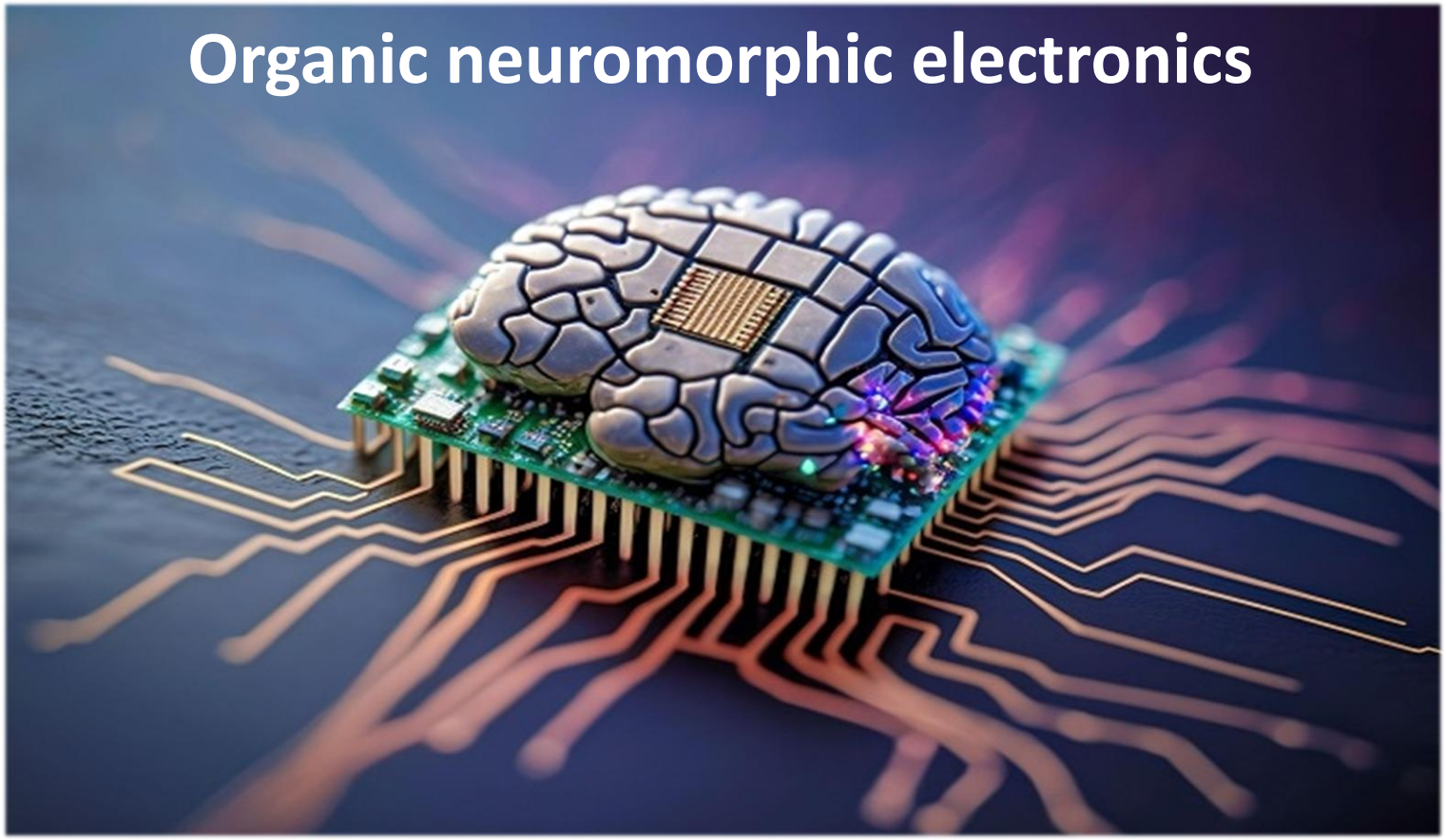
Organic neuromorphic electronics



Paschalis Gkoupidenis
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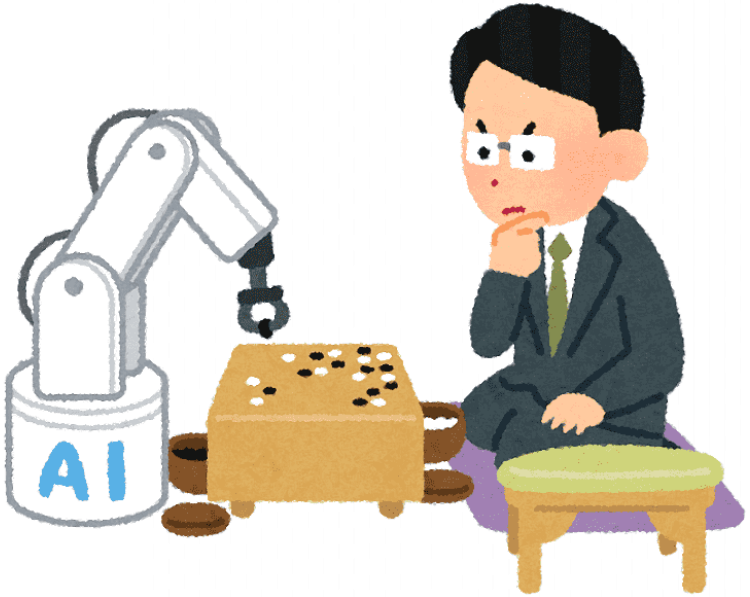
The 20th U.S.-Korea Forum on Nanotechnology, NC State University, Raleigh, Monday, September 14, 2026

