

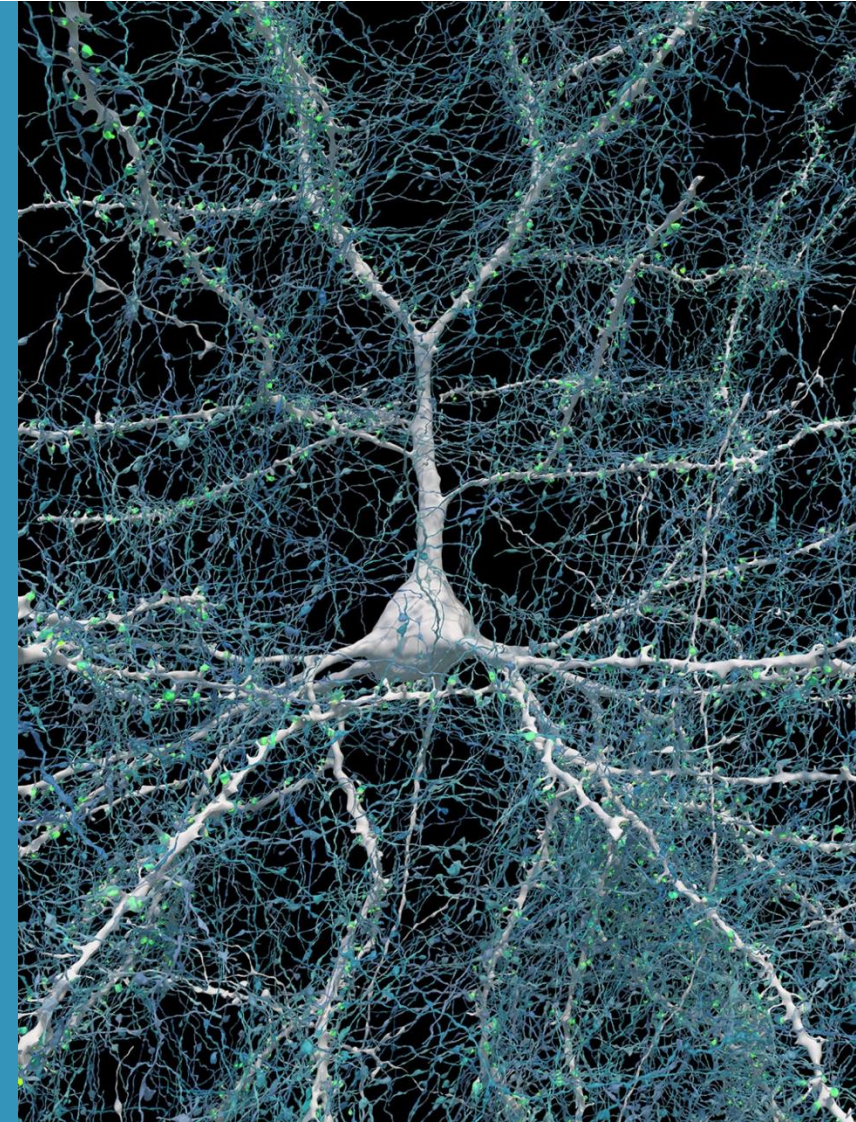
Nonlinear dynamics and memory effects in nanofluidic memristors

A neuromorphic computing implementation

Sergio Portillo Pous

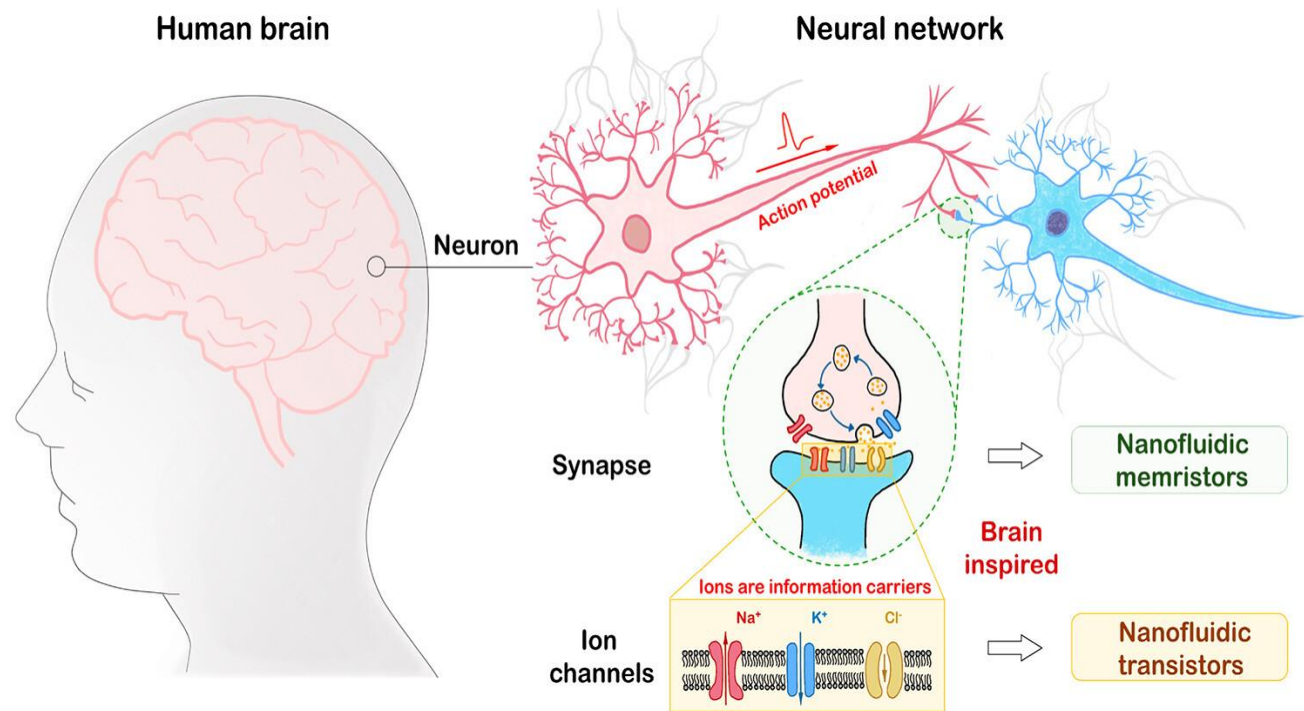
PhD student, Universitat de València

MAT Collaboration Meeting 2026



Brain-like computing

The human brain is a super efficient computer



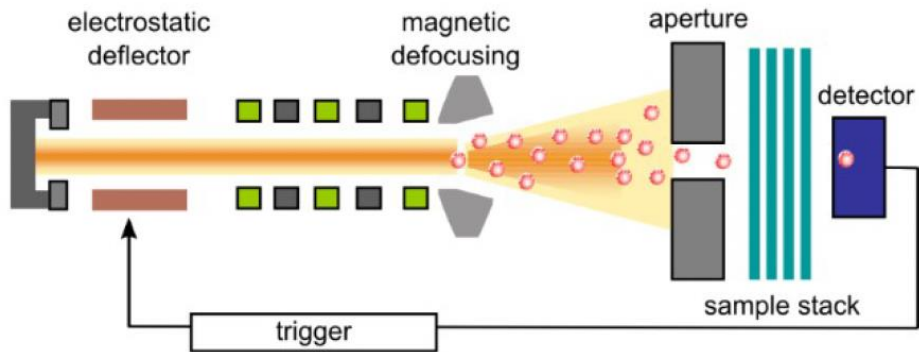
Hou et al, J. Phys. Chem. Lett. 14 (2023) 2891-2900

Nanopore membranes

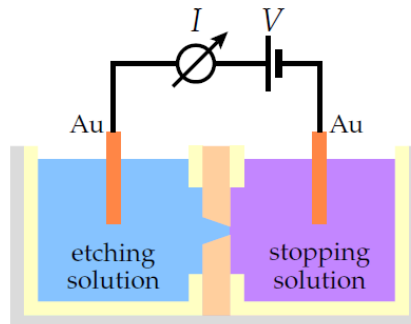
Fabrication



Irradiation with heavy ions



Asymmetric chemical etching



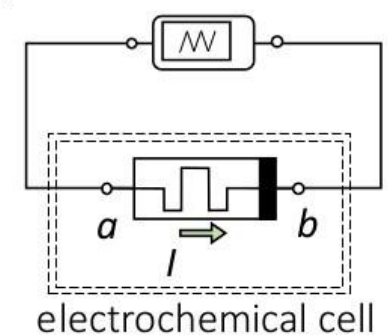
COO⁻ groups on nanopore surface

Experimental setup

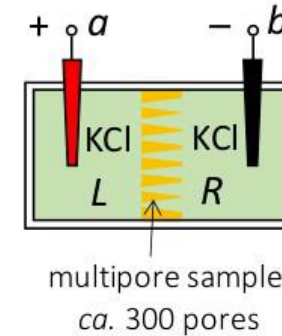
(a) double sided electromagnetic shield



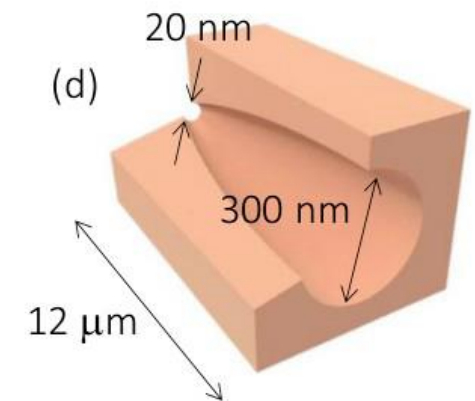
(b) potentiostat



(c)



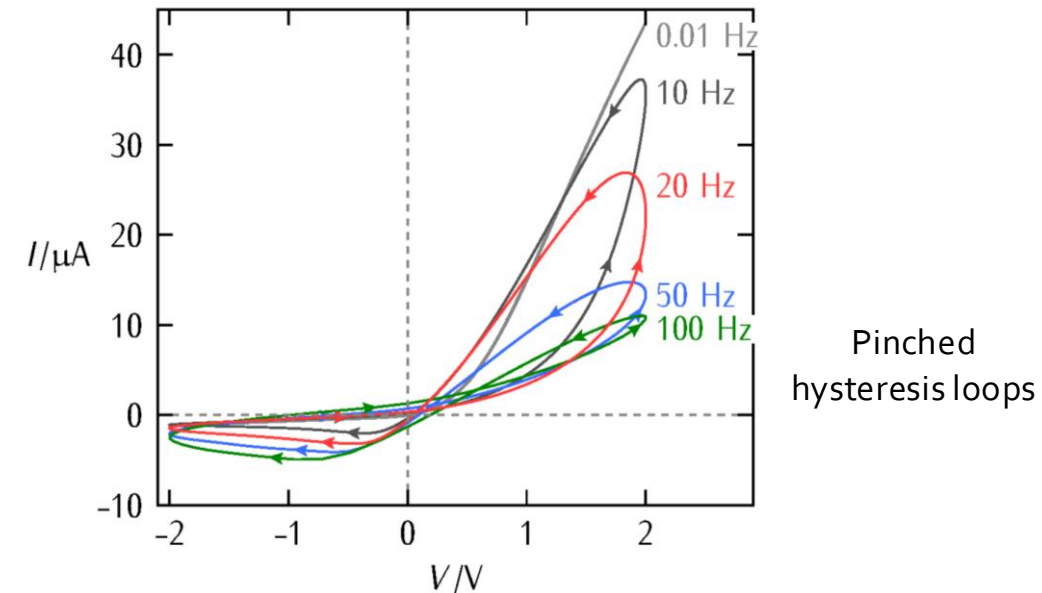
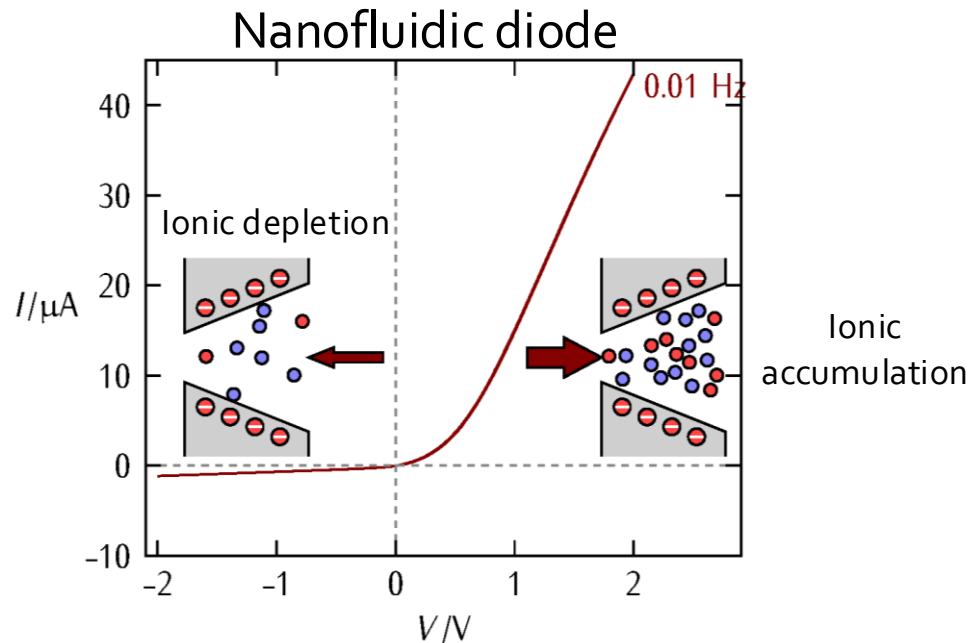
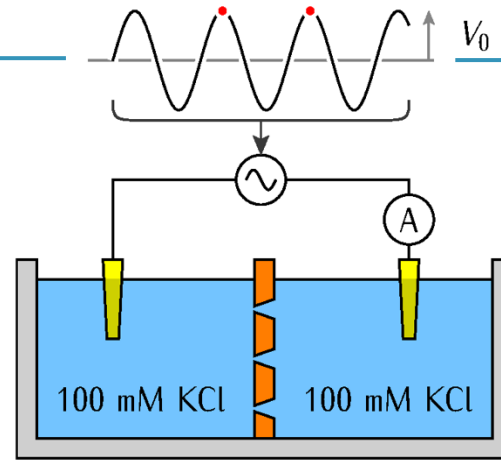
(d)



