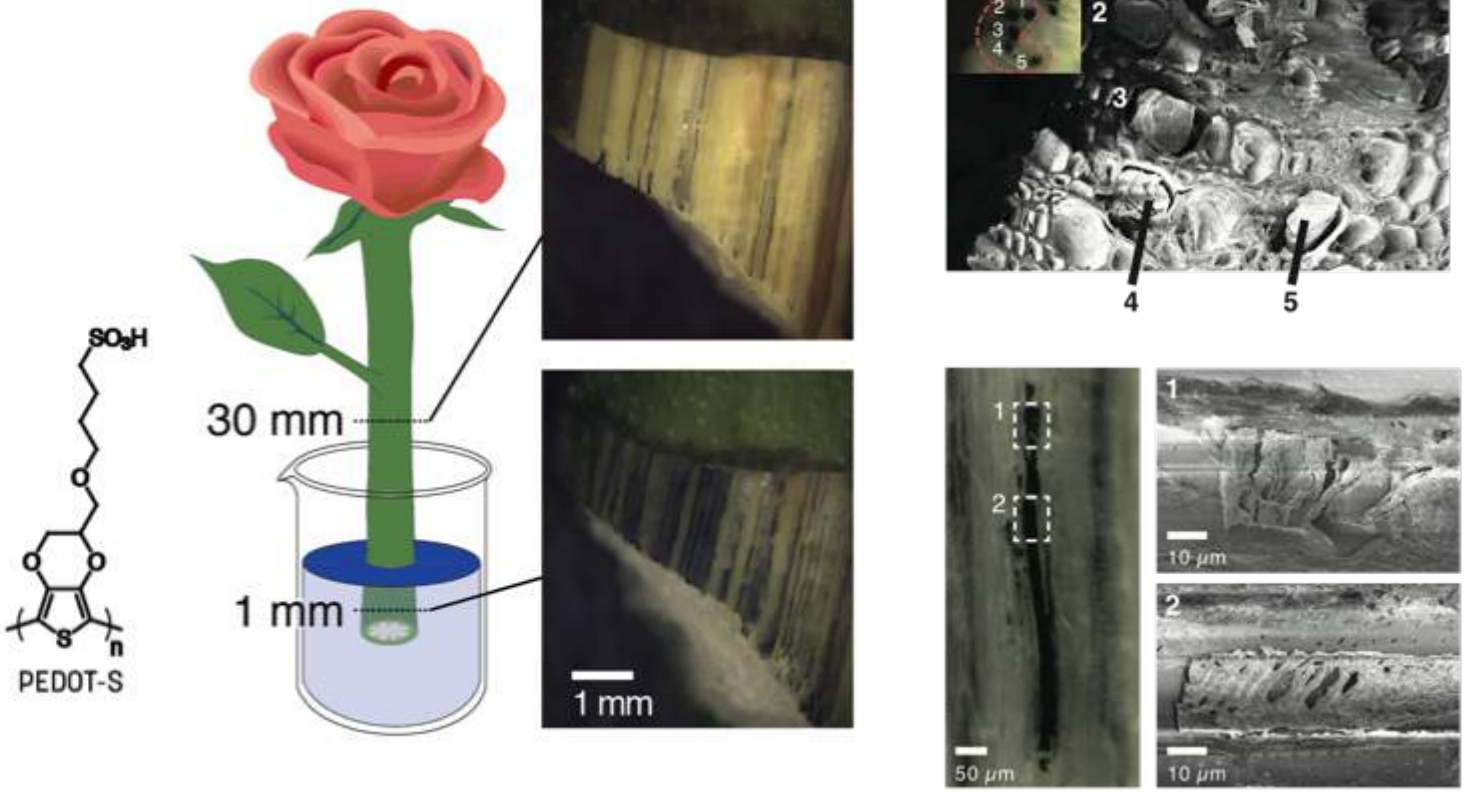

Eleni Stavrinidou


Roger Gabrielsson


Xavier Cripsin


Eliot Gomez


Daniel Simon

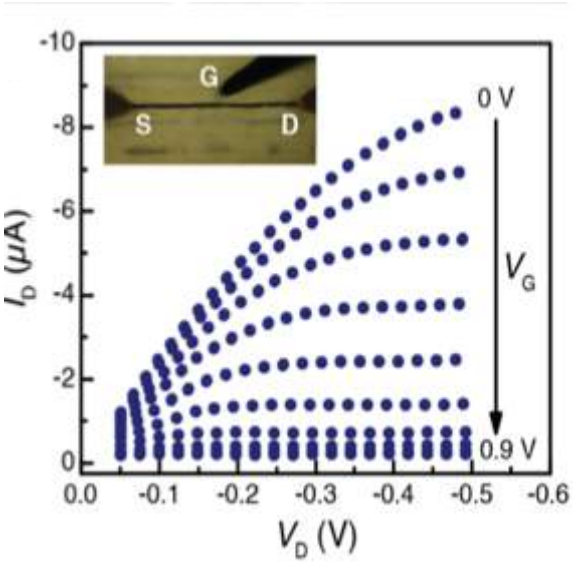


PEDOT-S self organizes in xylem vascular tissue, conductivity 0.13 S/cm

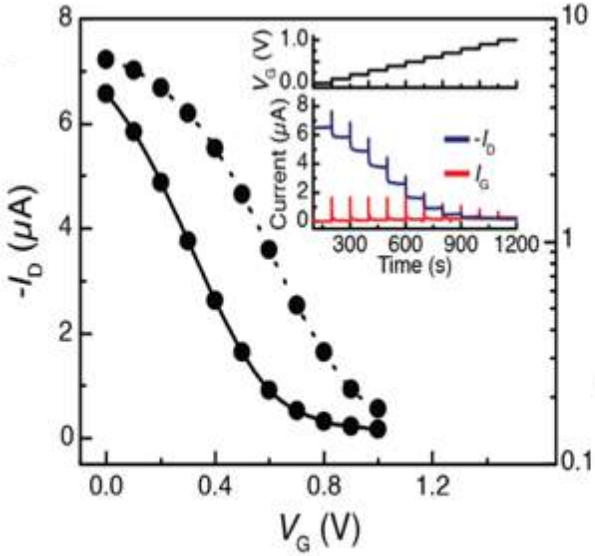
Science Advances; DOI: 10.1126/sciadv.1501136

Xylem circuits

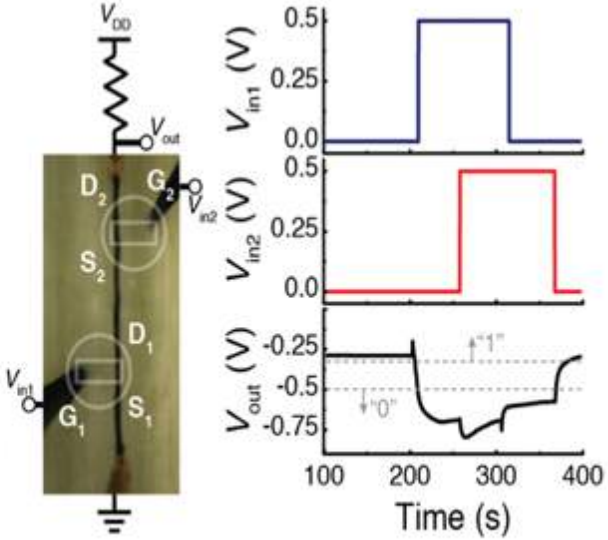
OECTs and logic circuits along the xylem of a *Rosa floribunda*