Artificial vs biological intelligence

Alpha Go vs **Lee Sedol : 4 - 1 (2016)**

Google DeepMind — WW champion

1920 × CPU, 280 × GPU

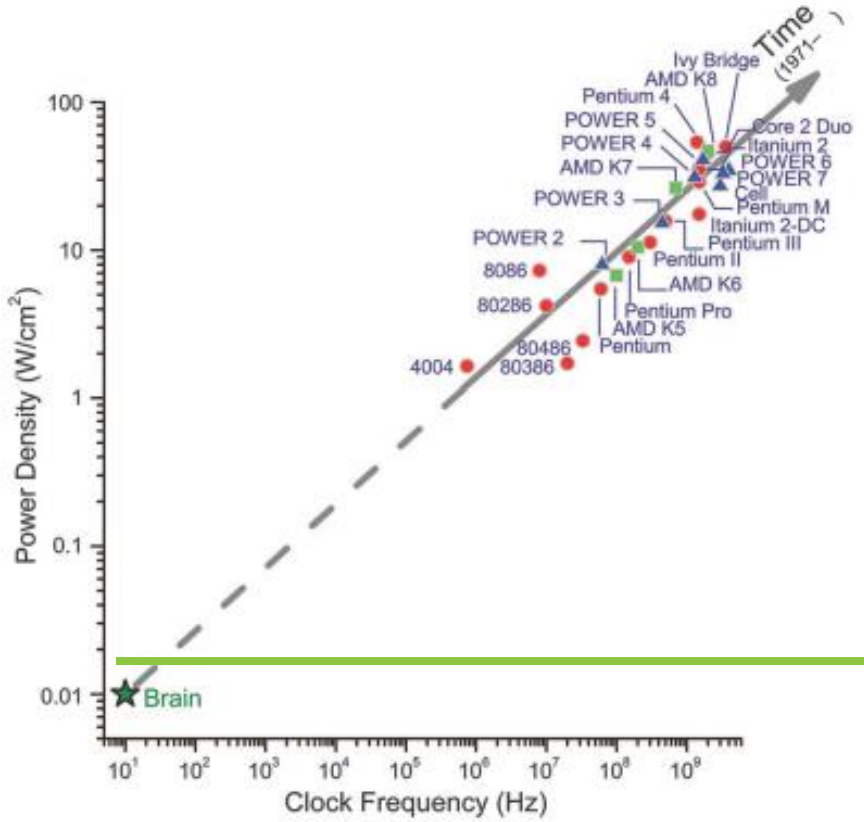


1 × meal

Intelligence benchmarking?

- **AI:** ~20kW, performance-oriented
- **Brain:** ~20W, general purpose
- New ways to emulate the nervous system
- Computational primitives of the nervous system

How about energy efficiency?