Nonlinear dynamics

Steady-state $I - V$ curve
For a "slow enough" signal

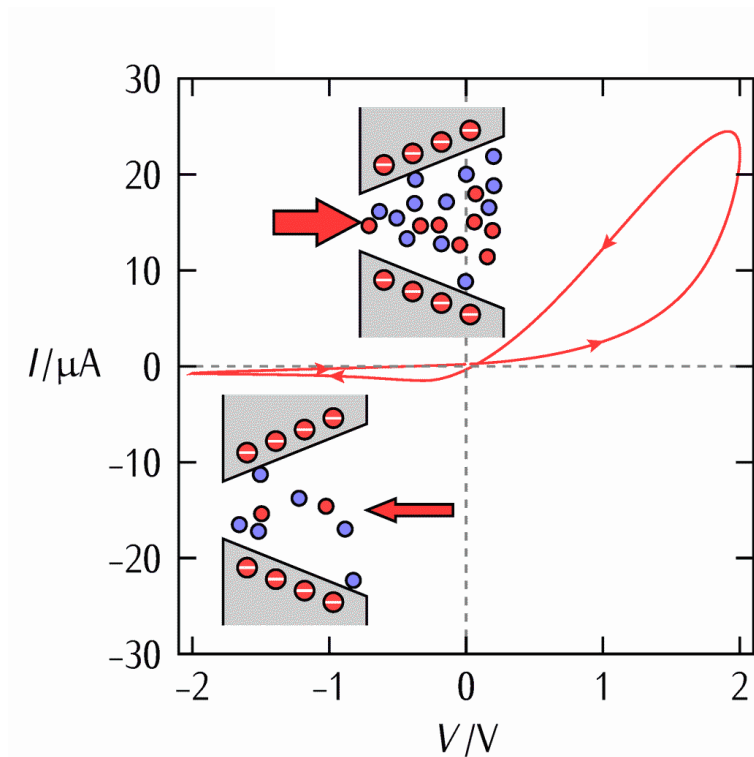
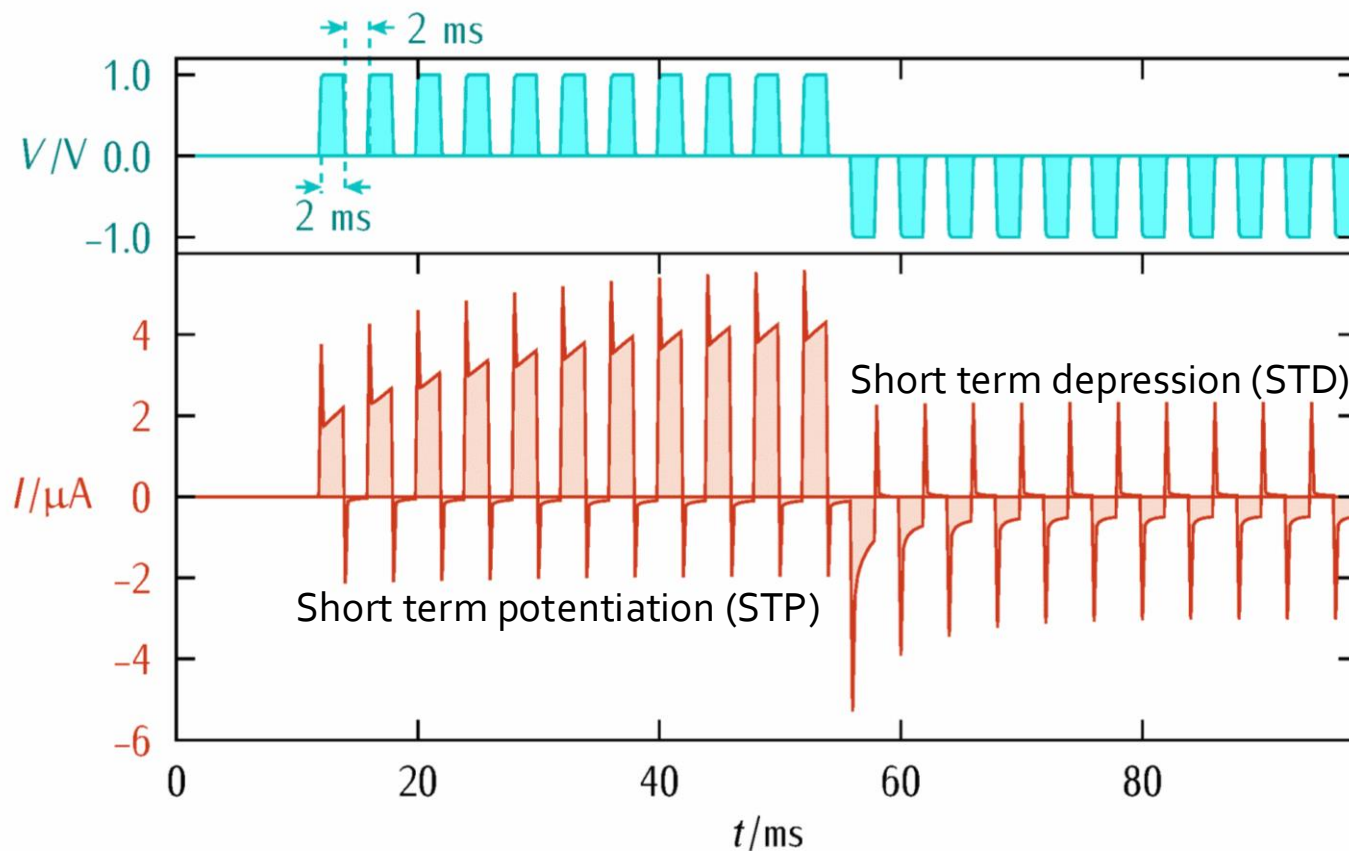
Memristive behavior
 $f \sim 10$ Hz



Ramirez et al, J. Phys. Chem. Lett. 14 (2023) 10930

Neuromorphic properties

Synaptic potentiation and depression of the conductance

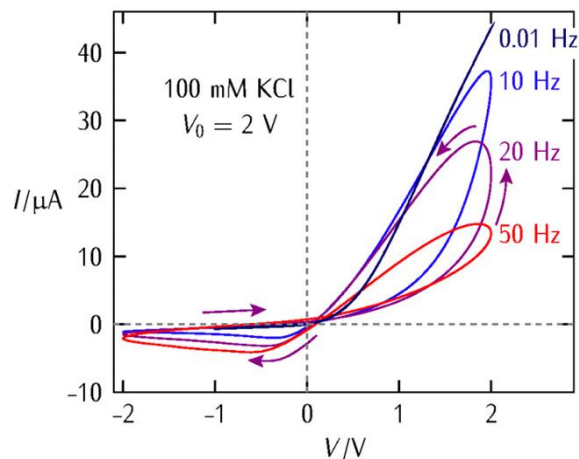


Ramirez et al, J. Phys. Chem. Lett. 14 (2023) 10930

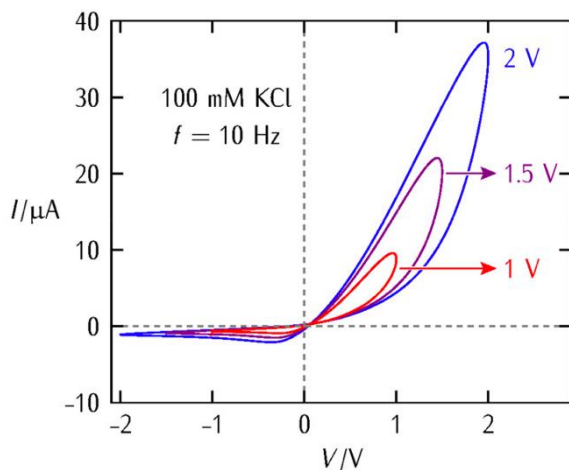
Electrochemical tuning

Electrical tuning

Signal frequency

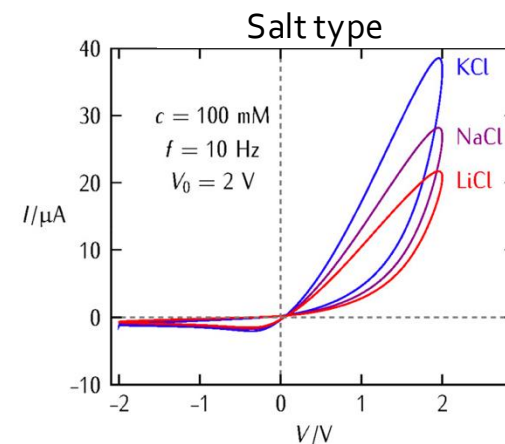
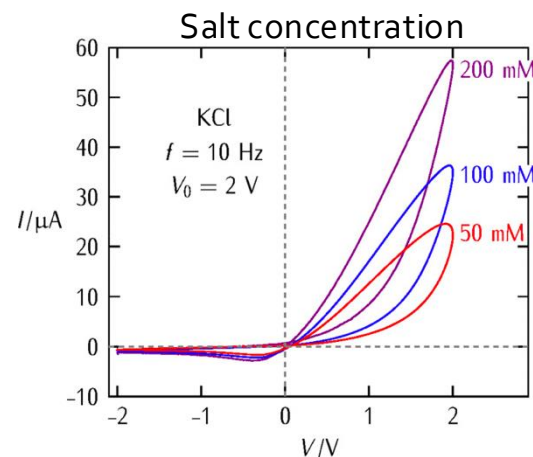


Signal amplitude

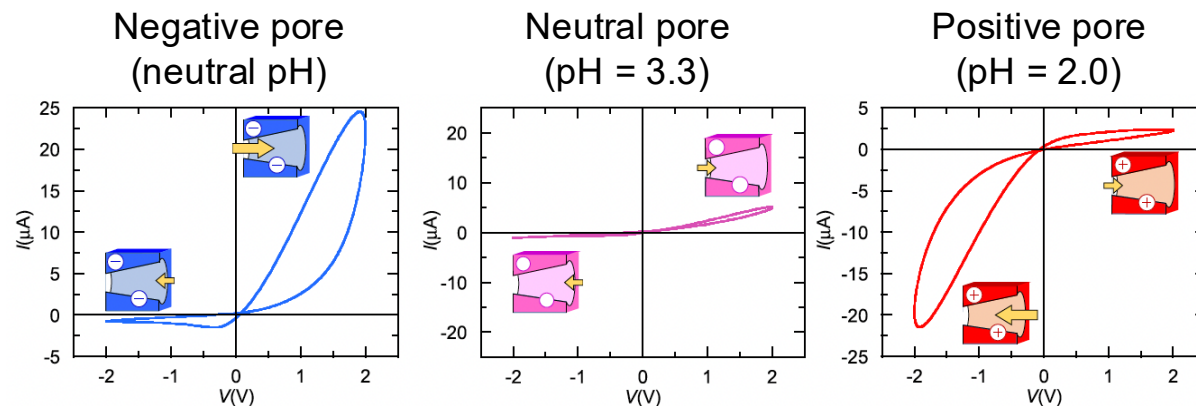


Cervera et al, Phys. Fluids. Lett. 36 (2024) 047129

Chemical tuning



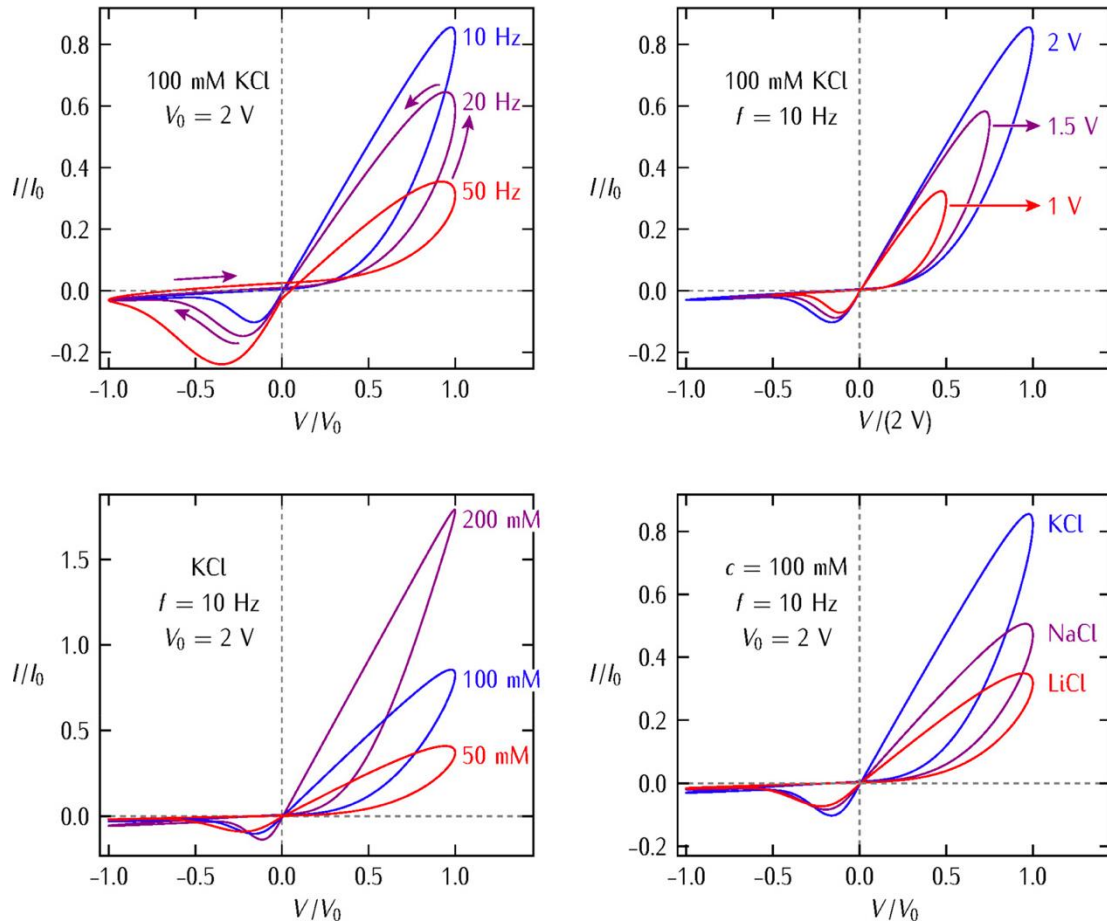
Cervera et al, Phys. Fluids. Lett. 36 (2024) 04712