Output characteristics of a xylem-OECT. The inset shows the xylem wire as source (S) and drain (D) with gate (G) contacted through the plant tissue



Transfer curve of a xylem-OECT V_D = -0.3 V

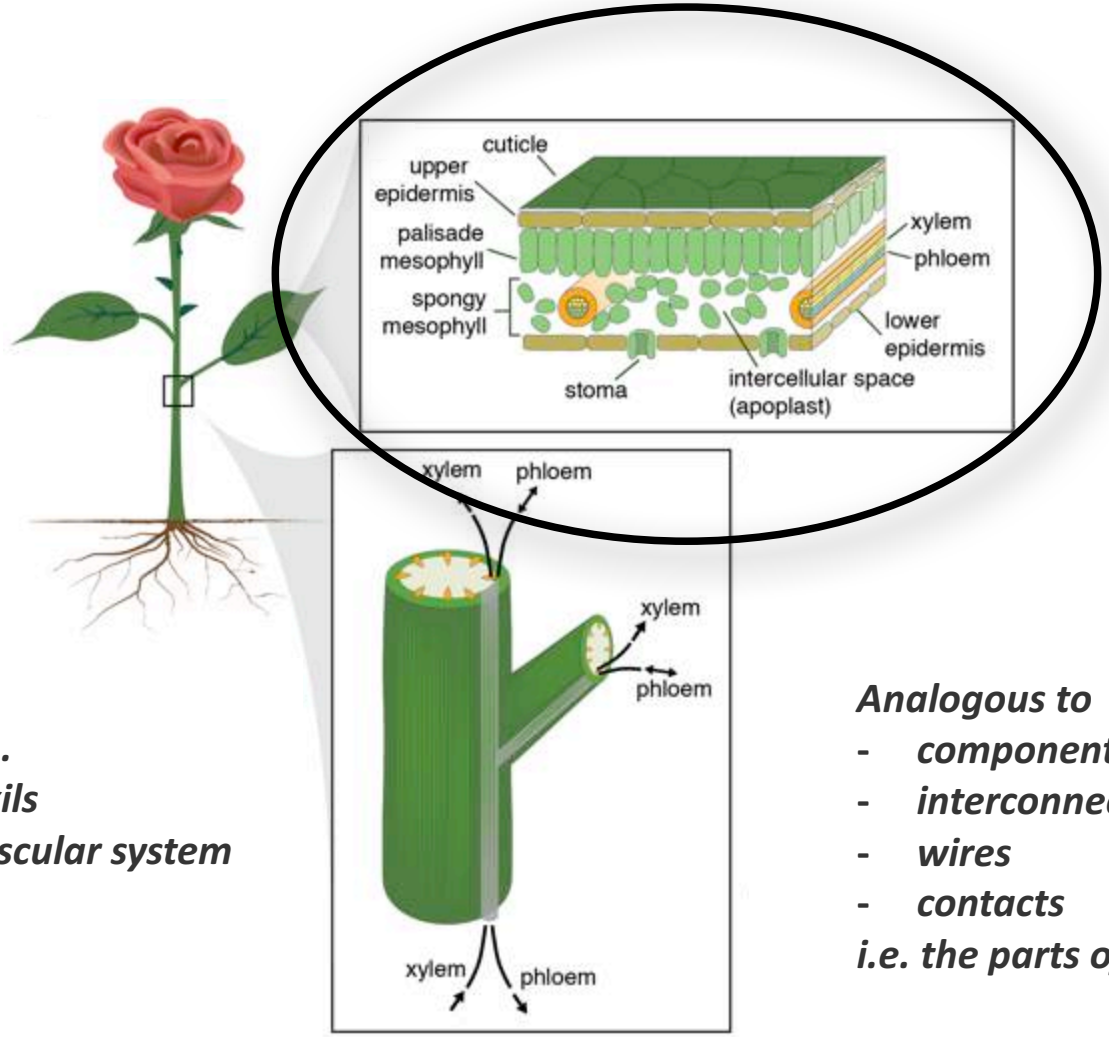


Logical NOR gate constructed along a single xylem wire

Science Advances; DOI: 10.1126/sciadv.1501136

Plants

e.g. Rosa floribunda



A plant is composed of

- *leaves, petals, roots, ..*
- *branches, petioles, axils*
- *phloem and xylem vascular system*
- *stoma and root hairs*

Analogous to

- *components*
- *interconnects*
- *wires*
- *contacts*

i.e. the parts of circuits

Our vision

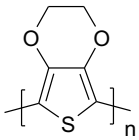
Using the chemical signals, tissue constructs, vascular system and overall shape of gymnosperms and angiosperms as the integral part and template to manufacture organic bioelectronics, *in vivo*.

Science Advances; DOI: 10.1126/sciadv.1501136

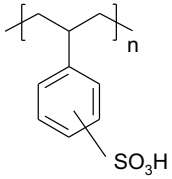
Spongy Mesophyl Circuits

Vacuum infusion of PEDOT:PSS-NFC electrodes

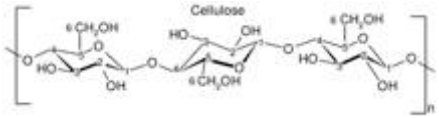
PEDOT

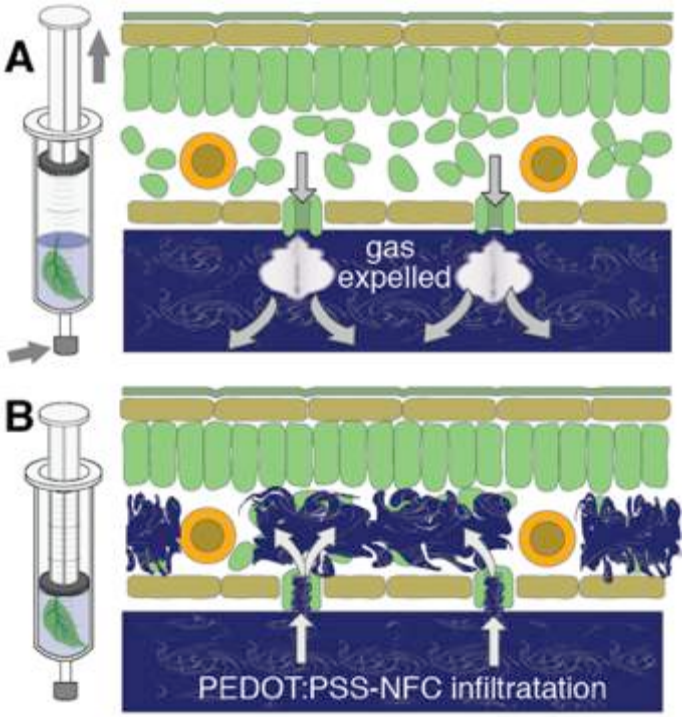


PSS



Nanofibrillated Cellulose (NFC)