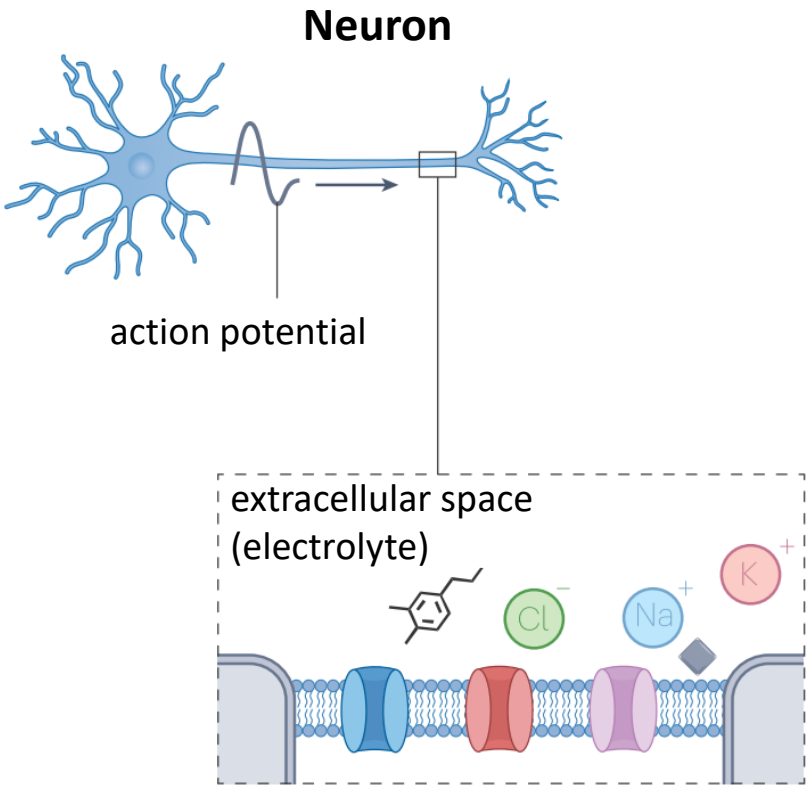


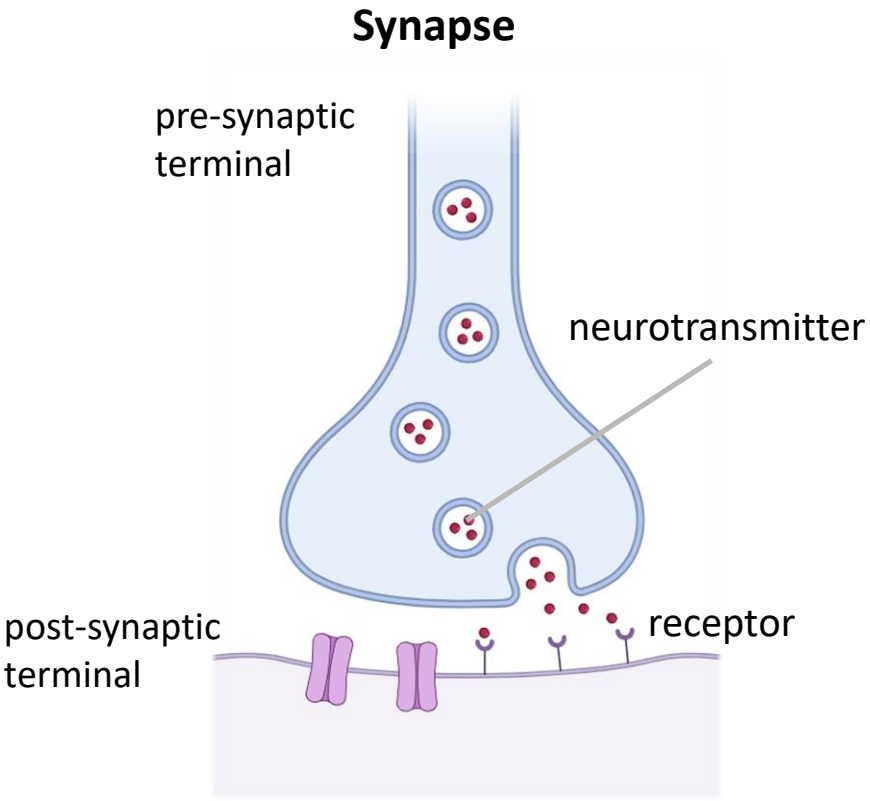
Nuclear energy (power plant) (100-500 W/cm^2)

ion battery, solar energy, wind, natural gas, geothermal (<0.02 W/cm^2)

P. A. Merolla et al., Science 345 (6197), 668-673 (2014).

How about diversity?





- Alkaline ions
- Common electrochemical environment

- Electrochemical carriers of “information”
- Receptors for recognition

How about embodiment?

LLMs

ChatGPT

The hardware

~$50 \cdot 10^4$ × GPUs
Avg. energy (training or inference) ~ GWh (~$M)
Google search < ChatGPT energy < Crypto mining

nature human behaviour

Comment | Published: 20 November 2023

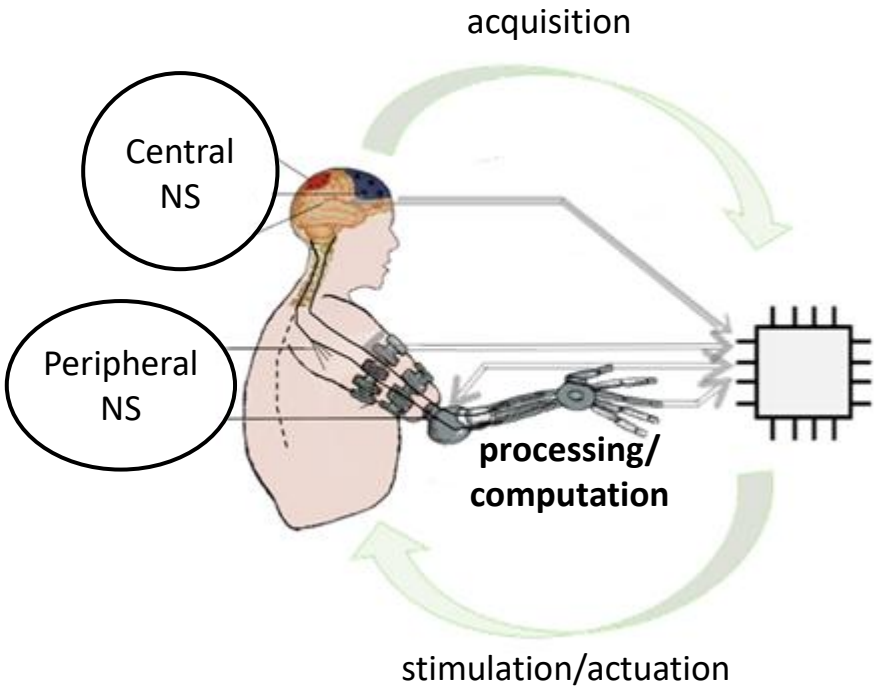
LLMs differ from human cognition because they are not embodied