Ramirez et al, J. Phys. Chem. Lett. 14 (2023) 10930

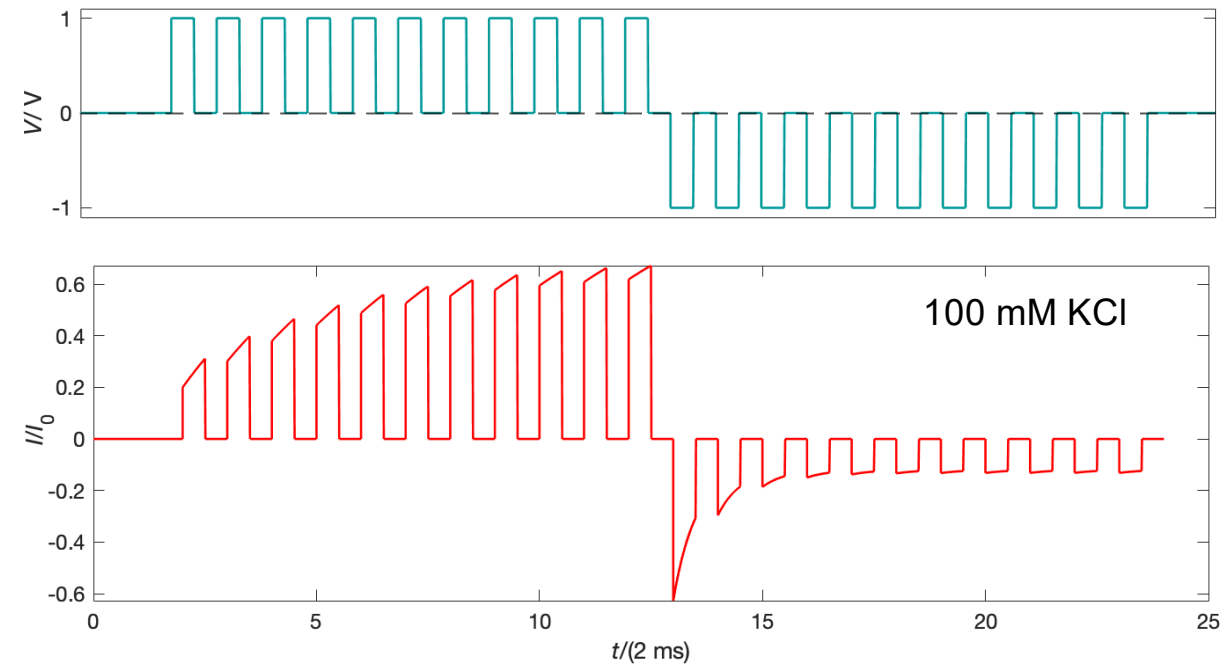
Theoretical model

$I - V$ curves



Cervera et al, Phys. Fluids. Lett. 36 (2024) 047129

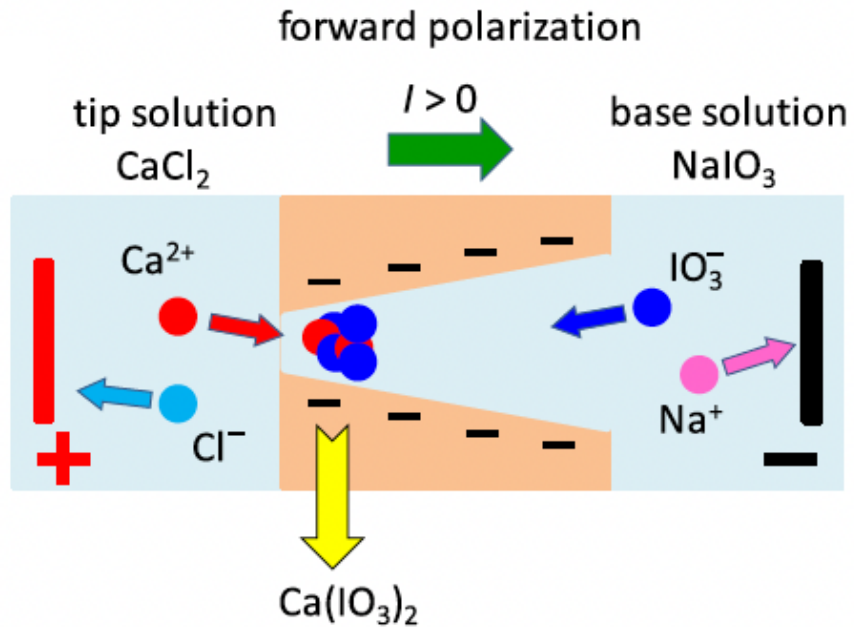
Neuromorphic properties



Portillo et al, Phys. Rev. E 110 (2024) 065101

Memory dynamics can be reproduced

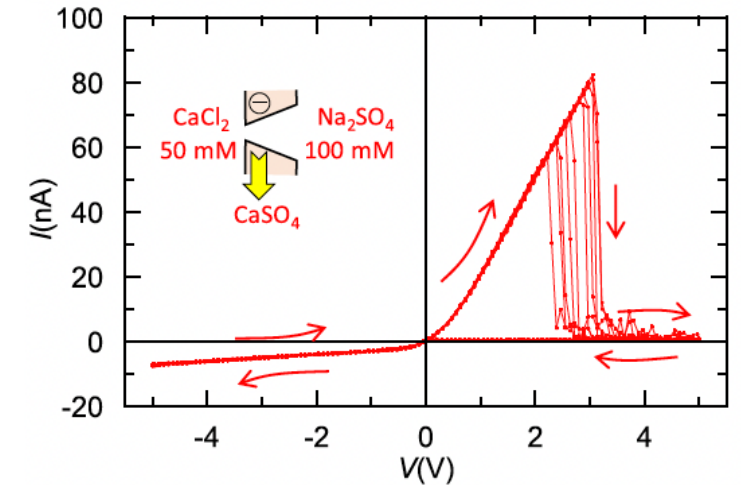
Negative Differential Resistance (NDR)



Pore blocking due to salt precipitation at V_{th}

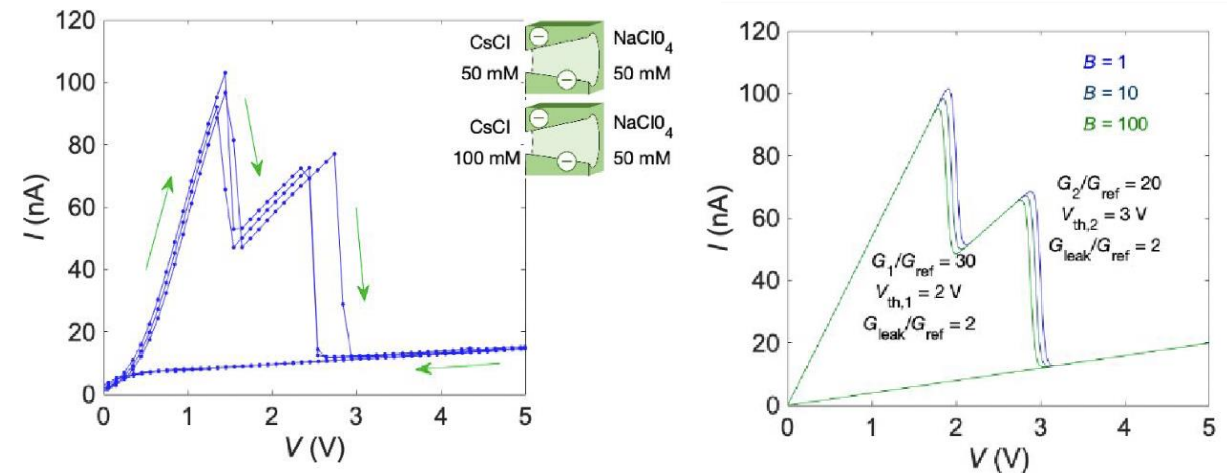
Ramirez et al, J. Chem. Phys. 162 (2025) 194707

Highly reproducible phenomena



Ramirez et al, J. Chem. Phys. 162 (2025) 194707

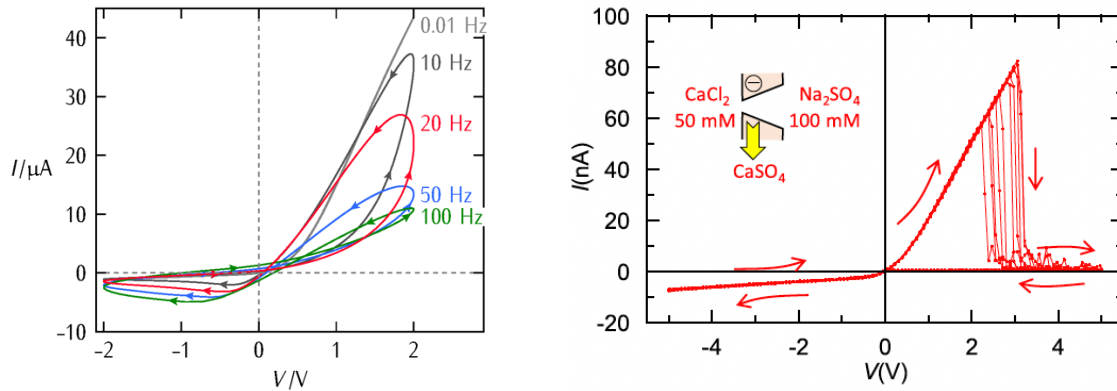
Can be also modeled



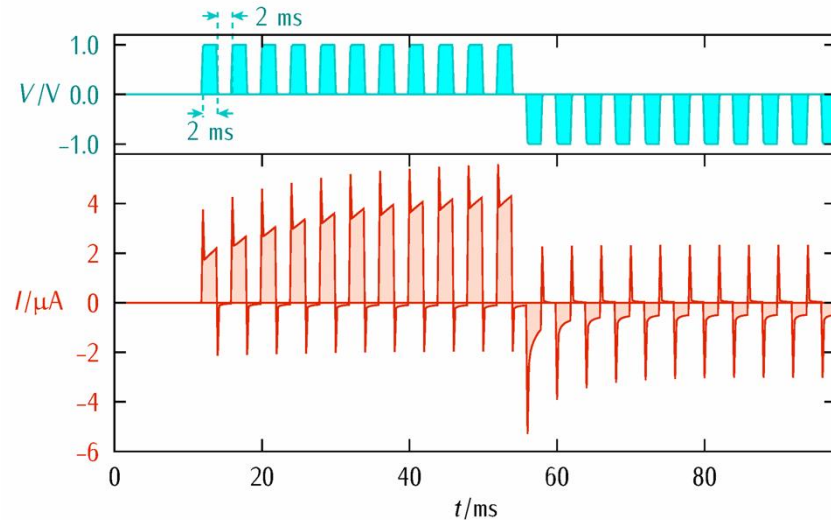
Cervera et al, J. Chem. Phys. Lett 16 (2025) 12321-12327

Nanopore membranes exhibit:

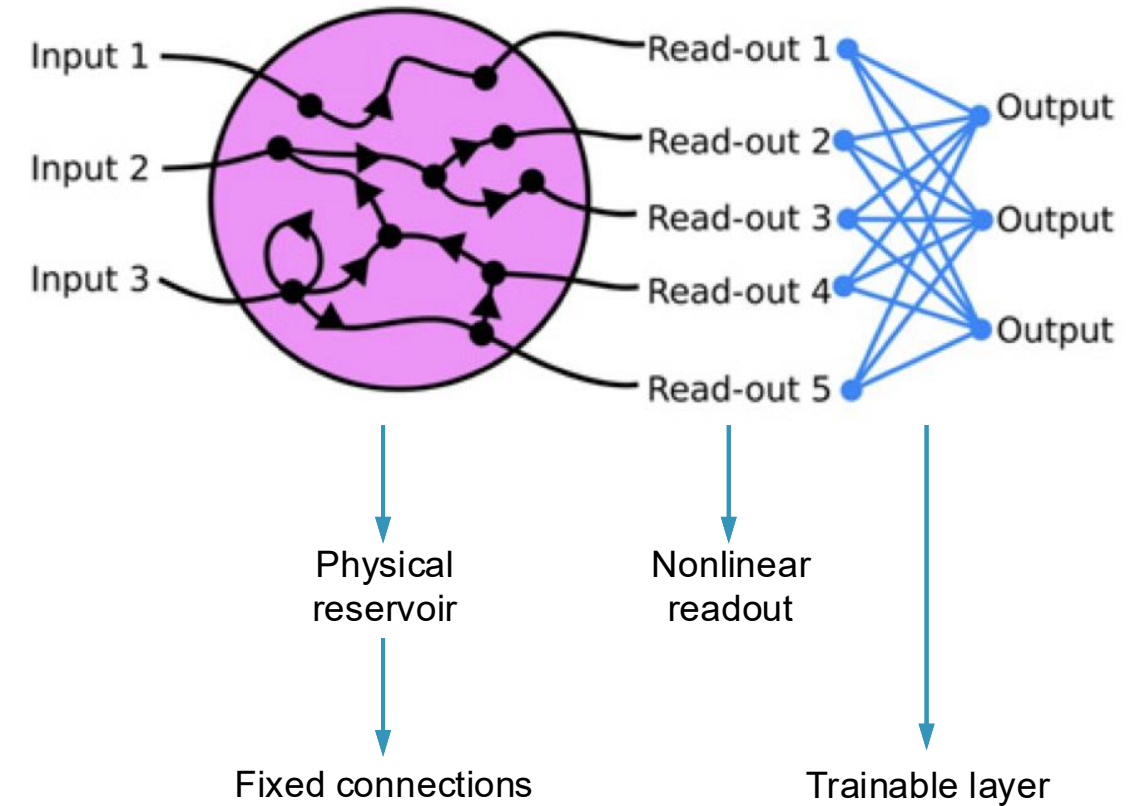
Rich nonlinear dynamics



Synaptic-like fading memory



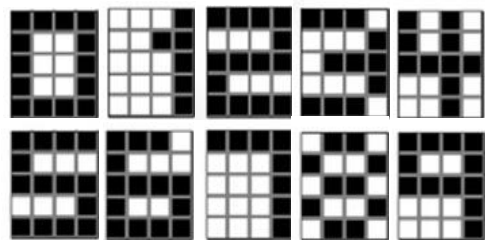
Neuromorphic Reservoir Computing schemes



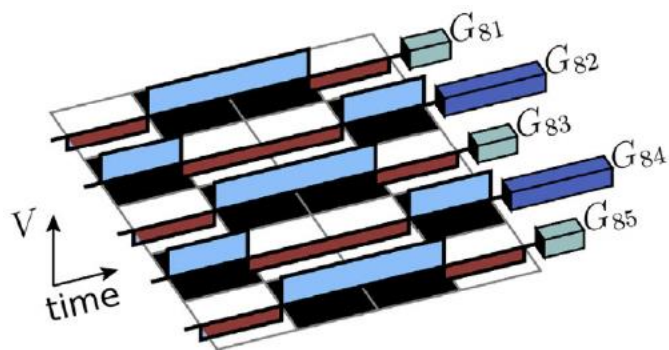
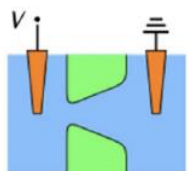
“Low-cost” machine learning models

RC scheme Vol. I: single nanopore

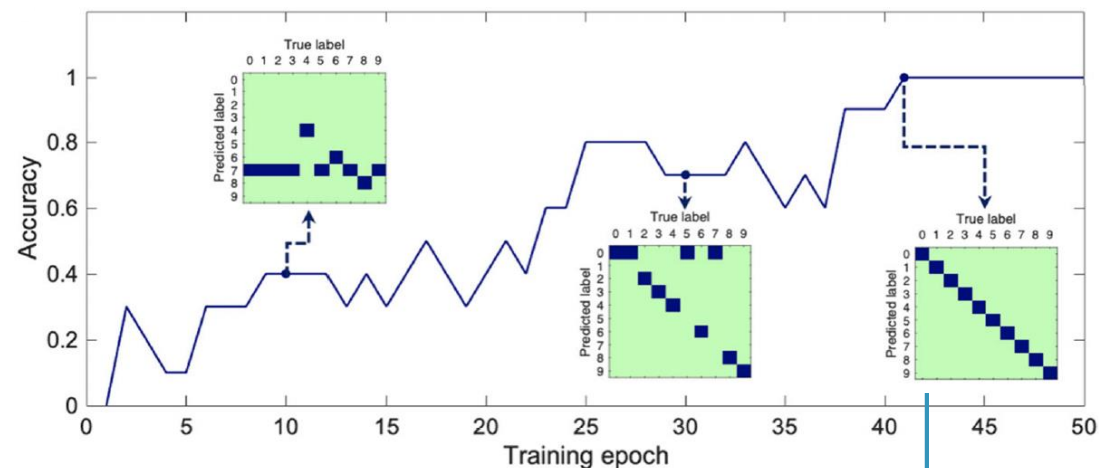
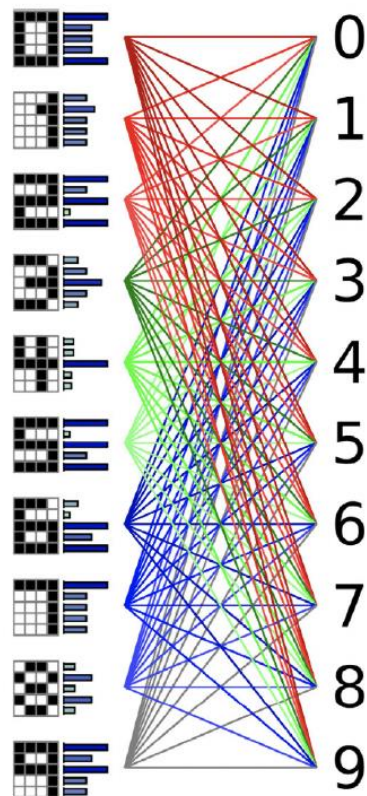
Binary image recognition