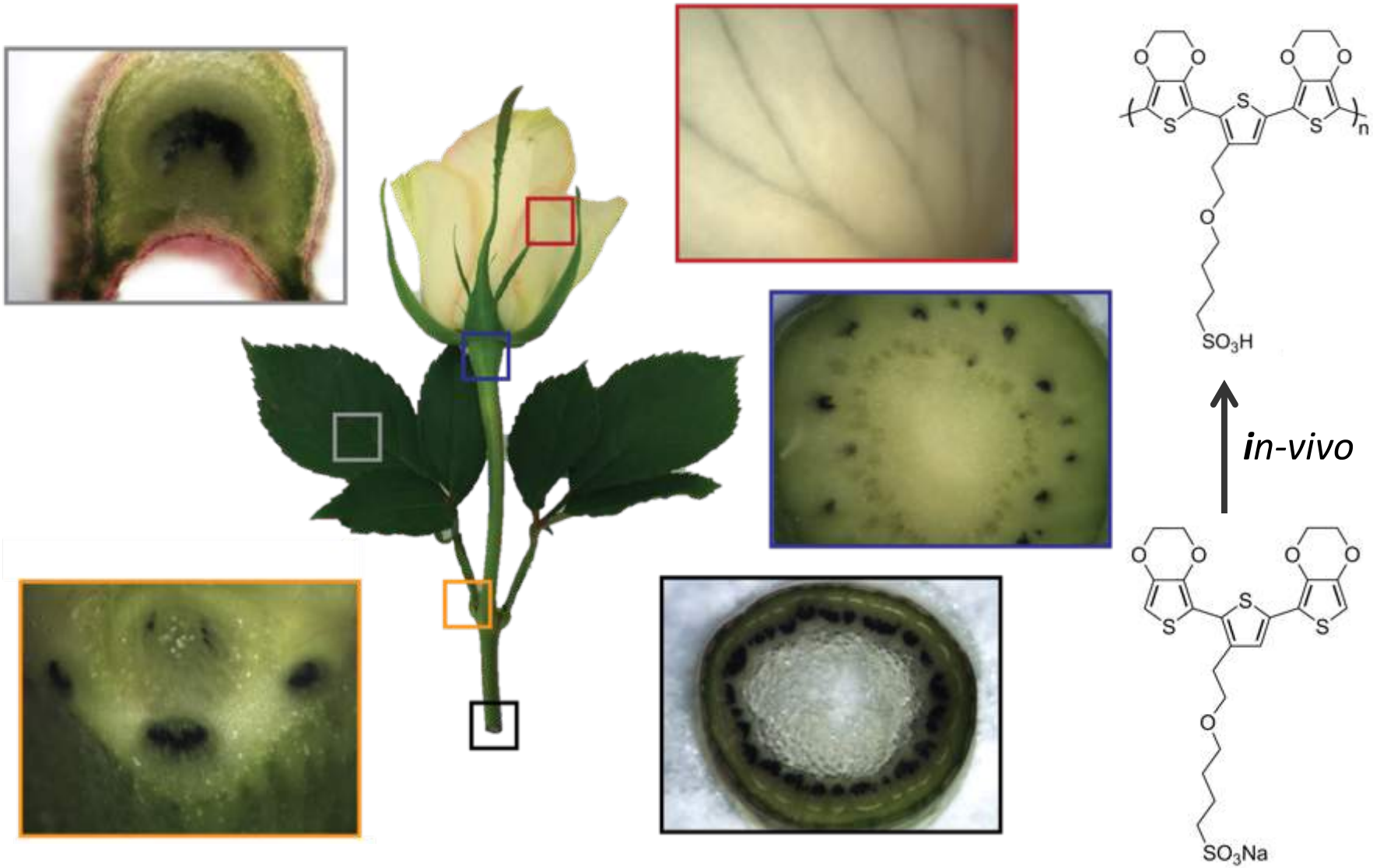


A and B. Vacuum infiltration
Leaf placed in PEDOT:PSS-NFC solution in a syringe with air removed. The syringe is pulled up creating negative pressure causing the gas inside the spongy mesophyll to be expelled

Spongy Mesophyl Circuits

PEDOT:PSS-NFC electrode in individual compartments form electrochromic pixels

In vivo-polymerization in plants



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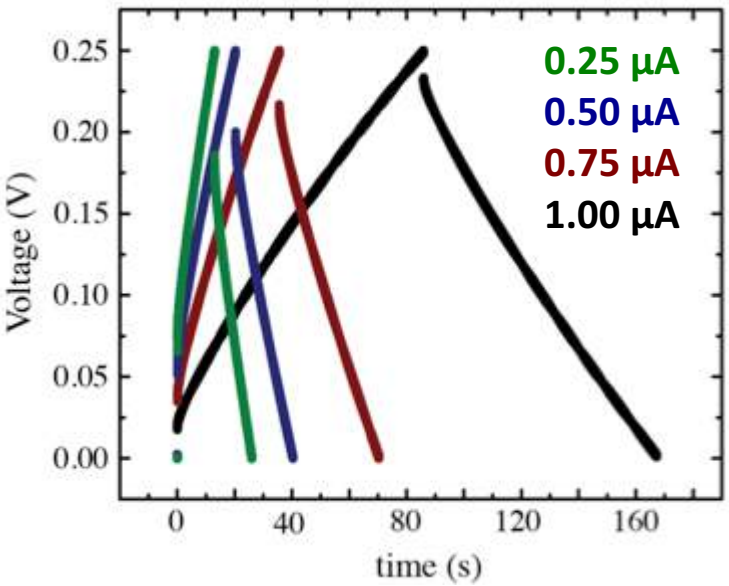
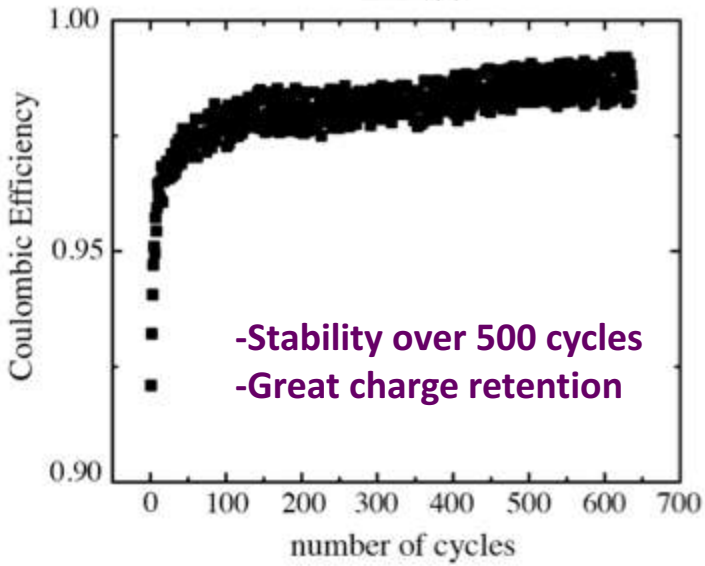
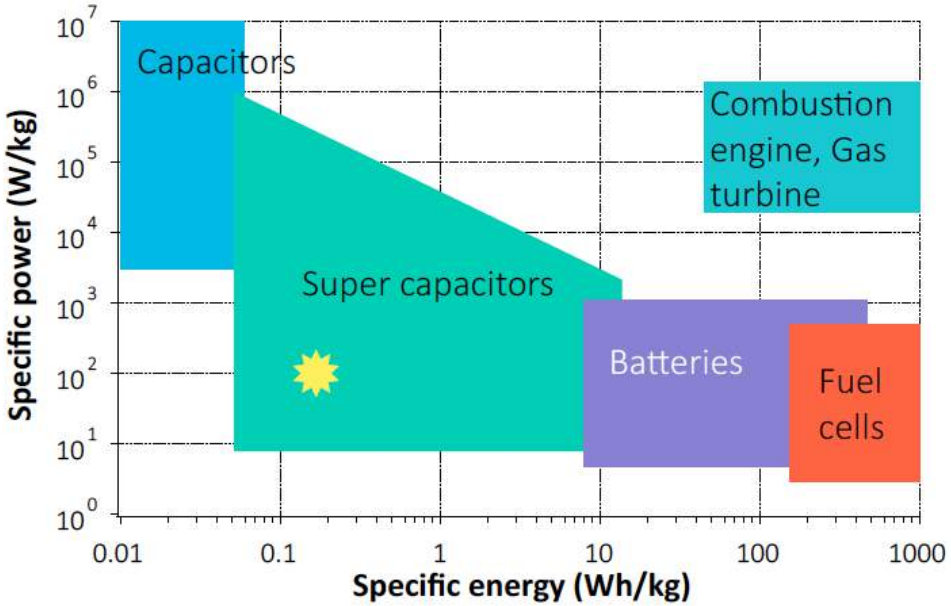
Rose Supercapacitor