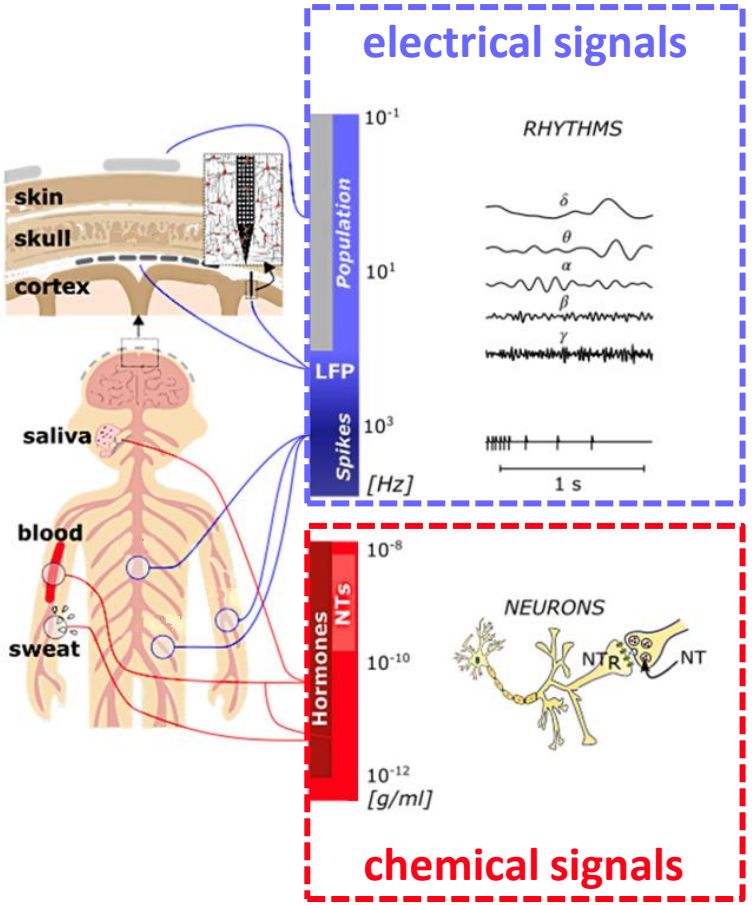
Anthony Chemero

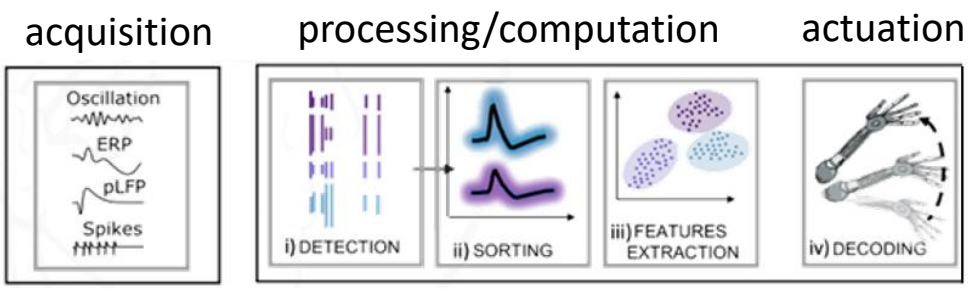
Nature Human Behaviour **7**, 1828–1829 (2023) | Cite this article

- Reading/writing recent in evolution
- Human-centric communication
- Living organisms are embodied
- Many ways to interact with our world