Voltage sequences



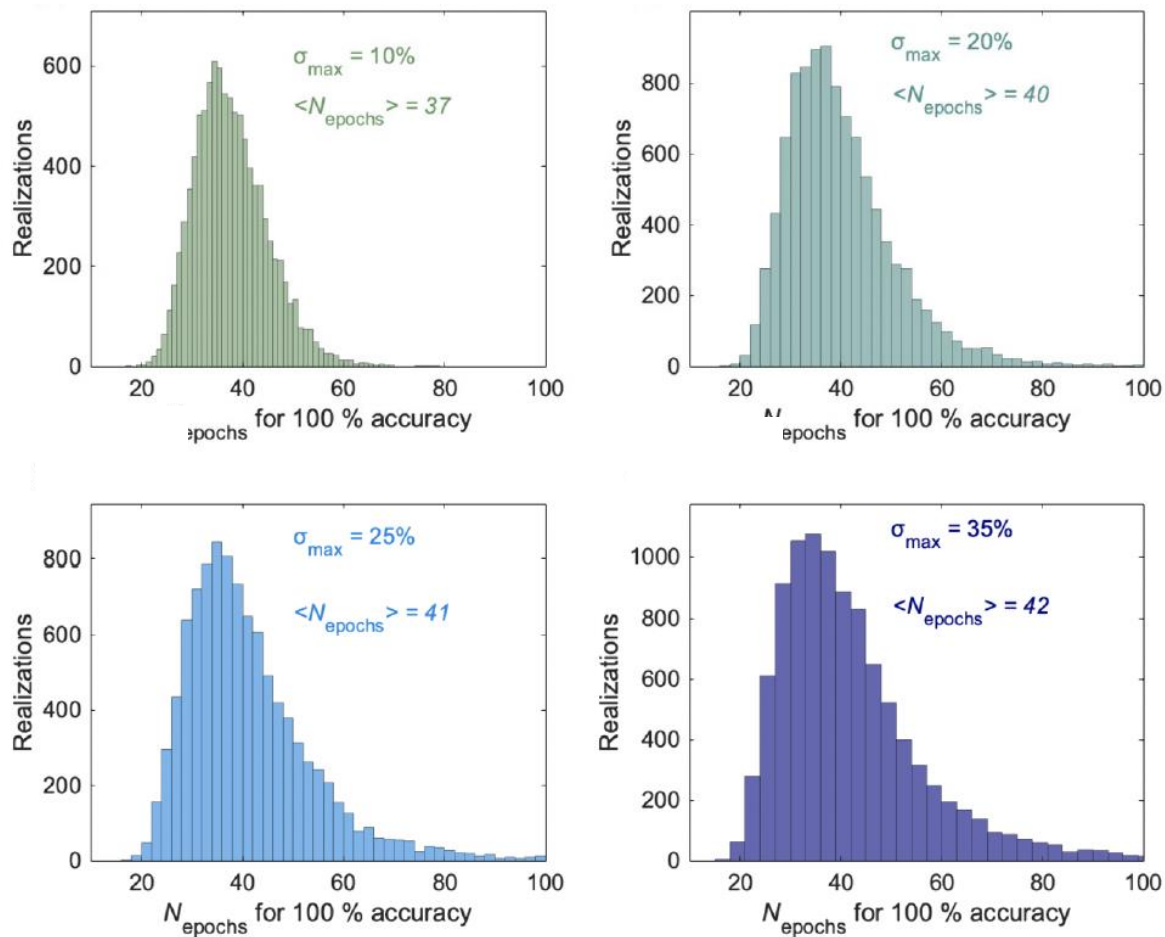
Trainable layer



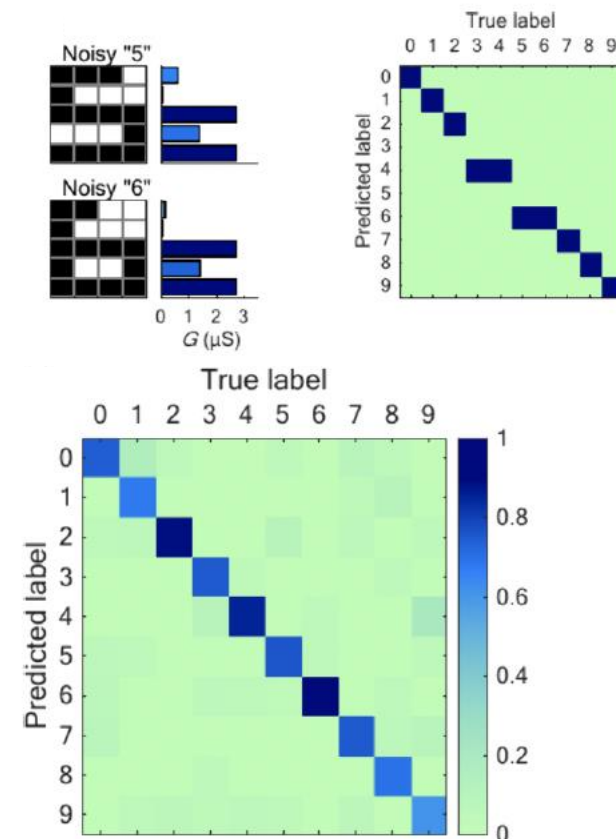
100% accuracy after 42 iterations

Portillo et al, Nano Lett. 25 (2025) 9928-9934

Robustness under conductance variability



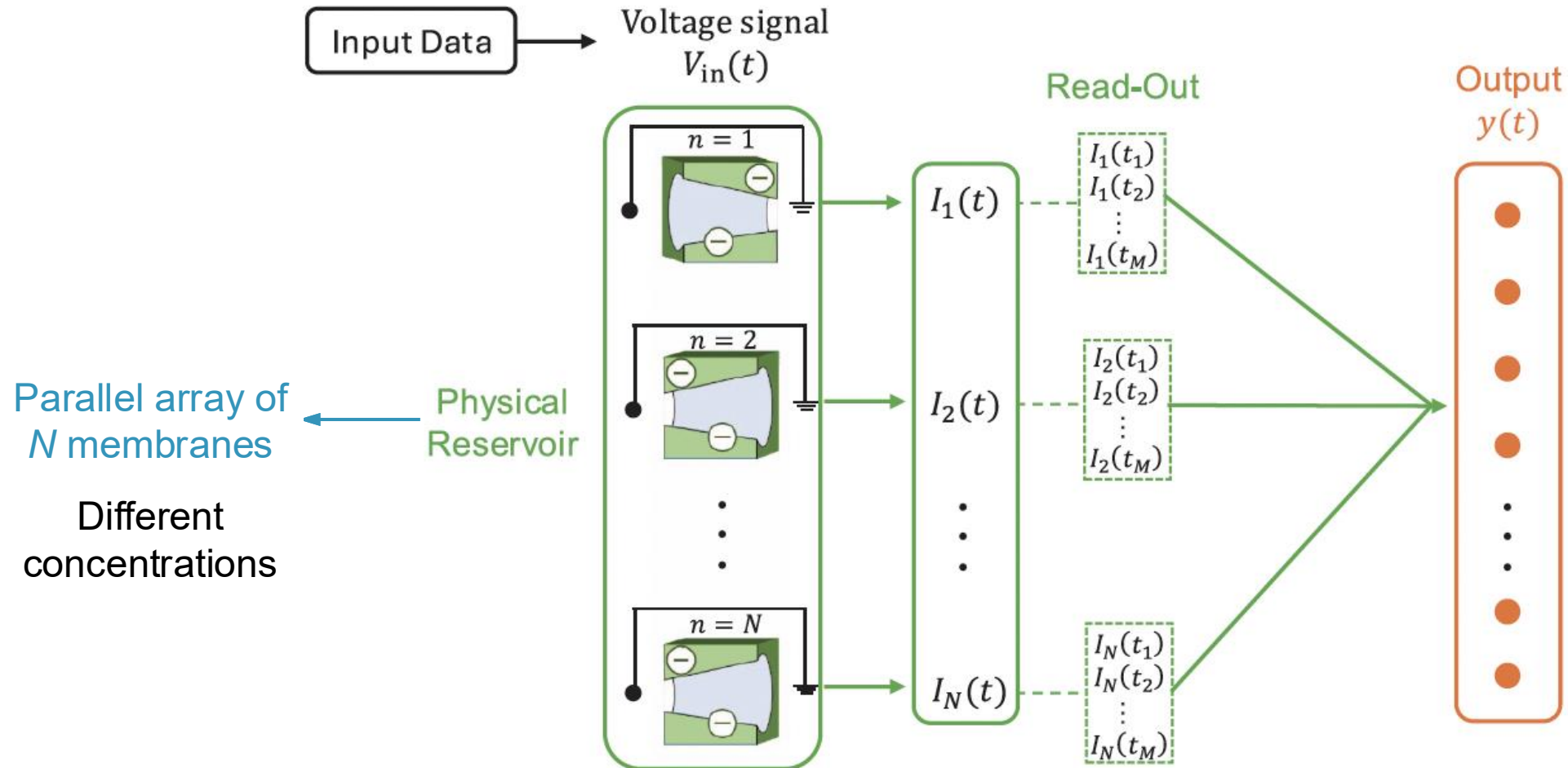
Robustness under corrupt inputs



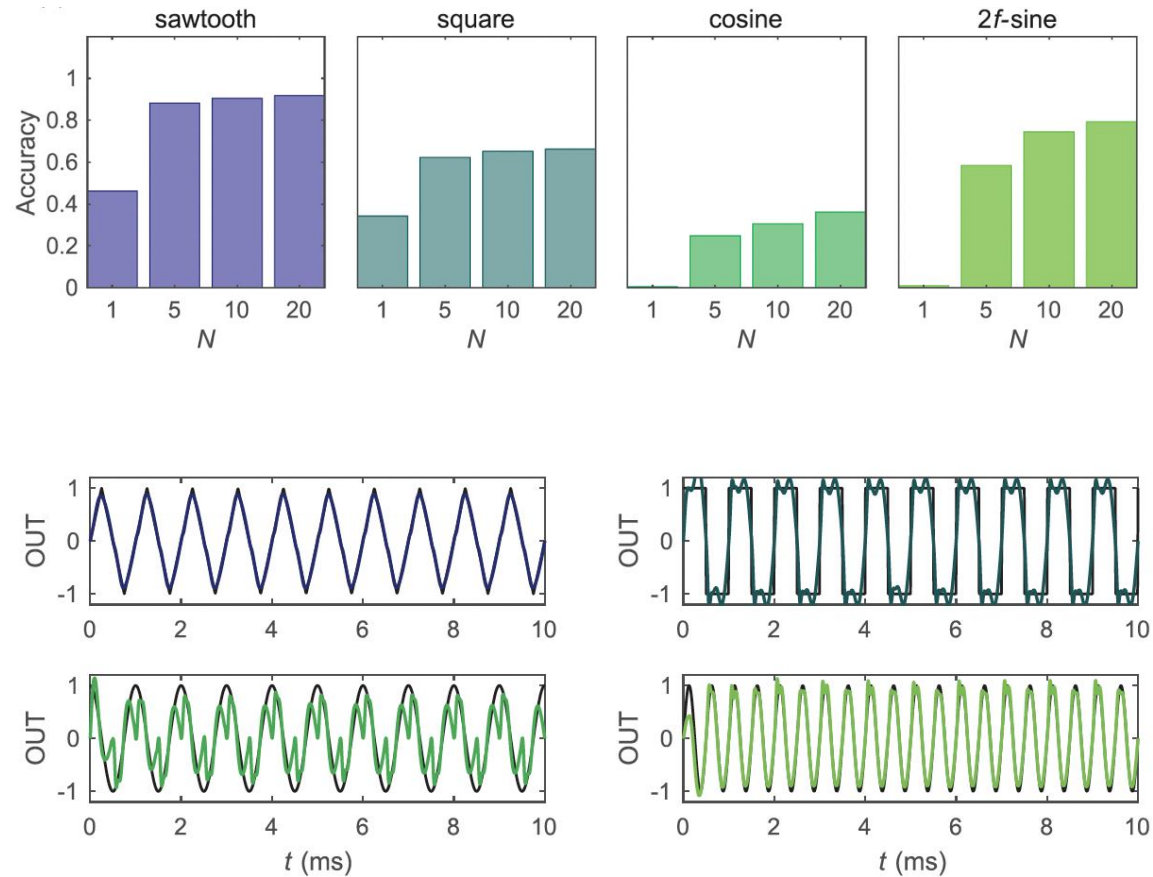
76% accuracy
without further
training