Max results:
1.7 cm xylem wire, Q=65µC , C=0.25mF @ 13 S/cm





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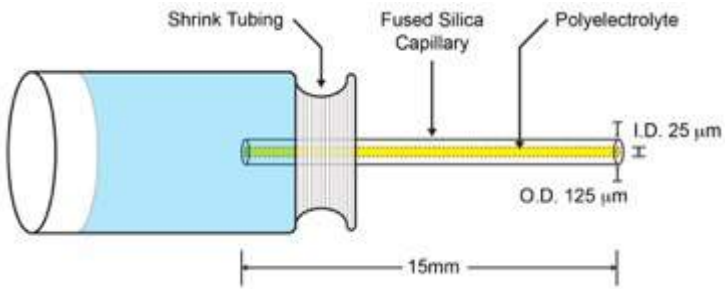
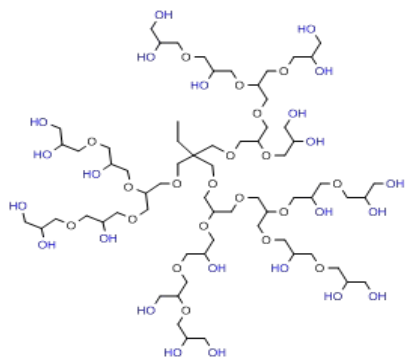
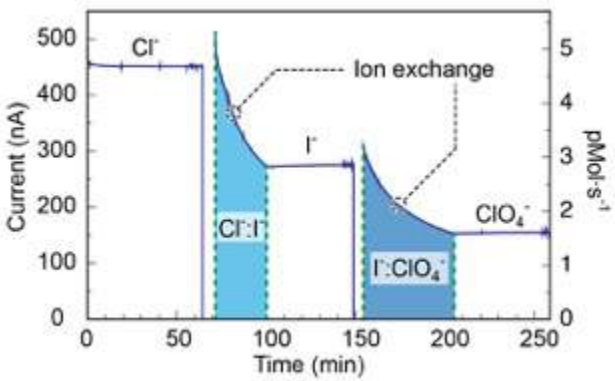
Capillary based OEIPs

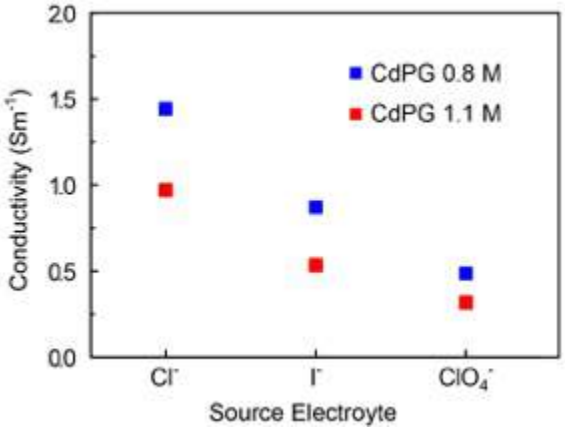
Dendrolytes
Cationic Dendritic Polyelectrolyte