Bioelectronics: interaction with the world

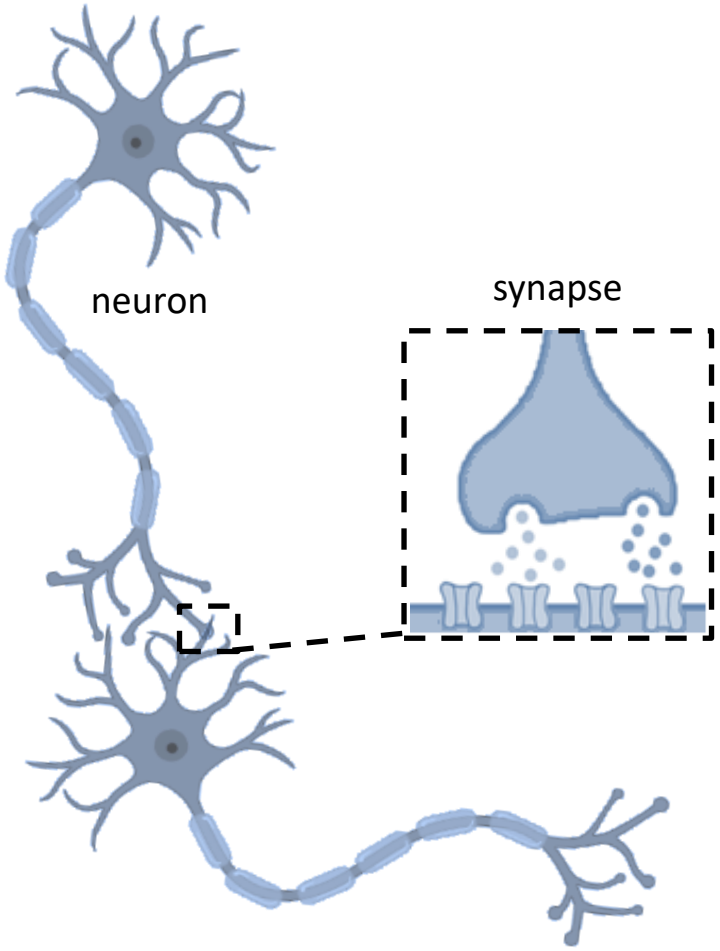






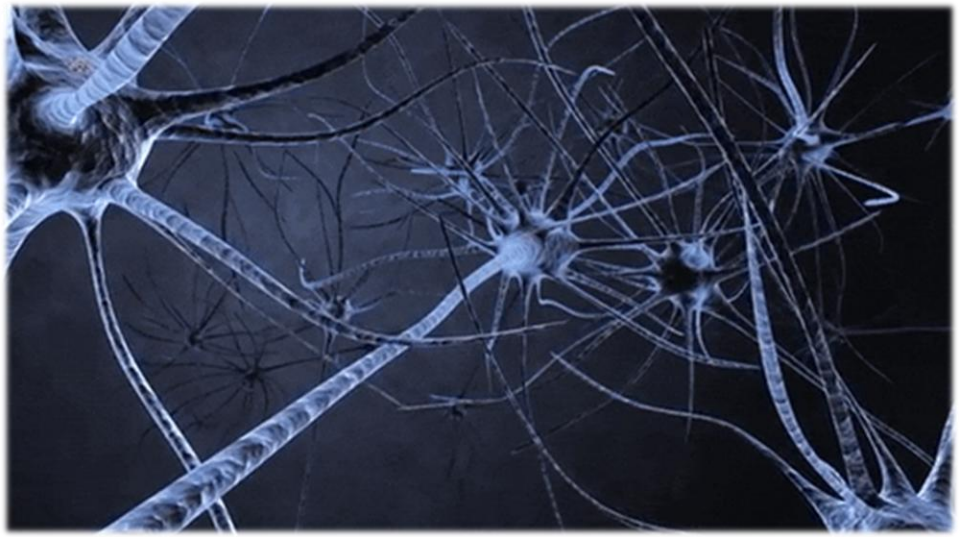
I. Tzouvadaki et al., Adv. Mat. 2210035 (2023). | M. Cucchi et al. Adv. Mat. 2209516 (2023). | I. Krauhausen et al., Adv. Funct. Mater. 2307729 (2023).