Portillo et al, Nano Lett. 25 (2025) 9928-9934

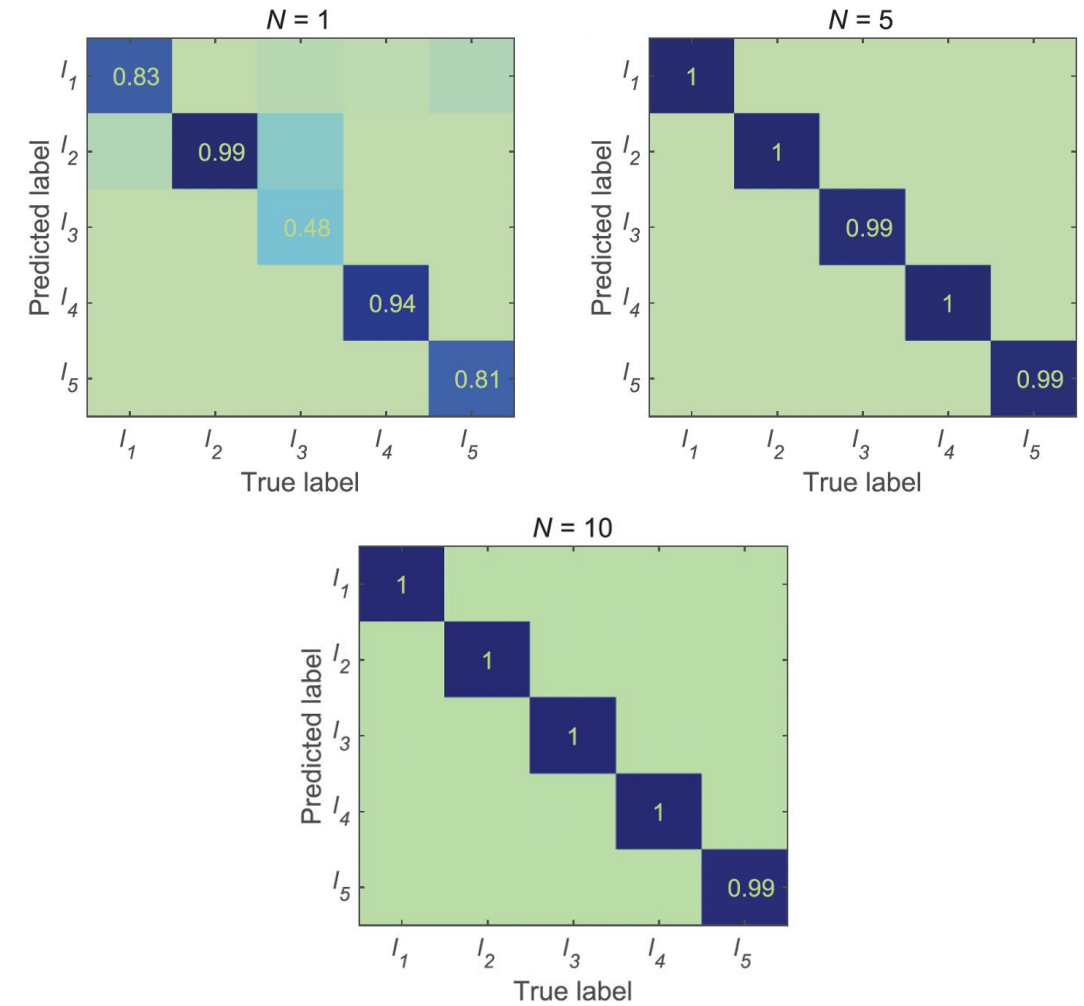
RC scheme Vol. II: heterogeneous array



Nonlinear transformation of a sine wave

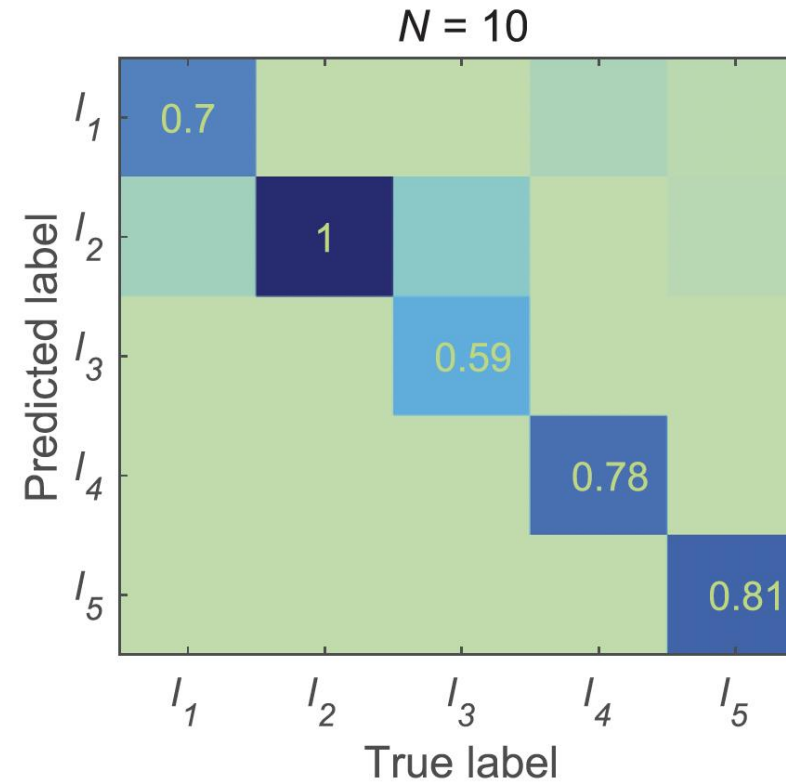
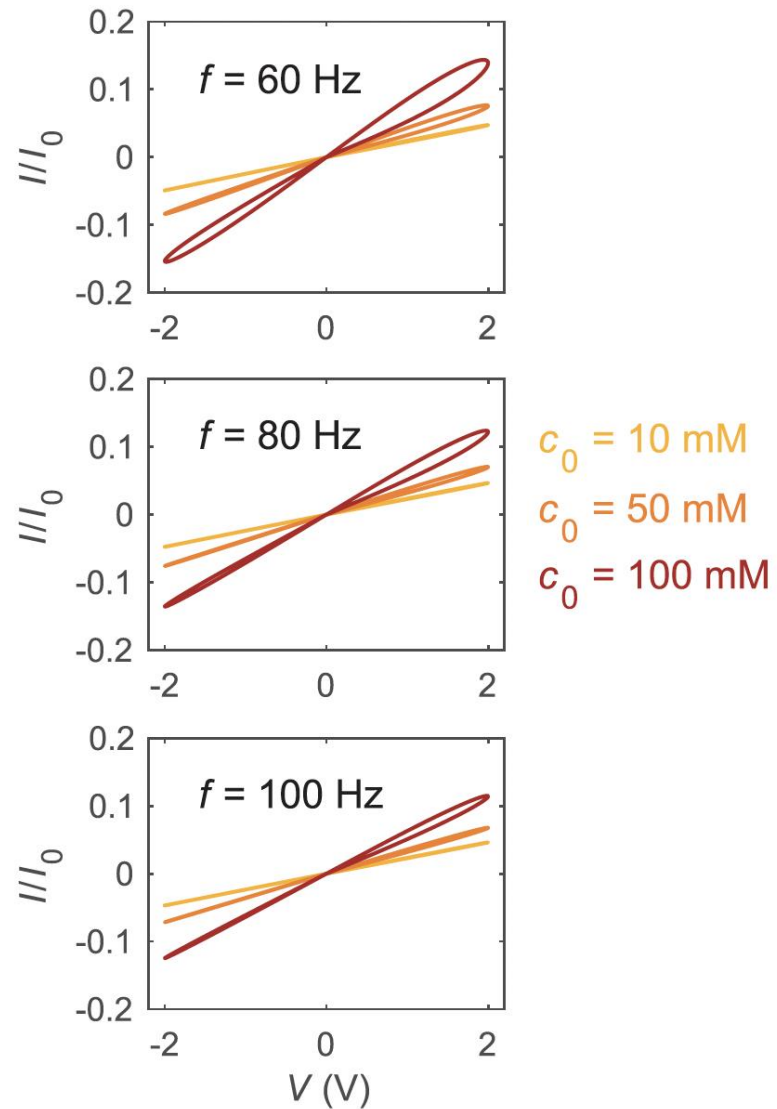


Waveform classification



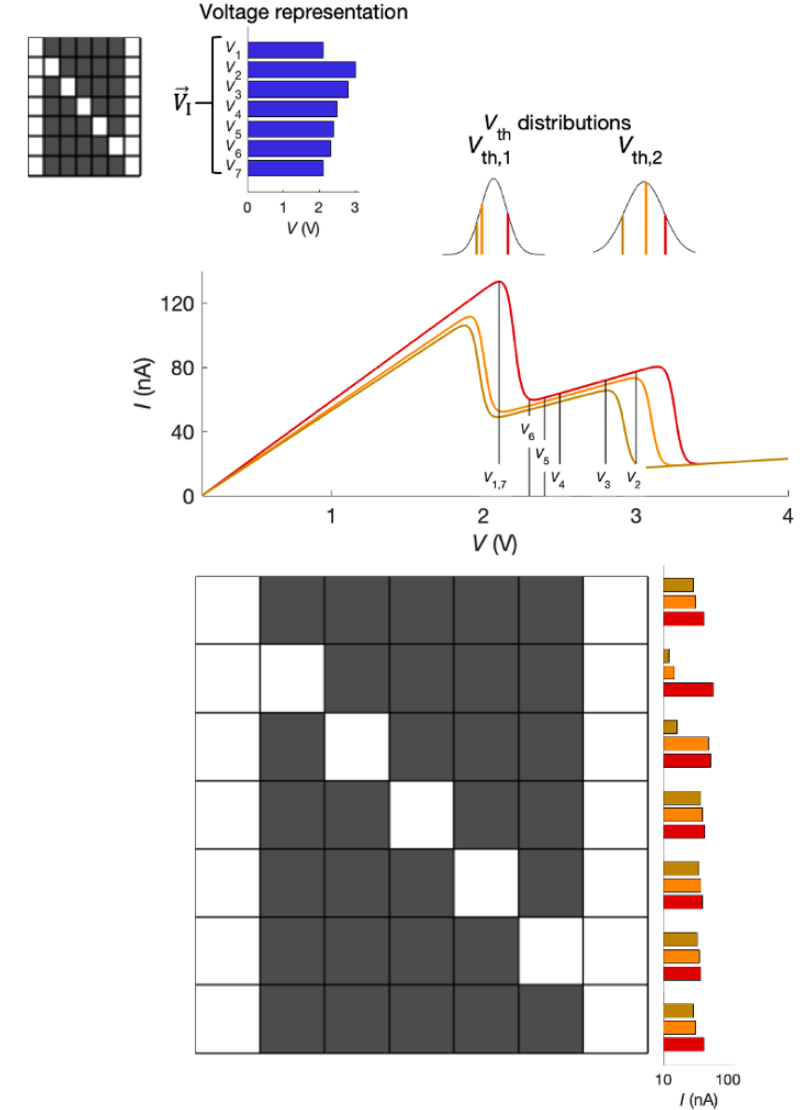
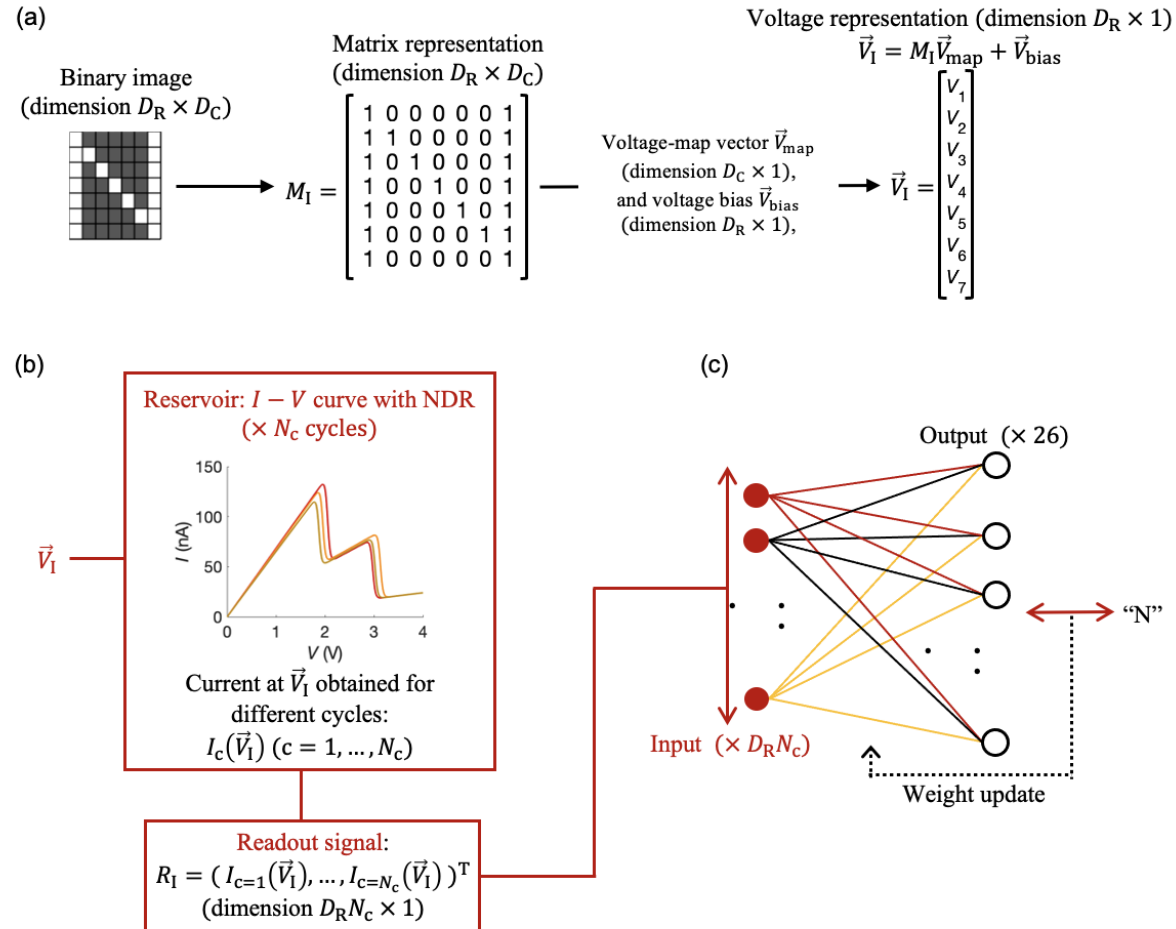
Portillo et al, Neuromorph. Comp. Eng. 6 (2026) 014013