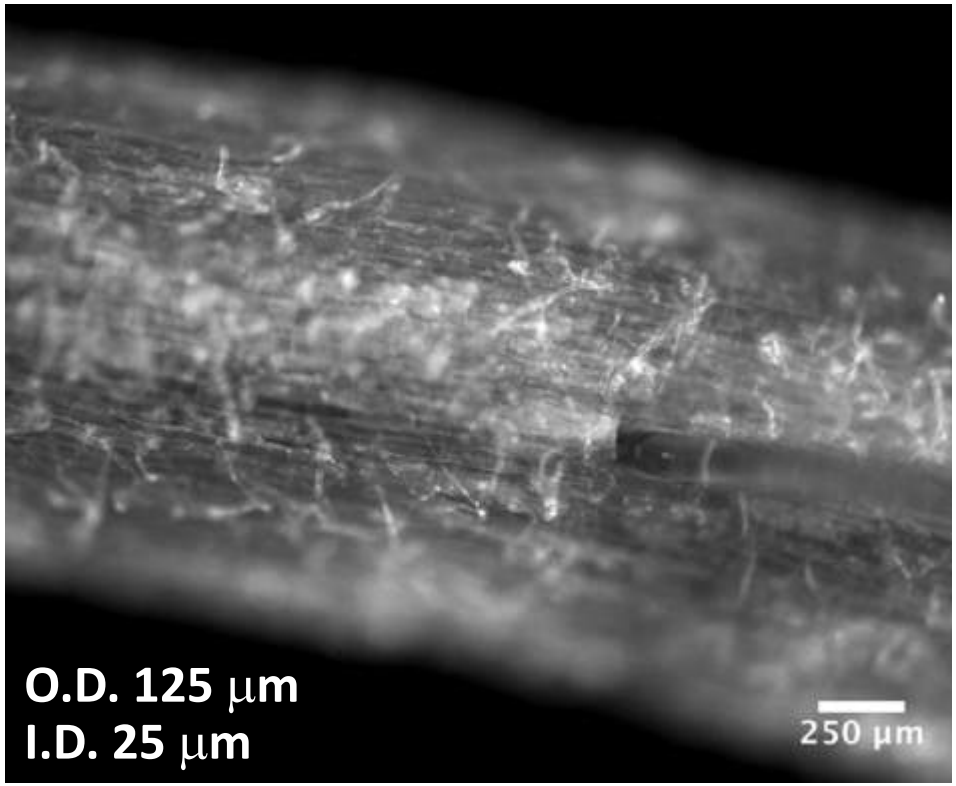




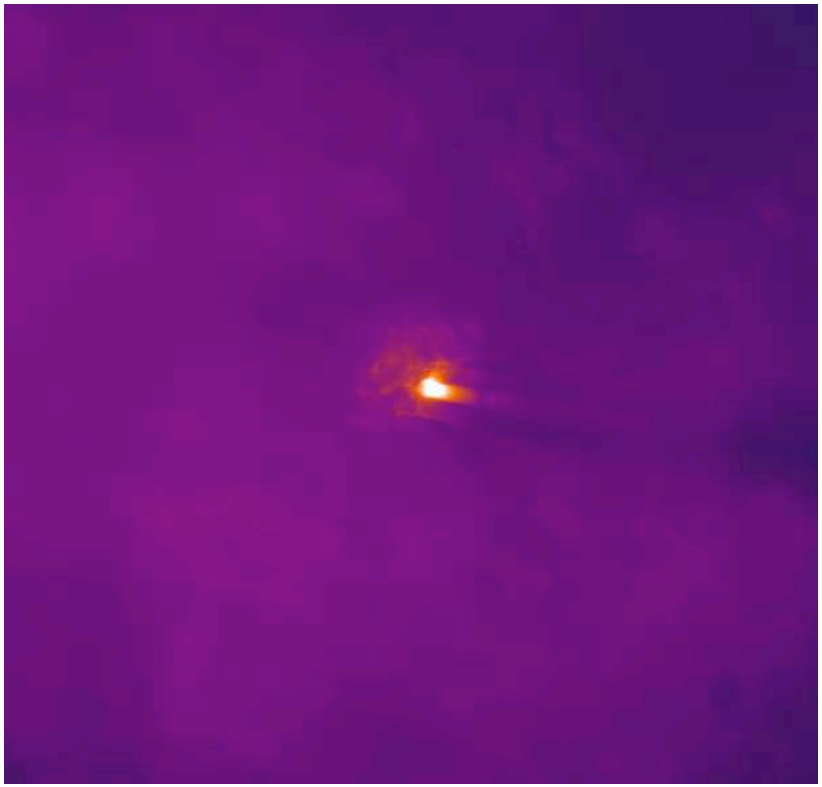
Actuating and recording nastic responses in Venus flytrap



Capillary OEIP inserted into tissue of bean root



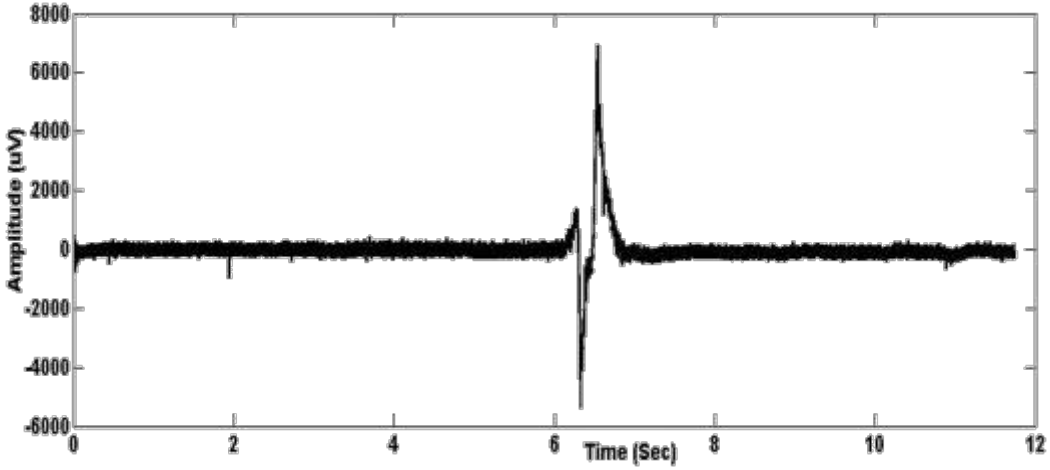
Zn^{2+} delivery with Zinpyr-1 fluorescent reporter



Unpublished Results

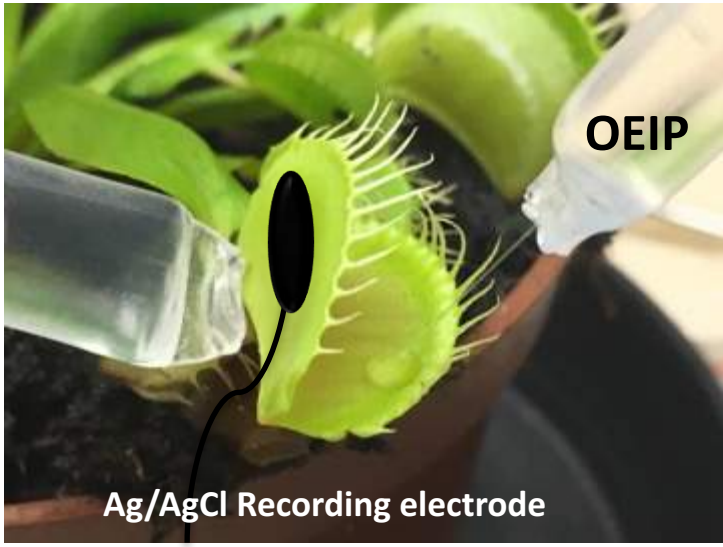
Unraveling electrical signaling in plants

- Fast and slow electrical signals in plants
- Defense mechanism
- Nastic movements



Investigation of Action potentials in plants
in response to different ions and phyto-hormones delivered by OEIP

Venus Flytrap
Carnivorous plant



Yusuf Mulla

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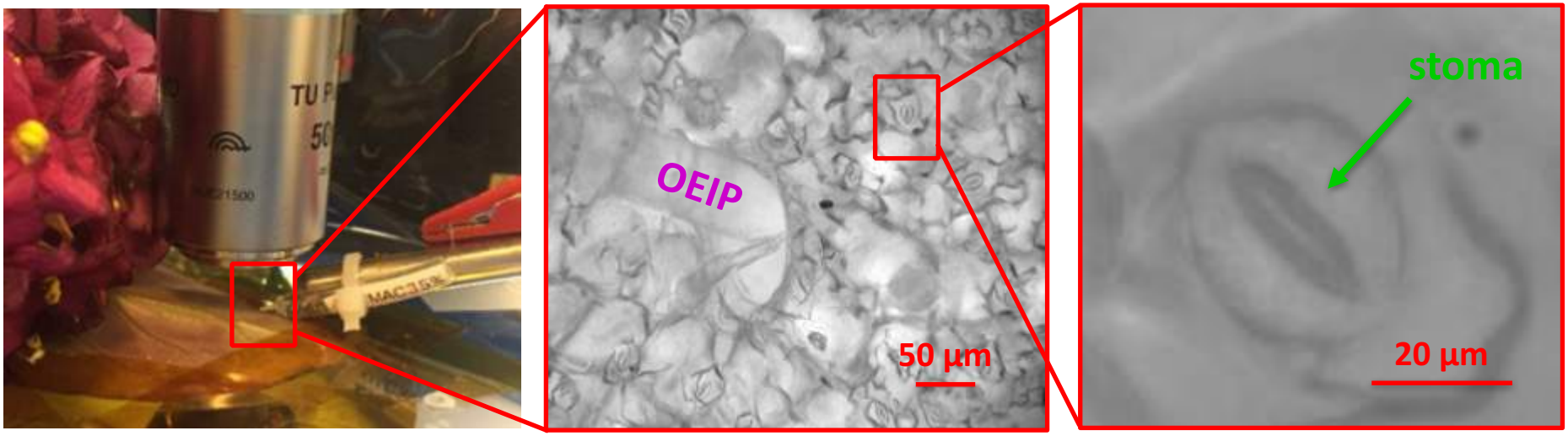
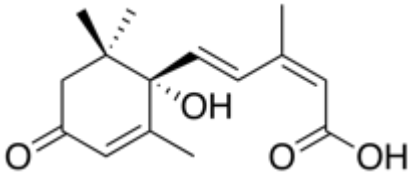
Y. Mulla et al, Unpublished results