The brain: model for biomimicry

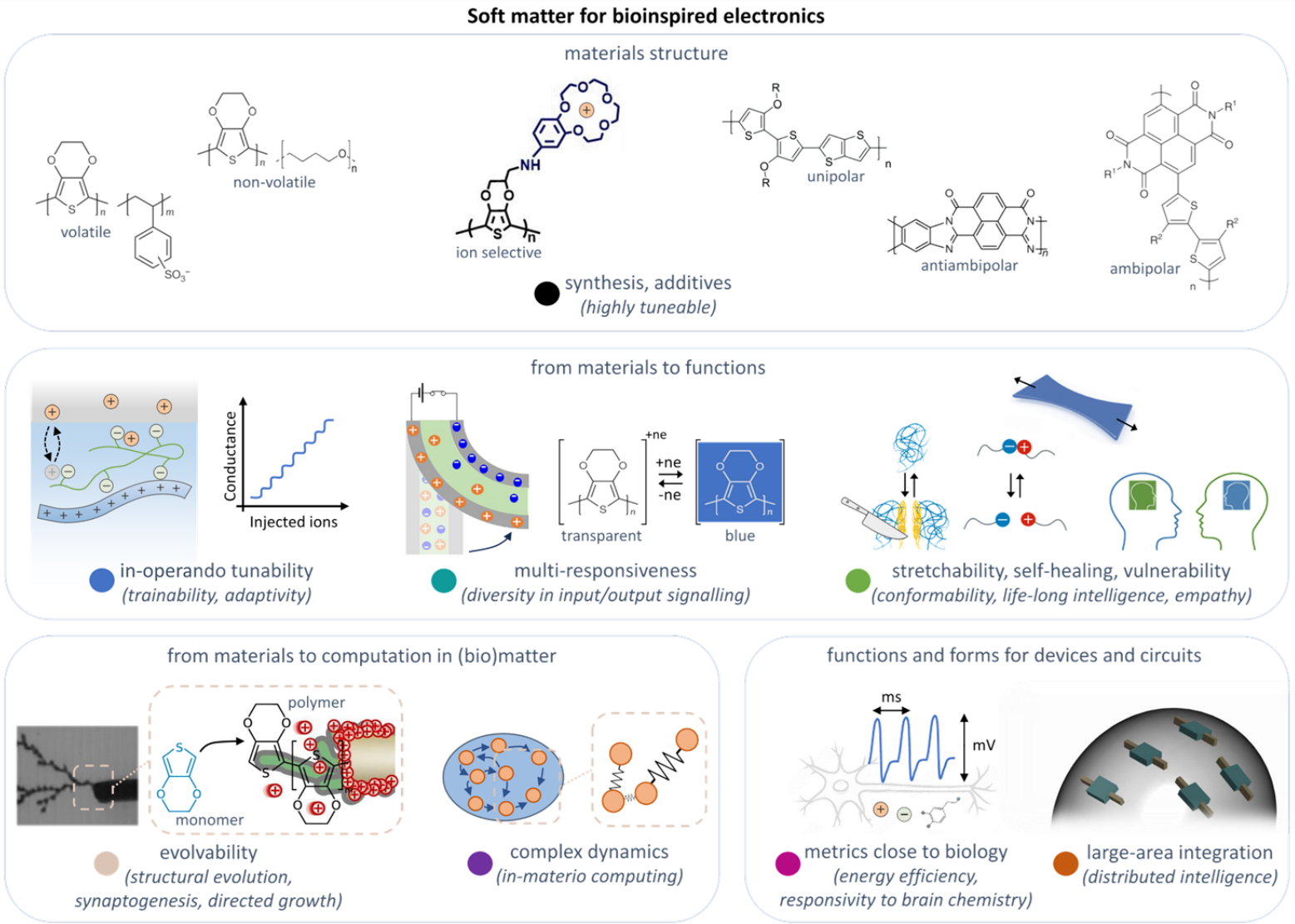


- **Neurons** → produce, process and transmit electrical impulses (computation)
- **Synapses** → Adjust the connectivity between the neurons (memory)

- **+ Sensing** → Physical interactions (bridging artificial to biological)

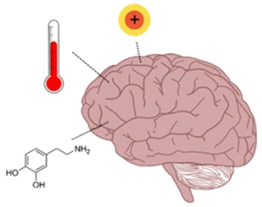


Soft matter for bioinspired electronics



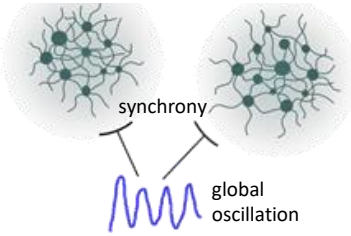
P. Gkoupidenis et al., Nat. Rev. Mater. 9 (2), 134-149 (2024).

Background: past research



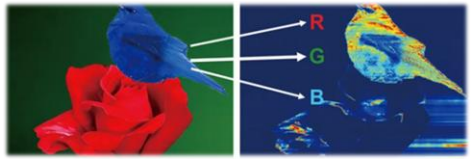
connectivity & homeostatic control

Nat. Commun. 8, 15448 (2017).
MRS Commun. 5, 1 (2018).
Adv. Funct. Mater. 31, 22 (2021).



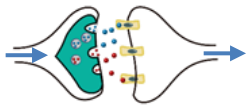
synchronization

Adv. Intell. Sys. 1, 1900013 (2019).



visuomorphic computing

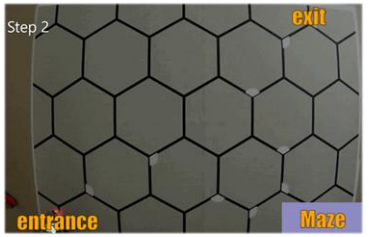
Sci. Rep. 6, 27007 (2016).
AIP Adv. 6, 111307 (2016).
Adv. Mat. 2208497 (2023).

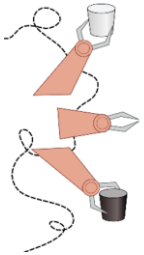


artificial synapses

Adv. Mat. 27, 7176–7180 (2015).
Appl. Phys. Lett. 107, 263302 (2015).

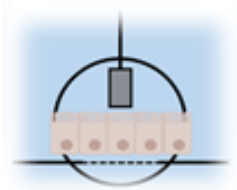
Organic (neuromorphic) electronics





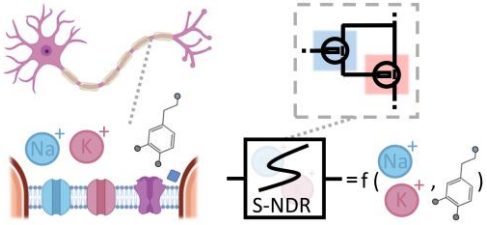
sensorimotor learning in robotics

Sci. Adv. 7, 50 (2021).
Nat. Commun. 15, 4765 (2024).