Importance of nonlinearity



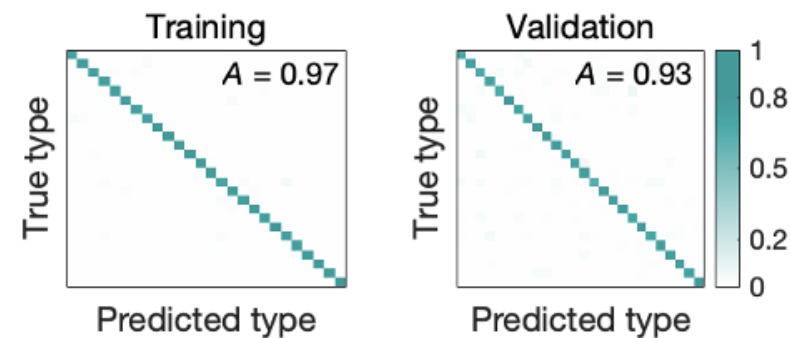
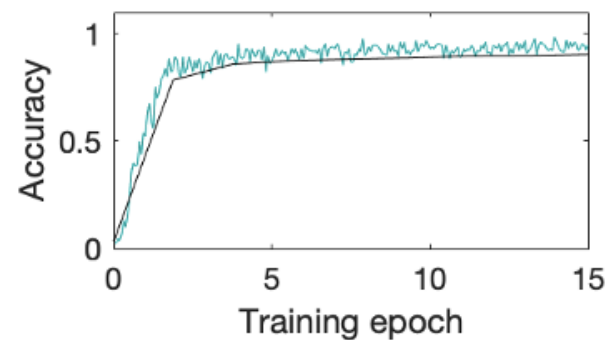
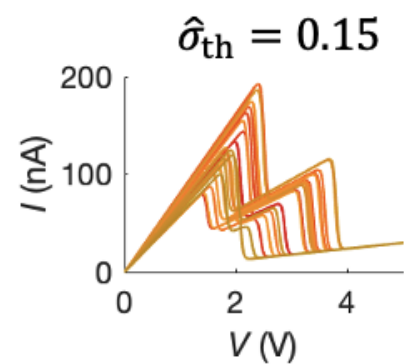
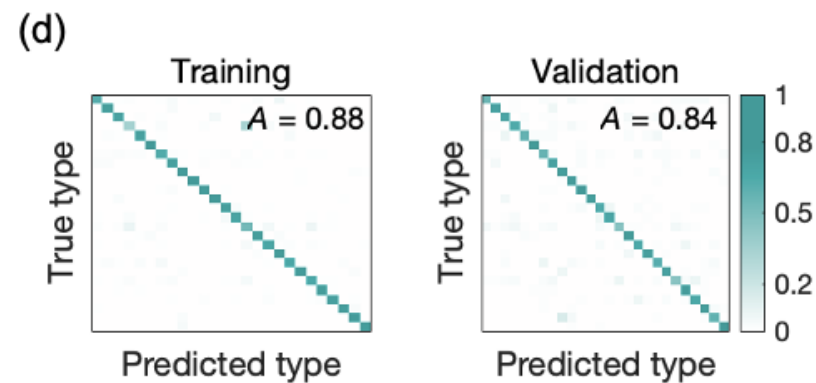
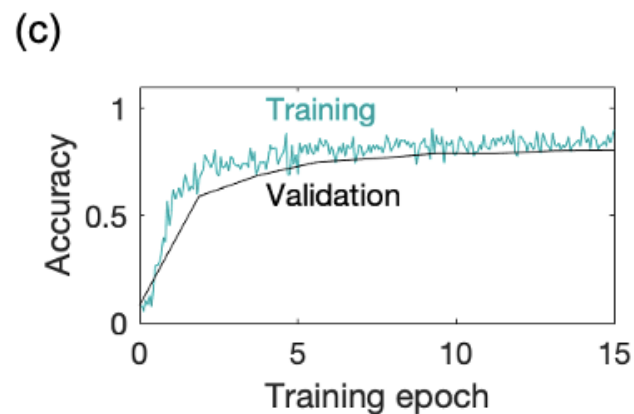
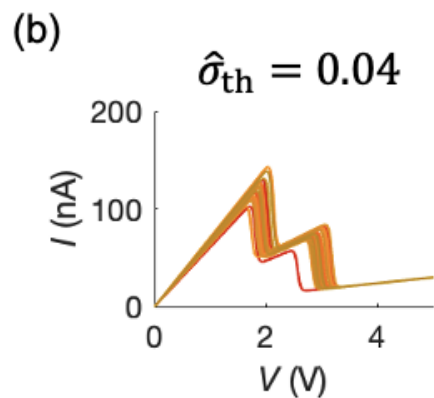
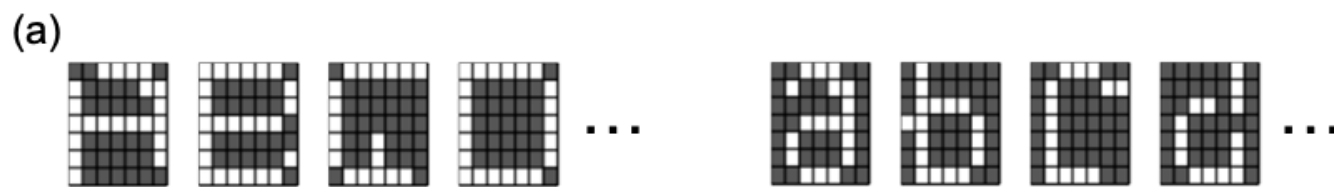
Portillo et al, Neuromorph. Comp. Eng. 6 (2026) 014013

RC scheme Vol. III: NDR reservoir



Work under review

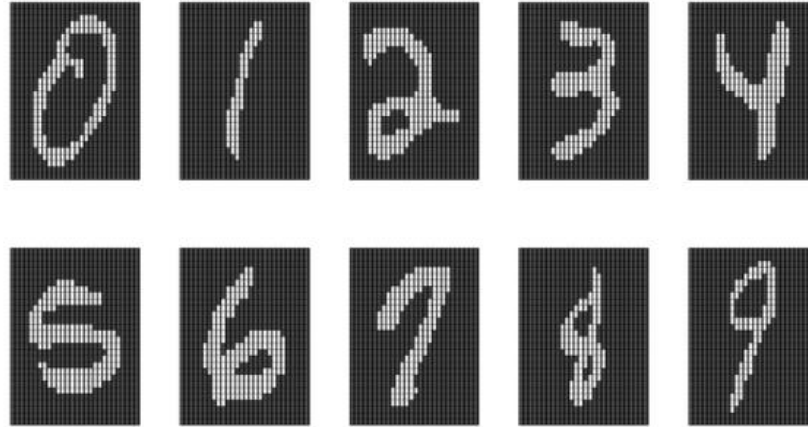
Alphabet letters



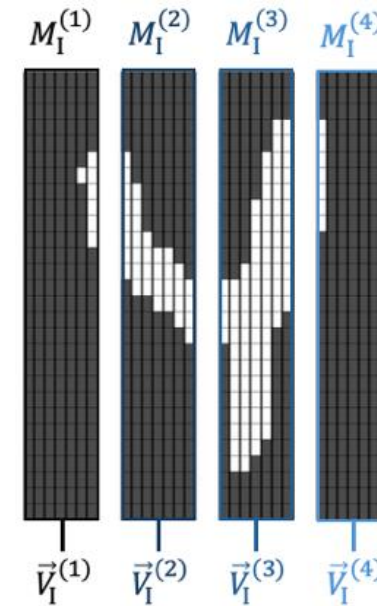
Work under review

Hand-written digits (MNIST dataset)

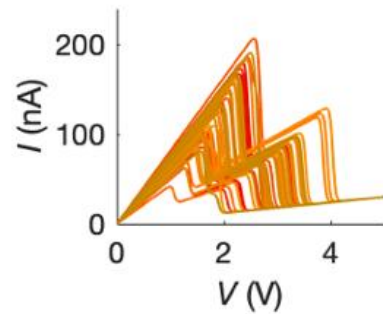
(a)



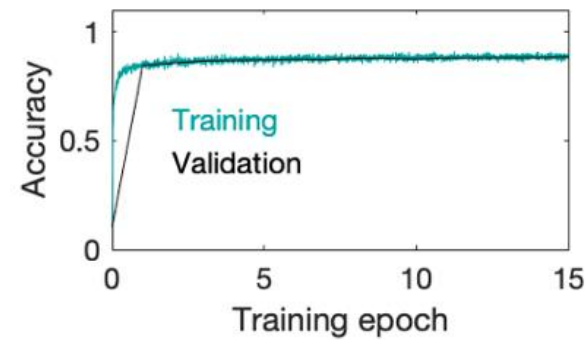
(b)



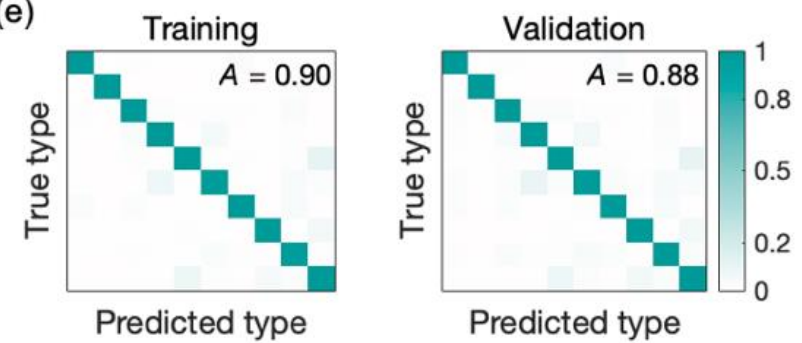
(c)



(d)

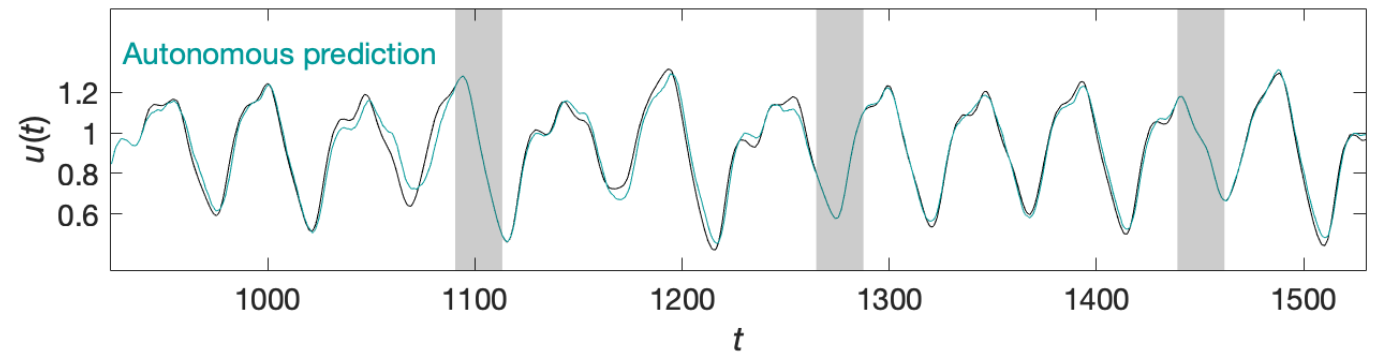
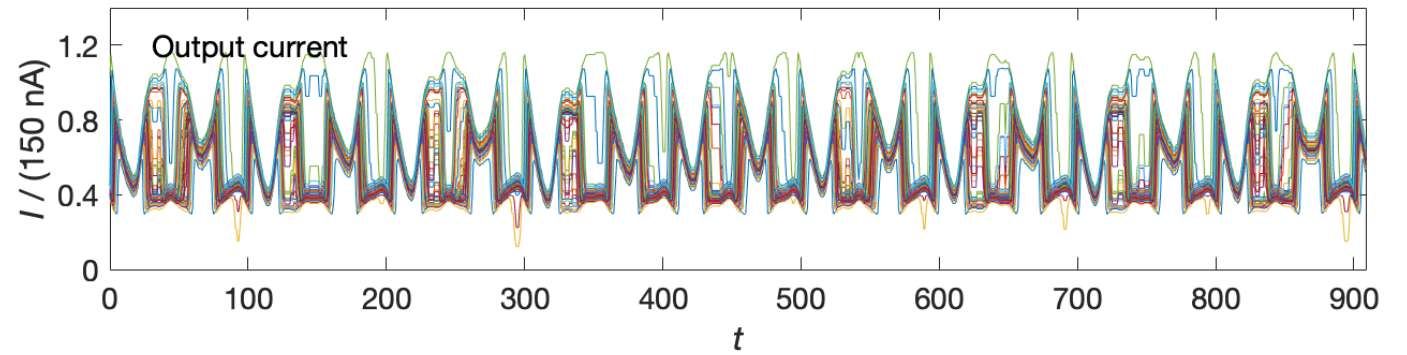
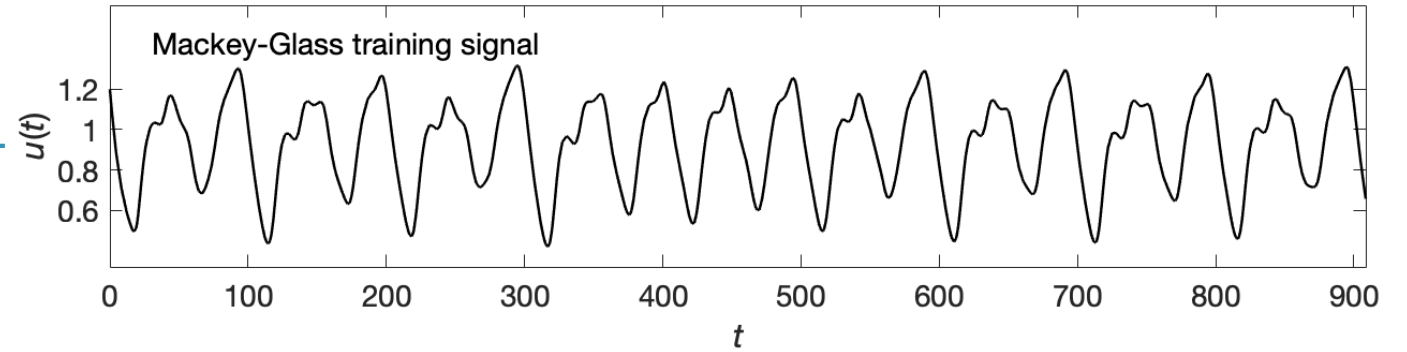
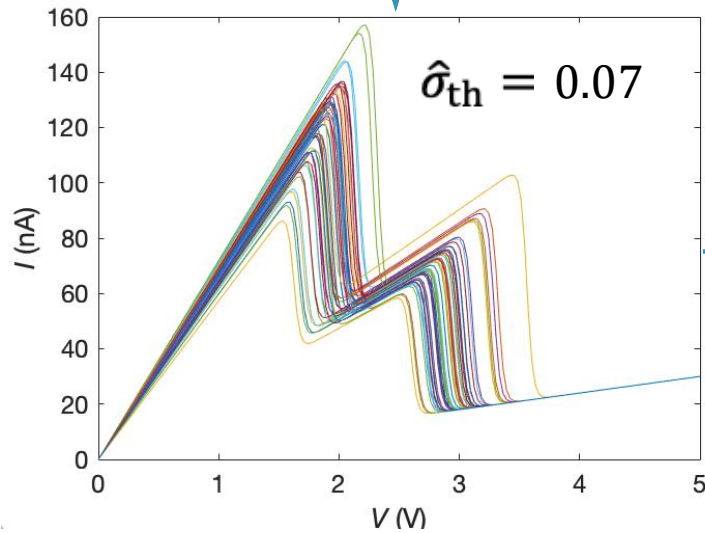


(e)



Work under review

Autonomous forecasting of chaotic time series



Work under review

Conclusions

- Track-etched nanopore membranes exhibit robust nonlinearity and history dependent behavior.
- Memristive properties are electrochemically tuned.
- NDR phenomena is also observed due to salt precipitation.
- Nanopore membranes dynamics enable the implementation of RC schemes.
- Nonlinearity and variability needed for good network performance.

¡Thank you!