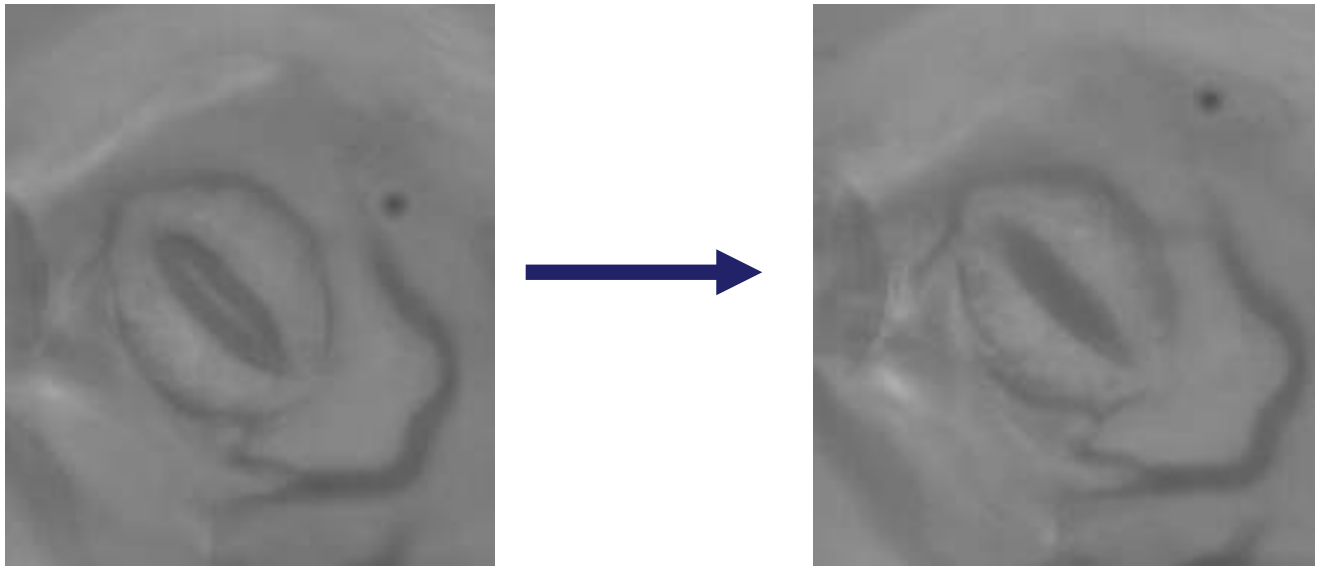
Electronic control of transpiration



ABA: Abscisic Acid stress hormone



Ivona Bernacka-Wojcik



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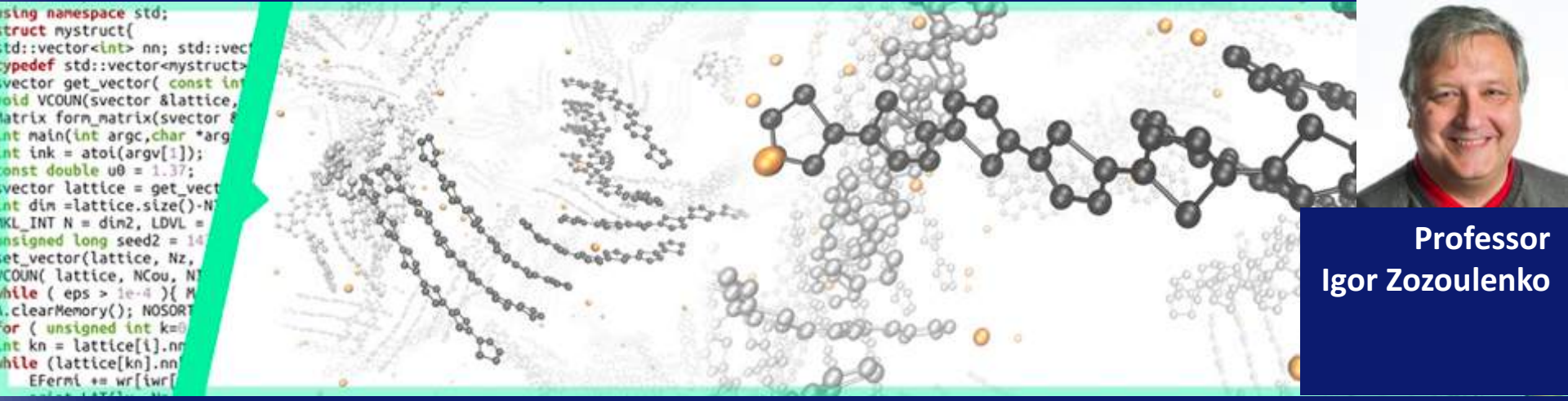
I. Bernacka-Wojcik et al, Unpublished results



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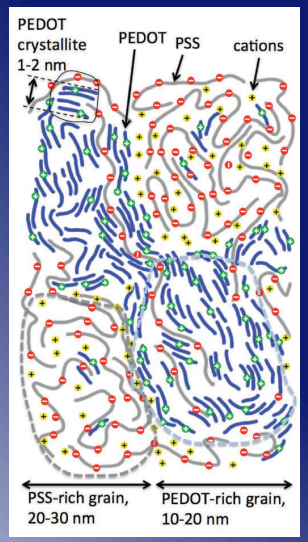
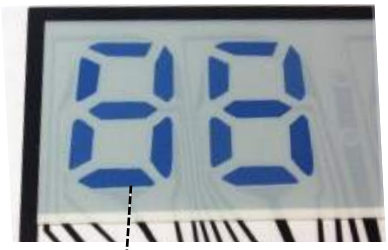
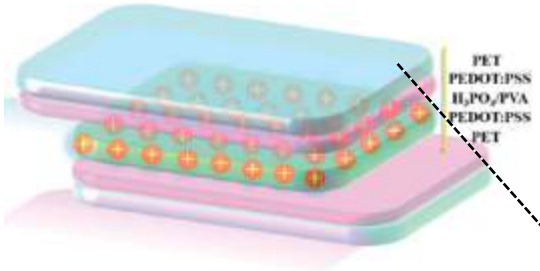