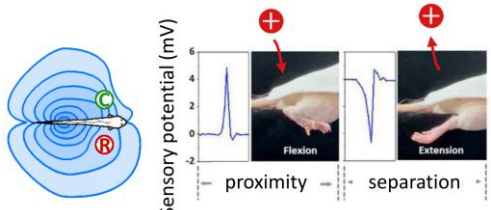
(bio)sensing

Adv. Health. Mat. 1901215 (2019).
Nat. Commun. 11, 3743 (2020).
Adv. Mat. Techn. 2000940 (2021).



in-vitro neuromorphic sensing/biointerfacing

Nat. Electr. 5, 774 (2022). | Nat. Electr. 5, 721 (2022). | Nat. Commun. 15, 5350 (2024).

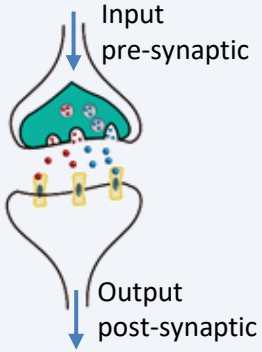


in-vivo sensorimotor restoration & augmentation

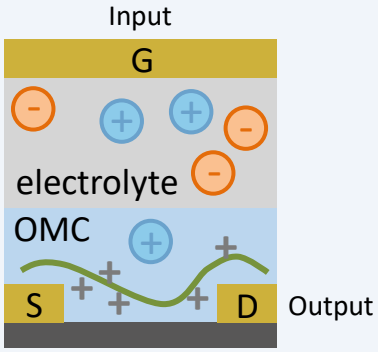
Sci. Adv. 8, 43 (2022)...

Synaptic plasticity in organic transistors

Analogy

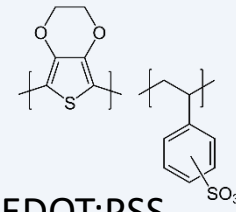


biological synapse



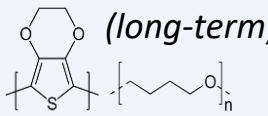
artificial synapse

Materials

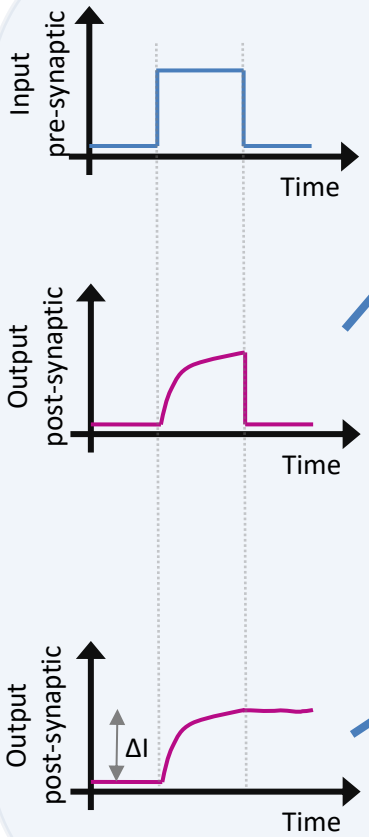


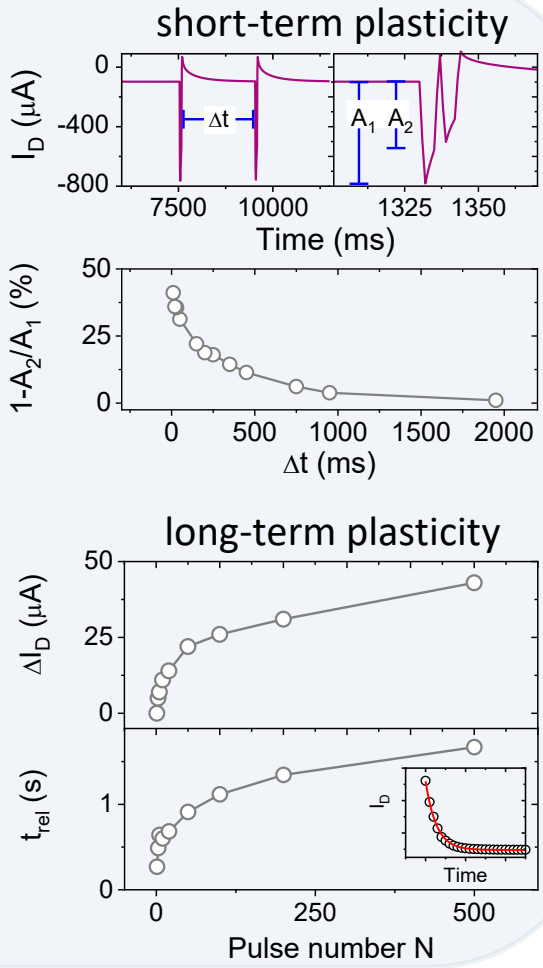
PEDOT:PSS
(short-term)