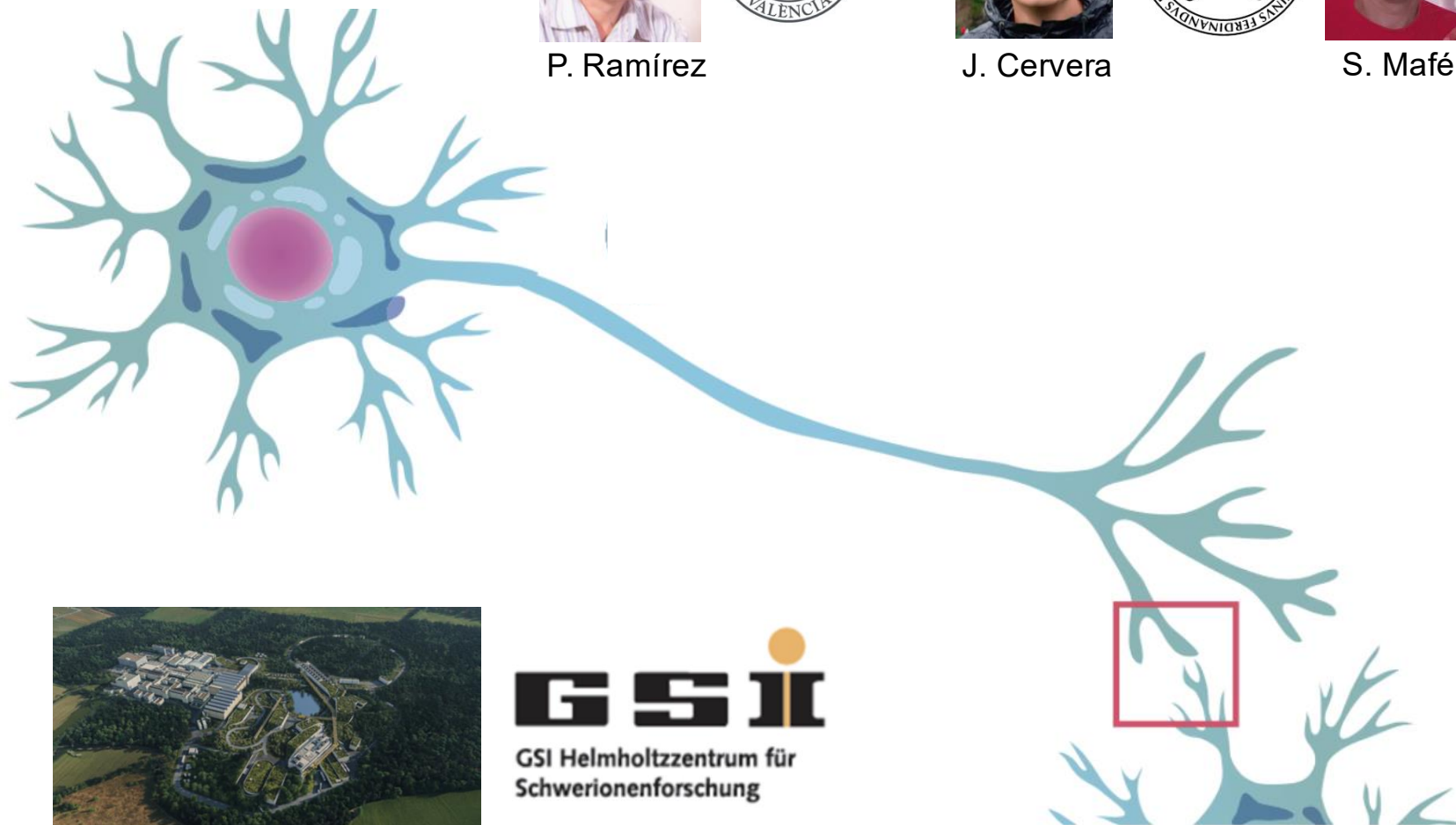
P. Ramírez



J. Cervera

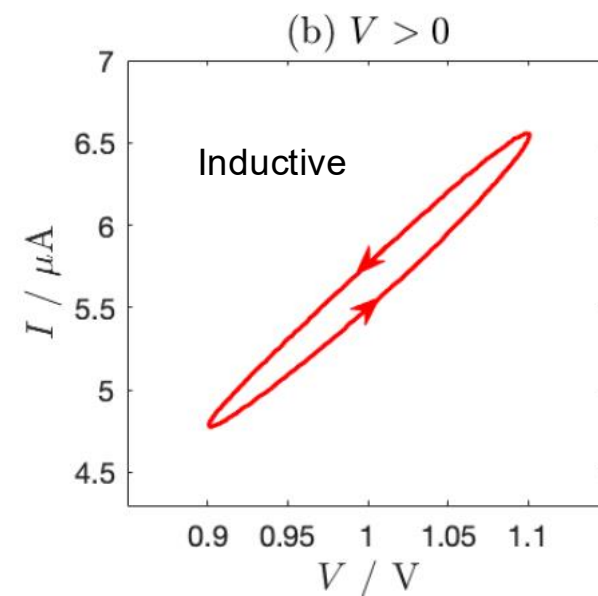
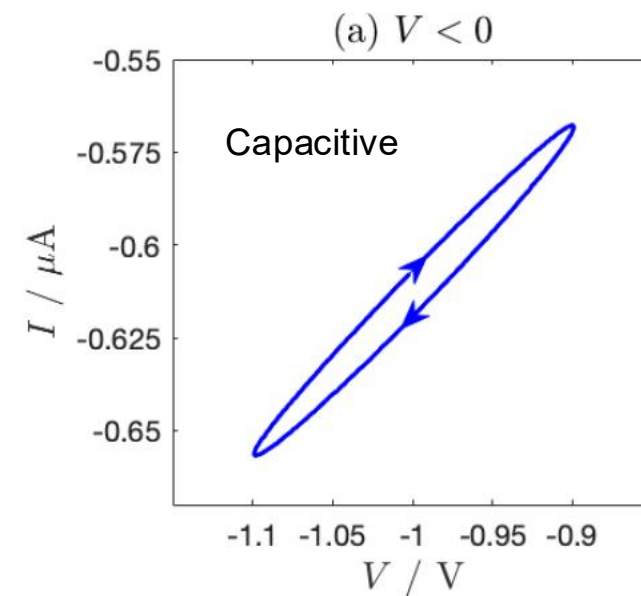
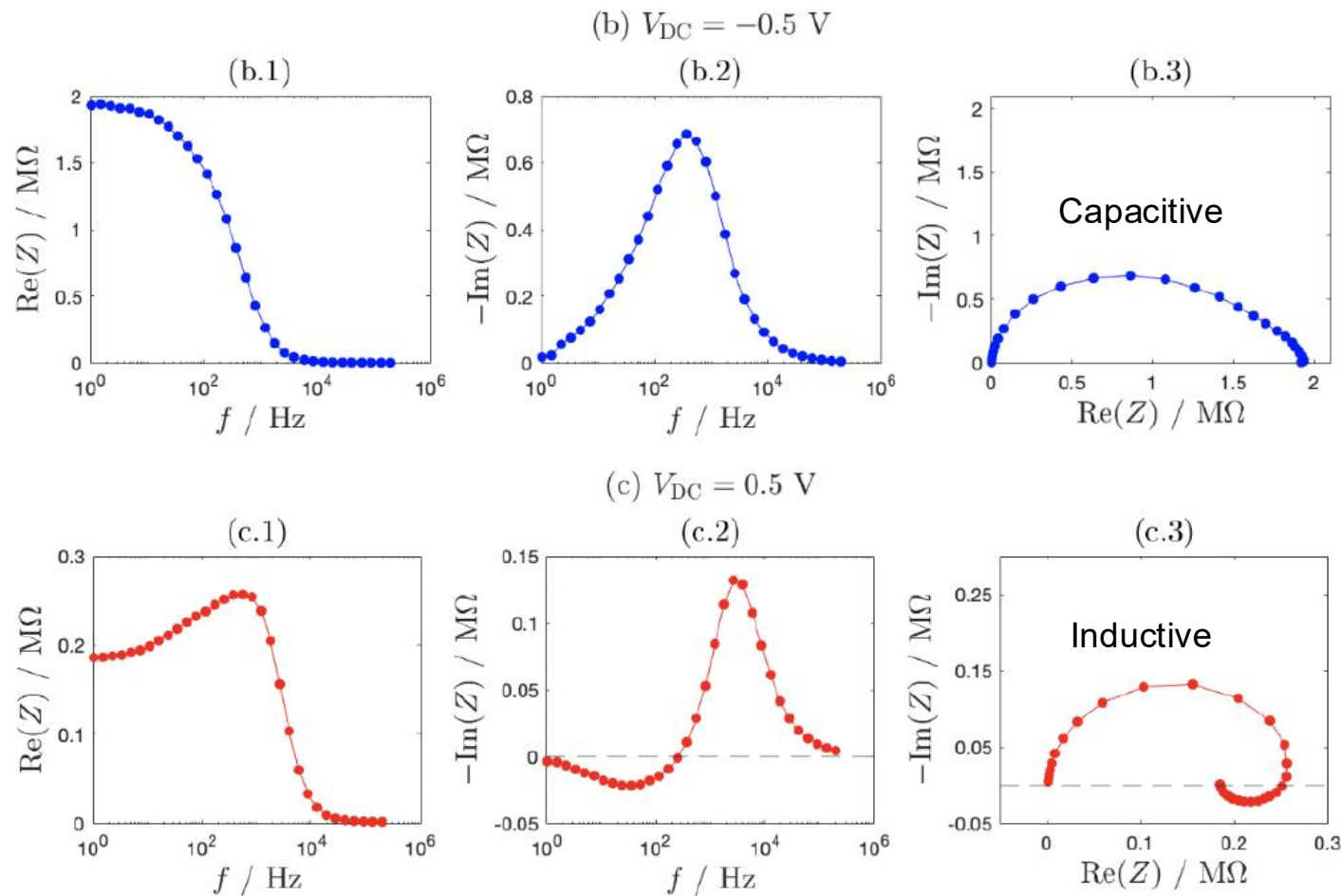


S. Mafé



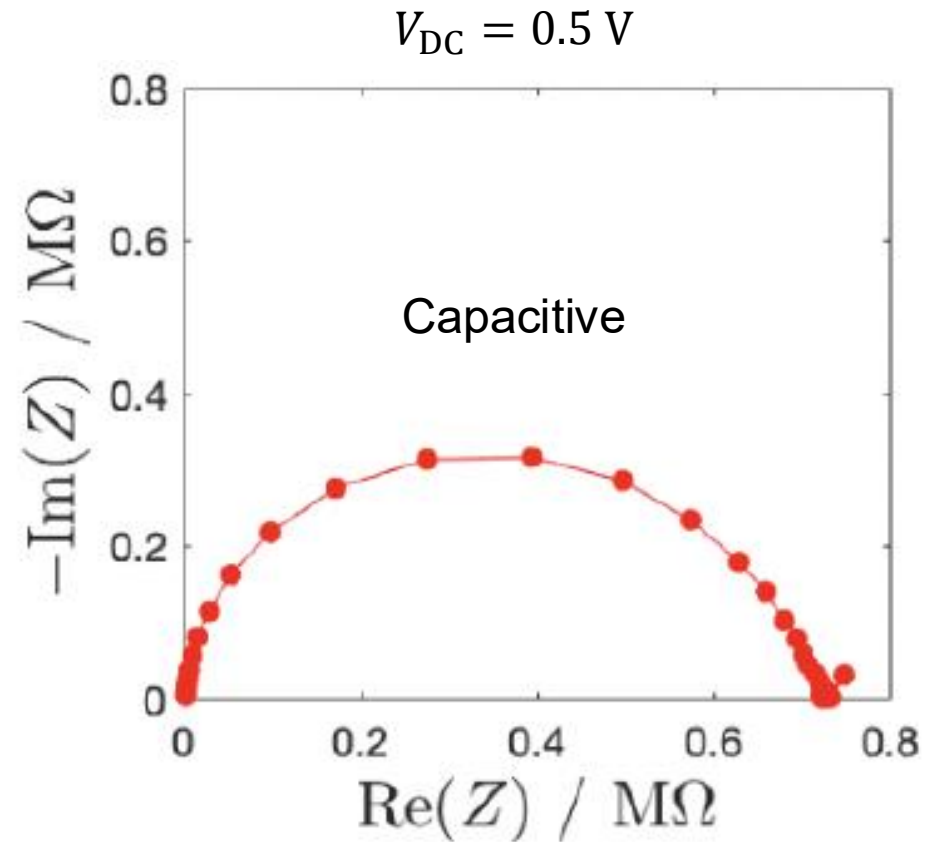
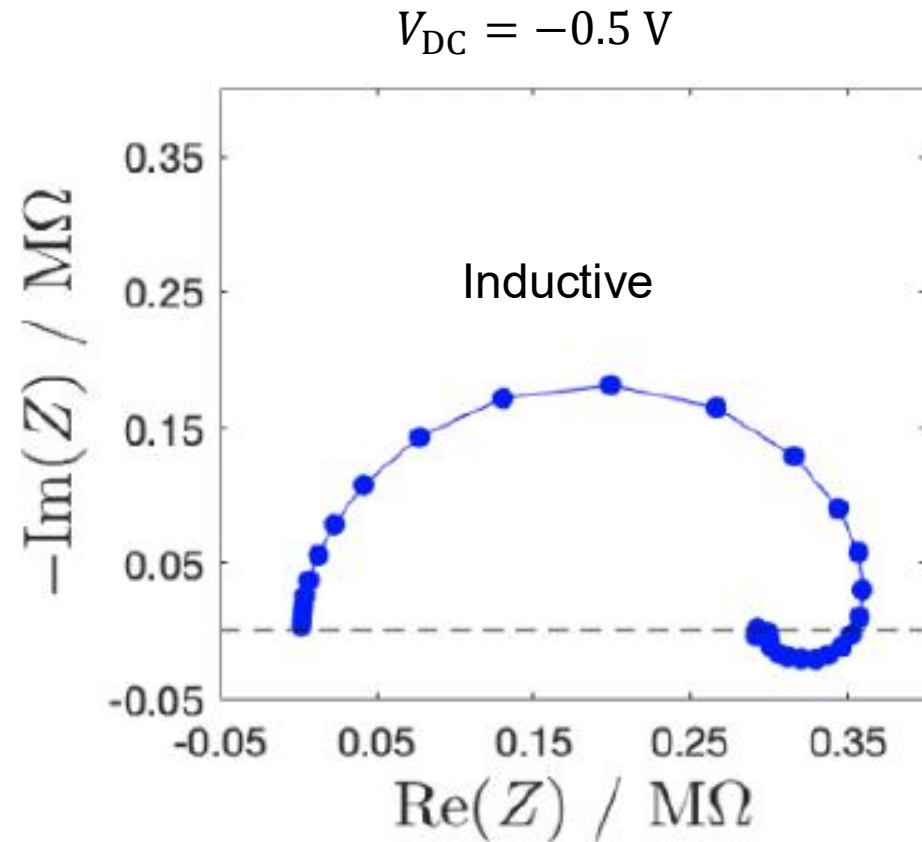
GSI
GSI Helmholtzzentrum für
Schwerionenforschung