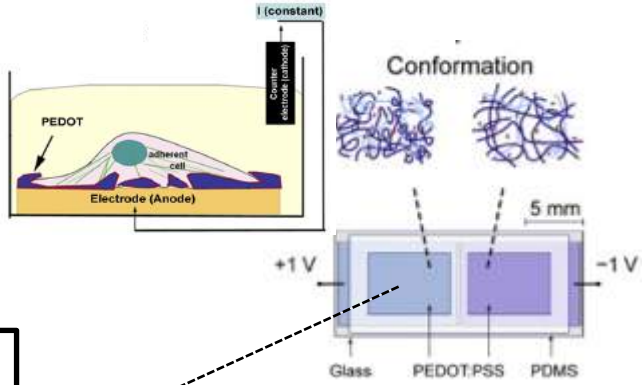
- Theoretical simulation and modelling of the basic properties of organic materials
- The electron and ion transport in organic devices
- *ab initio* methods for electronic structure calculations and the molecular dynamics technique (including coarse-grained methods) that is capable of studying the morphology of polymeric and reactive systems consisting of millions of atoms



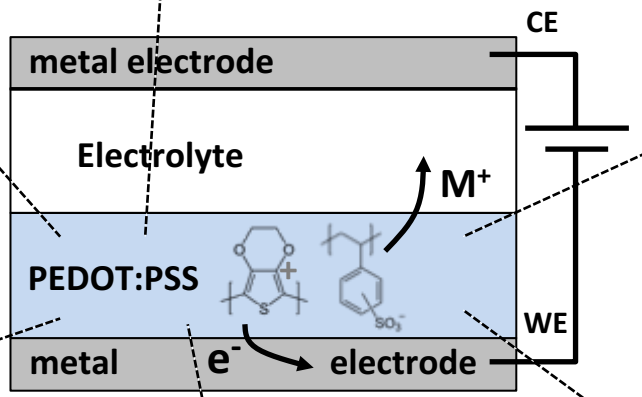
Electrochromic Displays
P. Tehrani *et al*, J. Mater. Chem
(© Acreo RISE)

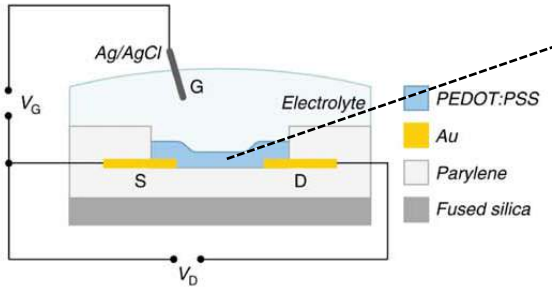


Supercapacitors
T. Cheng 14, 51, J. Mater. Chem. A 2016, 4, 10493

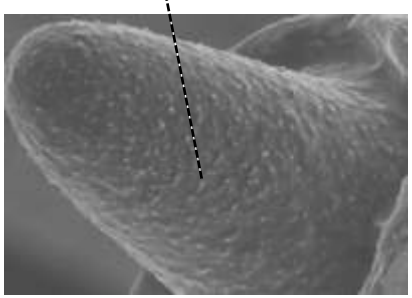


Electronic surface switches
A. M. D. Wan *et al*, BBA, 2013, 9, 1830

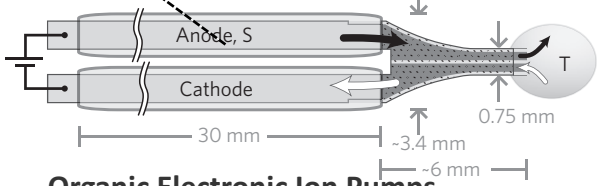




OECTs
D. Khodagholy *et al*, Nat. Commun. 2013, 4, 2133
D. Nilsson *et al* Adv. Mater. 2002, 14, 51

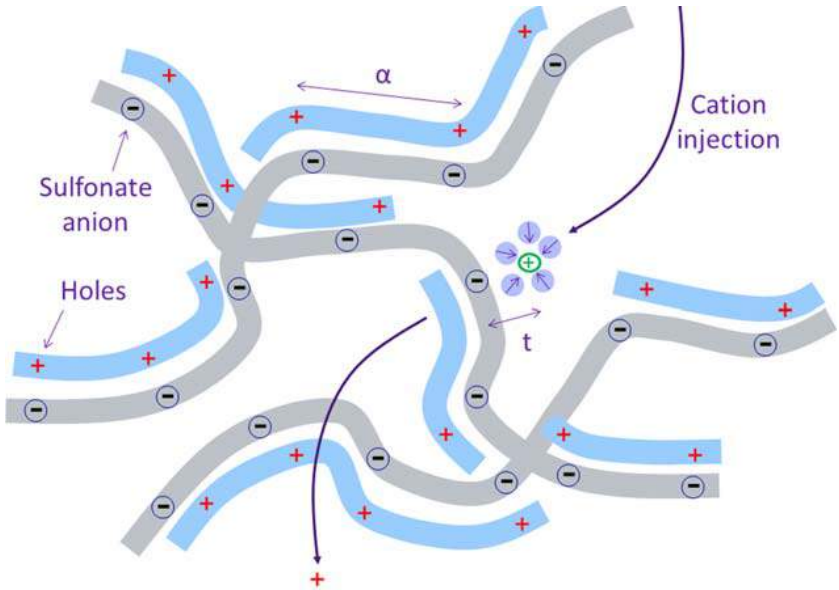


Neural probes
X. Cui *et al* Sens. Actuators B: Chem. 2003, 89, 92

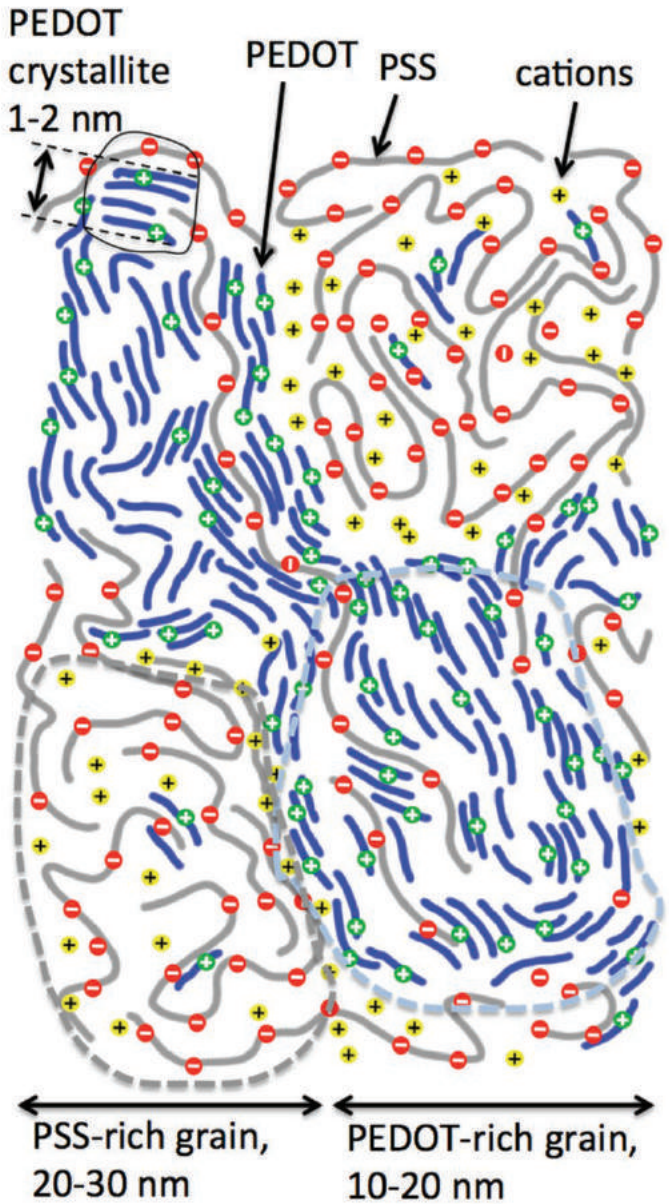


Organic Electronic Ion Pumps
D. T. Simon *et al,* Nature Materials 8, 742-746 (2009)