Impedance spectroscopy

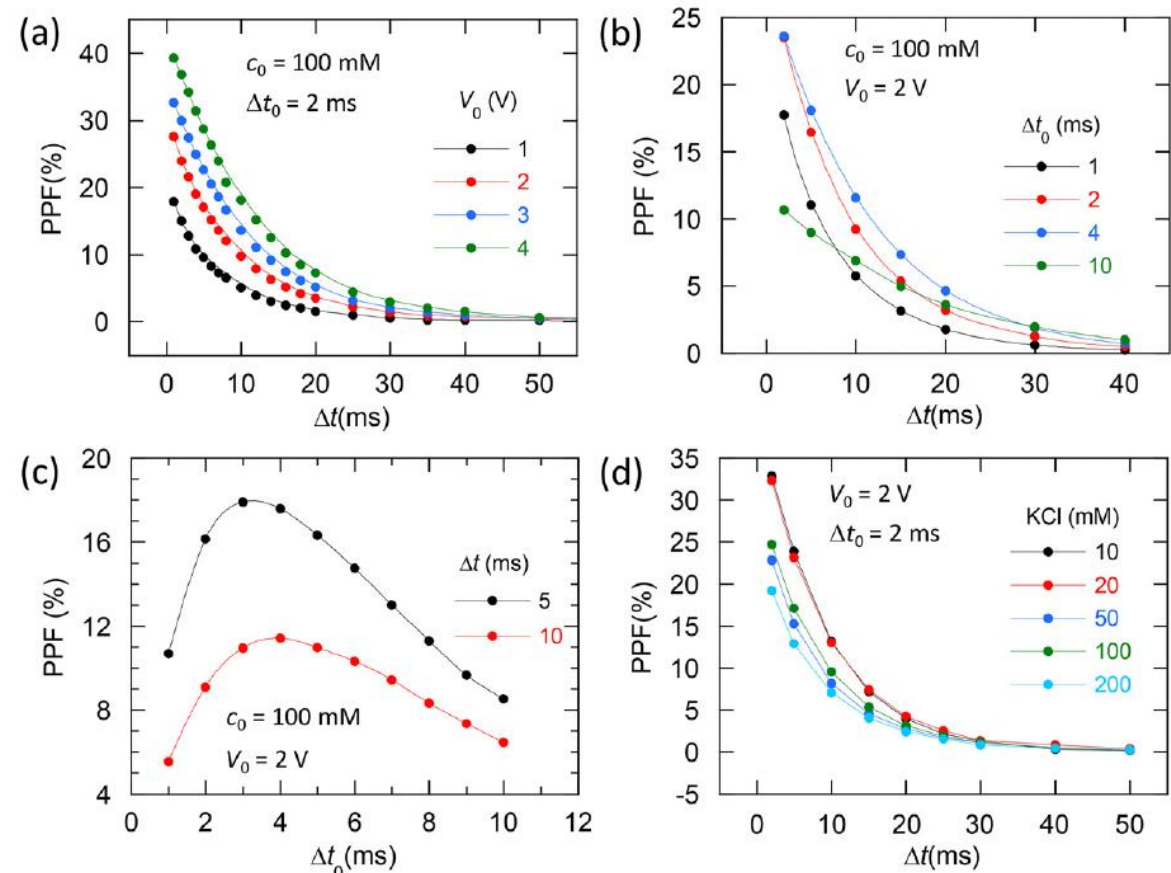
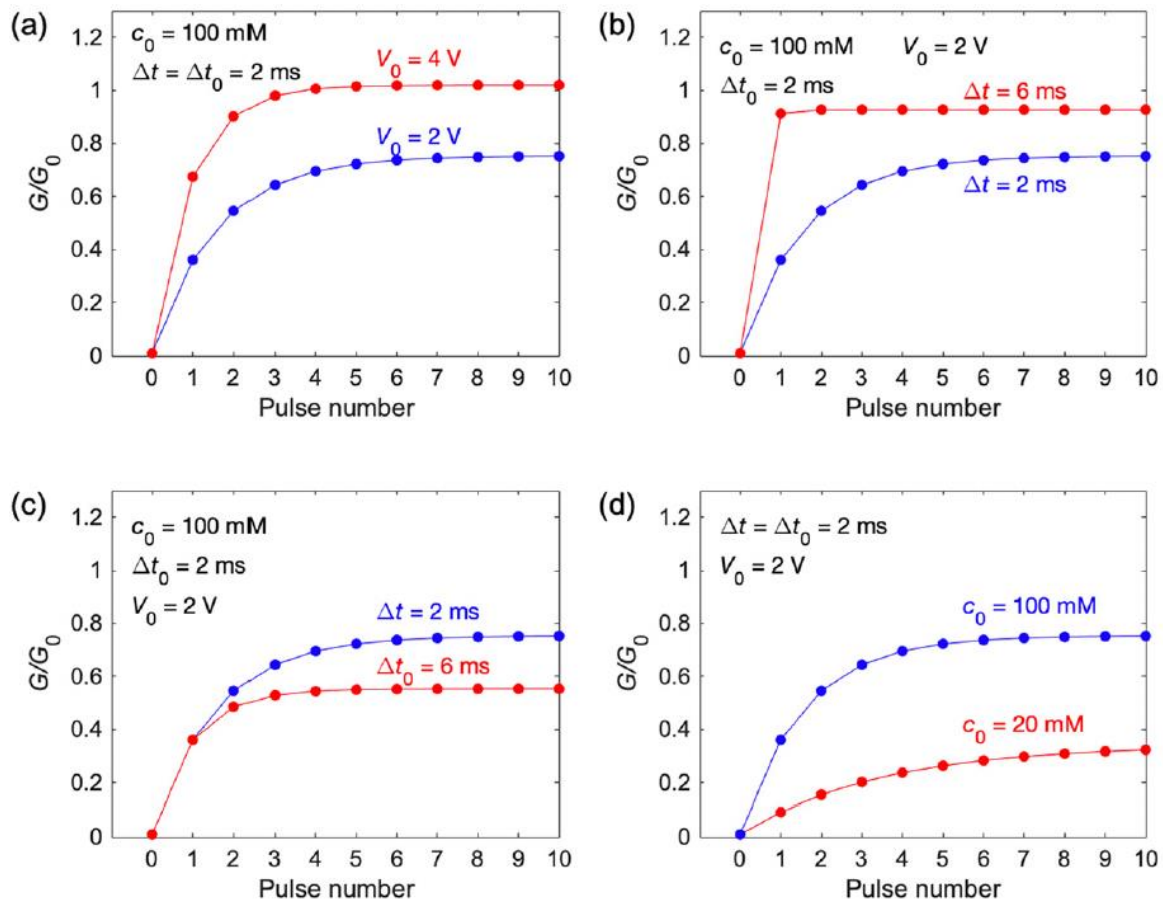


Impedance spectroscopy

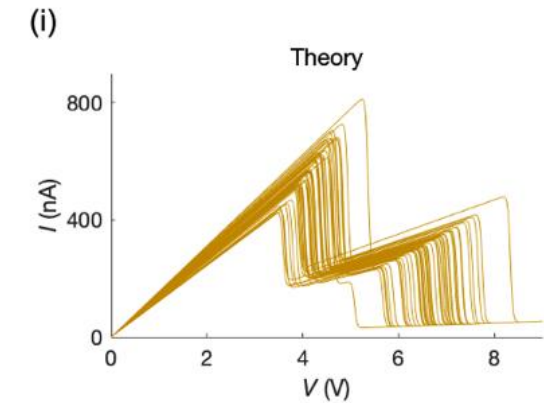
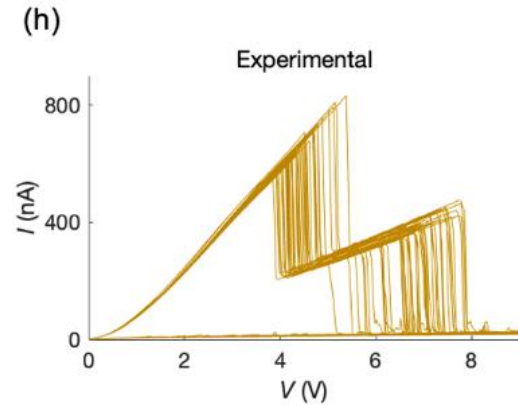
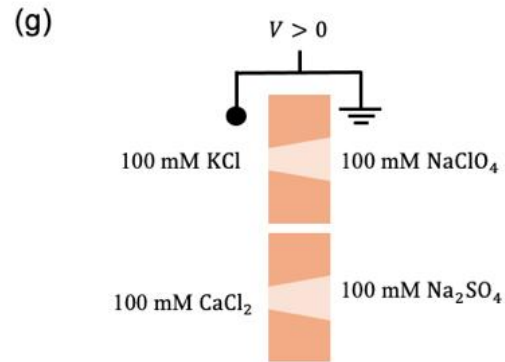
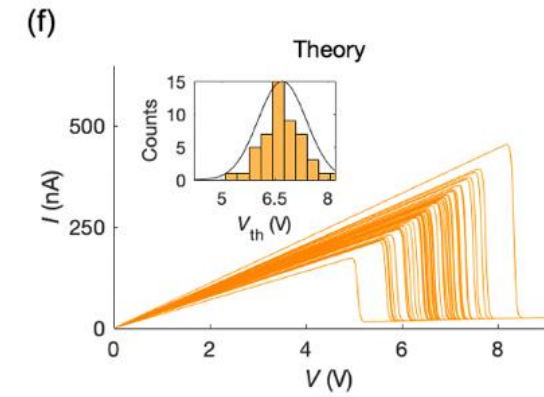
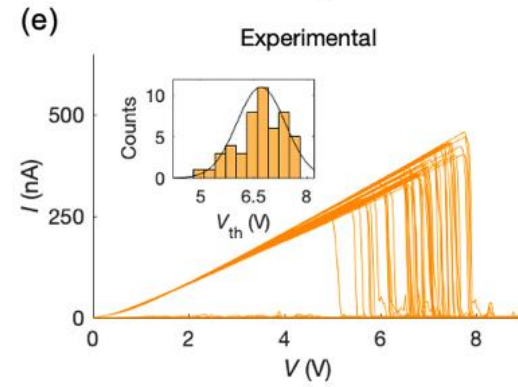
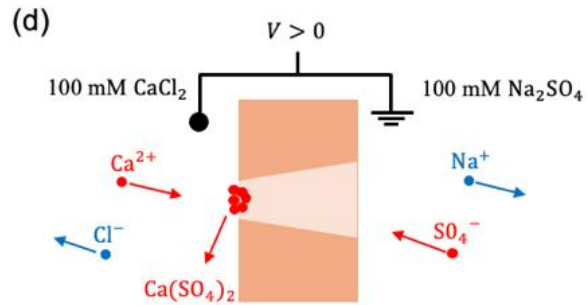
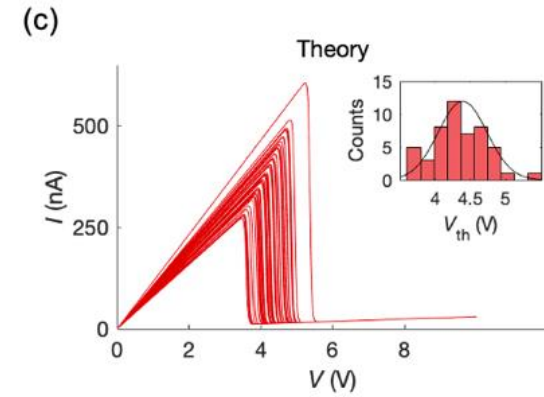
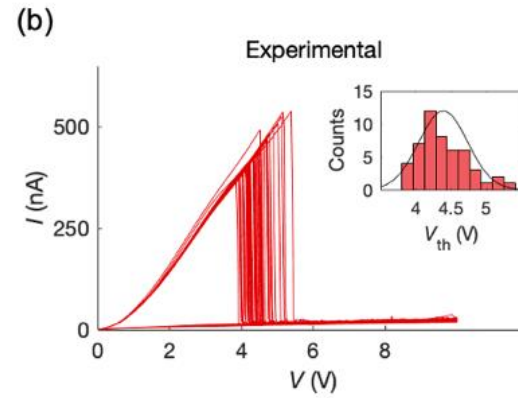
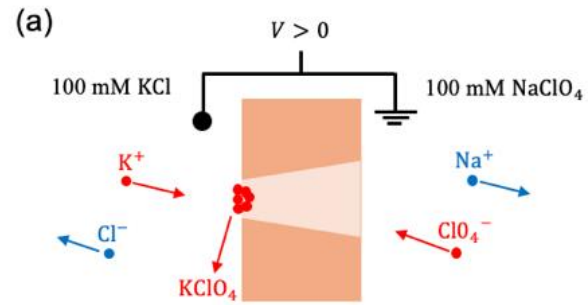
pH = 2 (positive membrane)



Learning phenomena

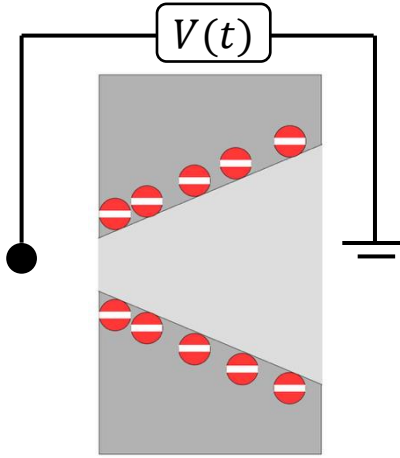


NDR for RC



Descripción teórica del sistema

Transporte iónico a través de un nanoporo cónico con cargas negativas en su superficie al aplicar una señal de voltaje dependiente del tiempo $V(t)$



Ecuaciones de Nernst-Planck:

$$\vec{J}_i = -D_i \vec{\nabla} c_i + D_i z_i c_i (F/RT) \vec{E}$$

Transporte por
difusión

Transporte por
electromigración

- Nanoporo con alta selectividad iónica: solo contribución de los contraiones
- Electromigración domina sobre la difusión

Aproximación de la
densidad de flujo

$$J_i = D_i z_i c_i (F/RT) E$$

Campo eléctrico axial

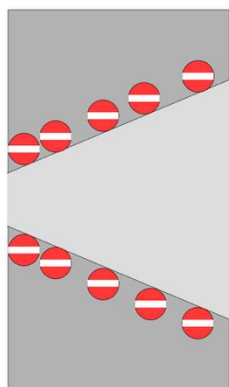
Descripción teórica del sistema

Voltaje constante
 V_0

Sistema asimétrico: dos relajaciones diferentes para $V_0 > 0$ y $V_0 < 0$

Se cumple la ecuación de continuidad: $\frac{\partial c_i}{\partial t} = -\frac{\partial J_i}{\partial x}$

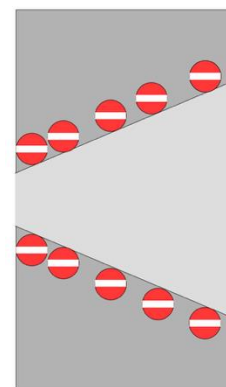
$V_0 > 0$



$$\frac{X_+}{\tau_{+0}} \approx \frac{F}{RT} D c_0 \frac{V_0/L}{L}$$

Concentración de carga fija en la punta
 $X_+ = 2\sigma/Fa_+$

$V_0 < 0$



$$\frac{X_-}{\tau_{-0}} \approx \frac{F}{RT} D c_0 \frac{V_0/L}{L}$$

Concentración de carga fija en la base
 $X_- = 2\sigma/Fa_-$

- Dos tiempos de relajación distintos: τ_{+0} y τ_{-0}
- $\tau_{+0}/\tau_{-0} \sim a_-/a_+ \sim 10 - 100$
- Introducen la asimetría del sistema en el modelo

$$V = V(t) \longrightarrow \tau_{j0} \rightarrow \tau_j(t) \approx \frac{X_j(L^2/D)}{c_0 F V(t)/(RT)} \quad (j = +, -)$$

Relajación de la conductancia:

$$\frac{dG_j(t)}{dt} = -\frac{G_j(t) - G_j^f}{\tau_j(t)}$$