PEDOT:PSS, its nano- and micro-structure

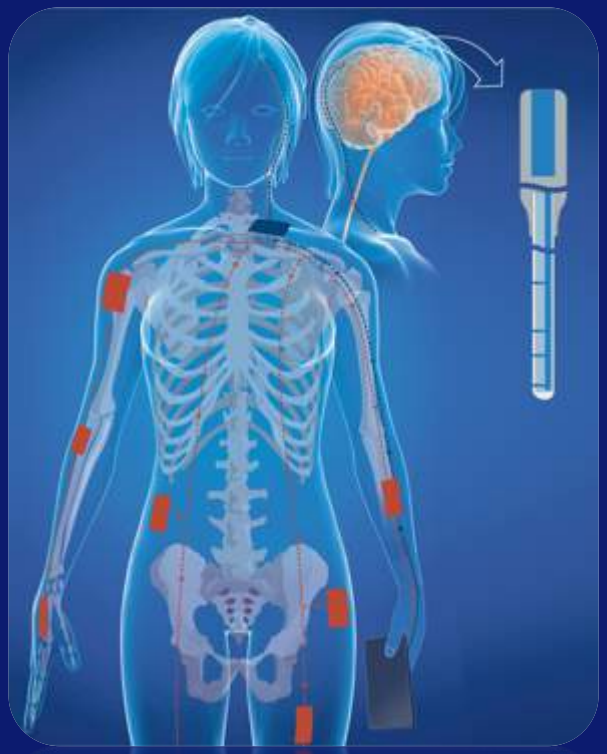


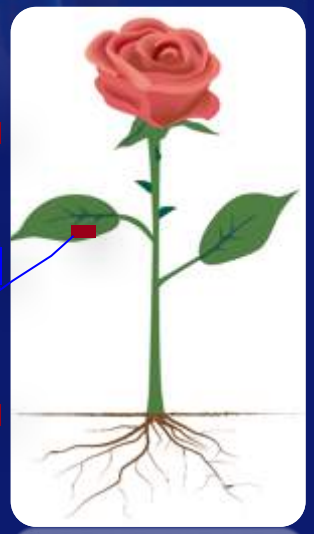
Understanding Volumetric Capacitance in Conducting Polymers
Proctor, C.M., Rivnay, J., Malliaras, G.G.
Journal of Polymer Science, Part B: Polymer Physics
54(15), pp. 1433-1436



Outlook WWSC 2.0

- Electro- and photo-catalysis in paper
- Producing fuels in paper bulks
- Digital paper-area networks
- Paper as the outpost in sensor networks
- Electro-active paper-filters
- Paper electro-actuators
- Paper diagnostics and sampling
- The solar cell tree
- Electronic control over the performance of plants or wood product quality
- All-forest based electronics and power technology





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B. Meyersson
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Team of Bernard
@ Univ. Marseilles

The teams of Nilsson, Grebe and Robert
@ Umeå Plant Science Center

F. Biscarini team
@ Univ. Modena, Italy

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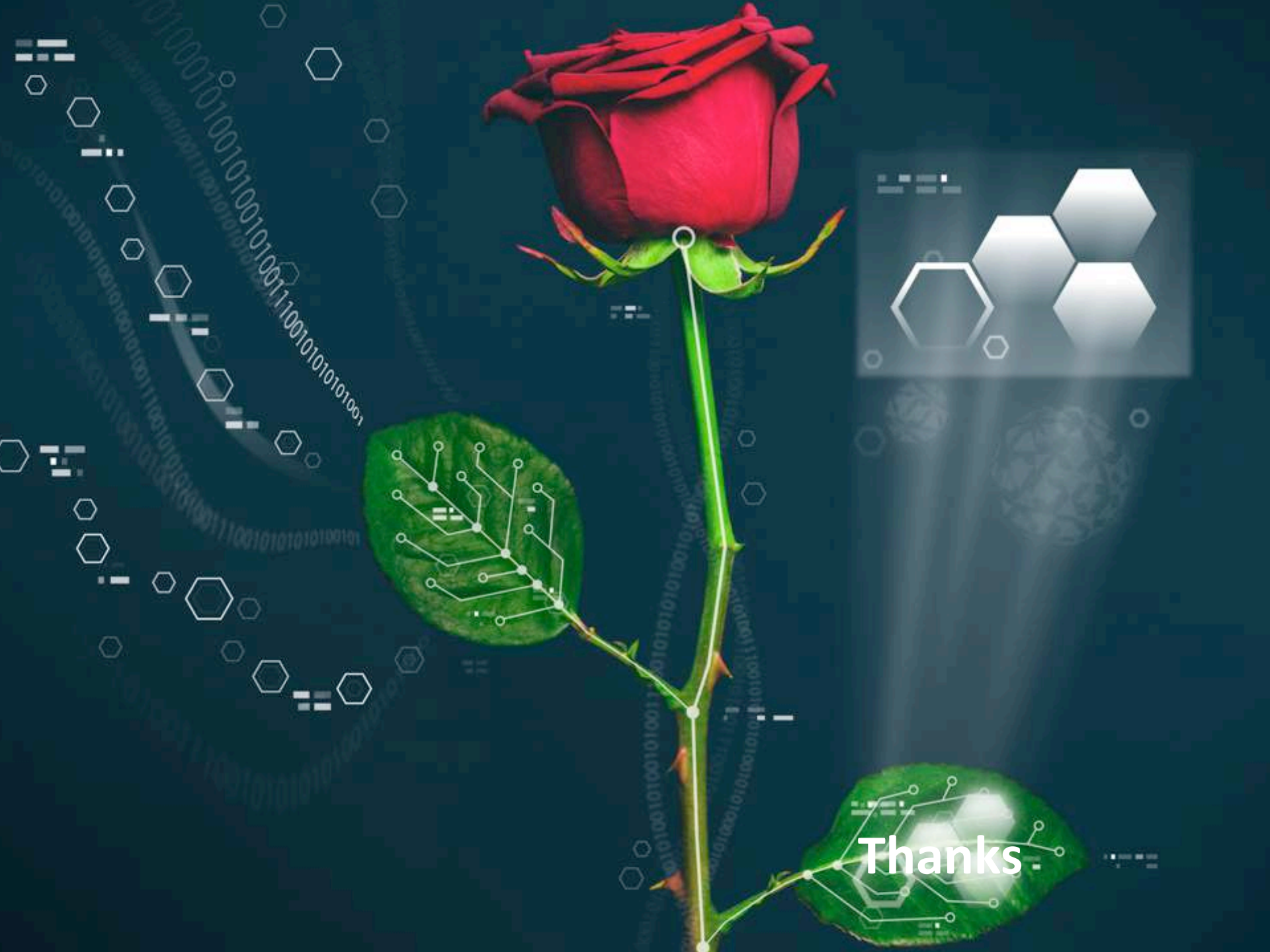
Thanks