PEDOT:PTHF
(long-term)



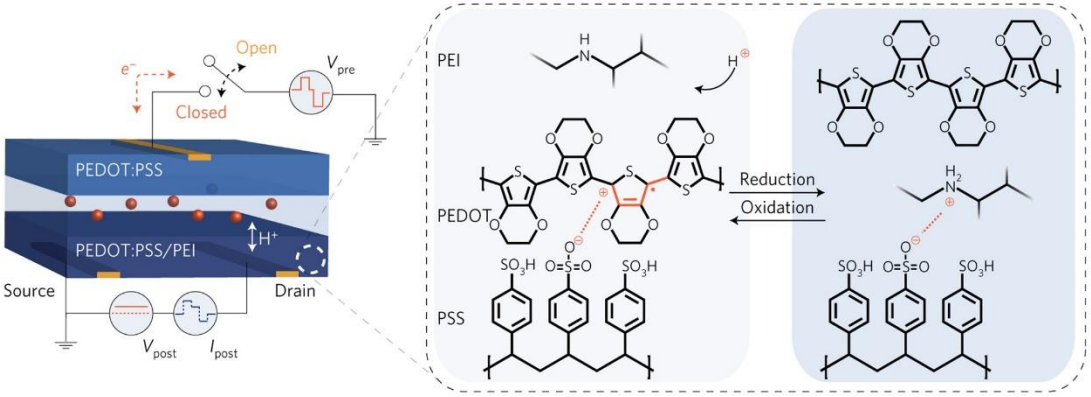
Plasticity functions

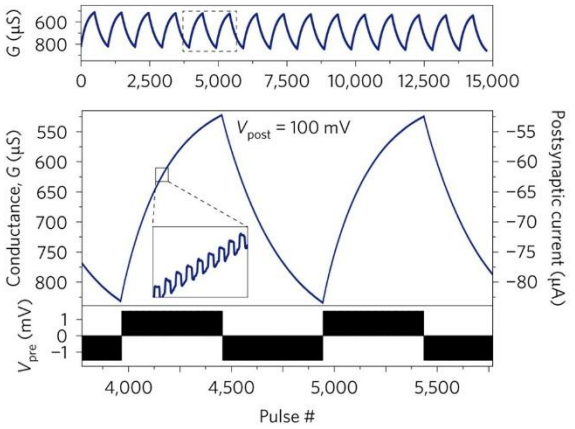




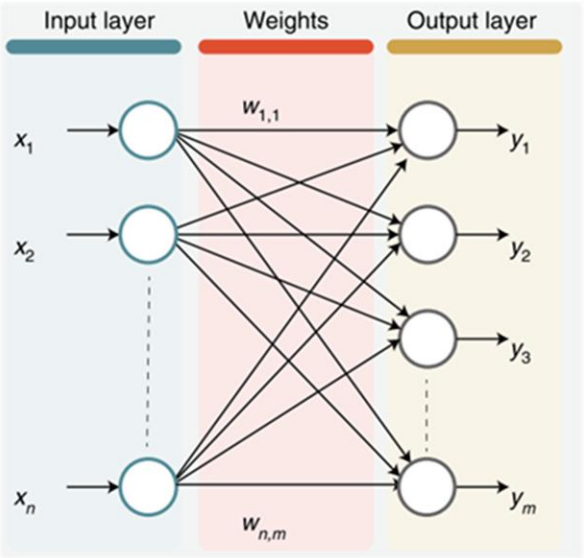
P. Gkoupidenis et al., Adv. Mat., 27, 7176–7180 (2015). I P. Gkoupidenis et al., Appl. Phys. Lett. 107, 263302 (2015).

Synaptic plasticity



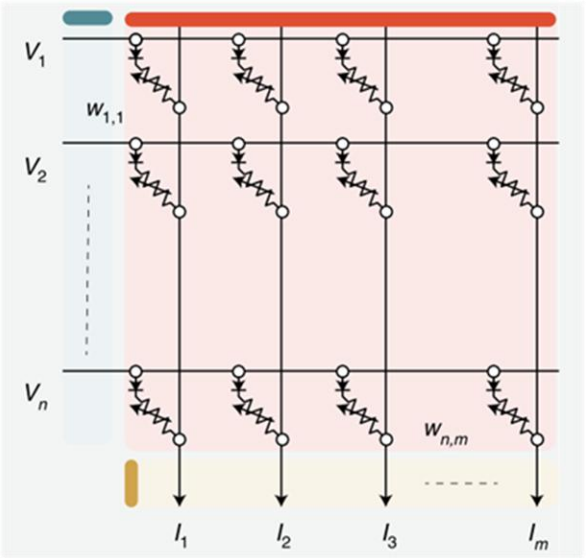


ANN



$$y_m = \sum_n w_{n,m} \cdot x_n$$

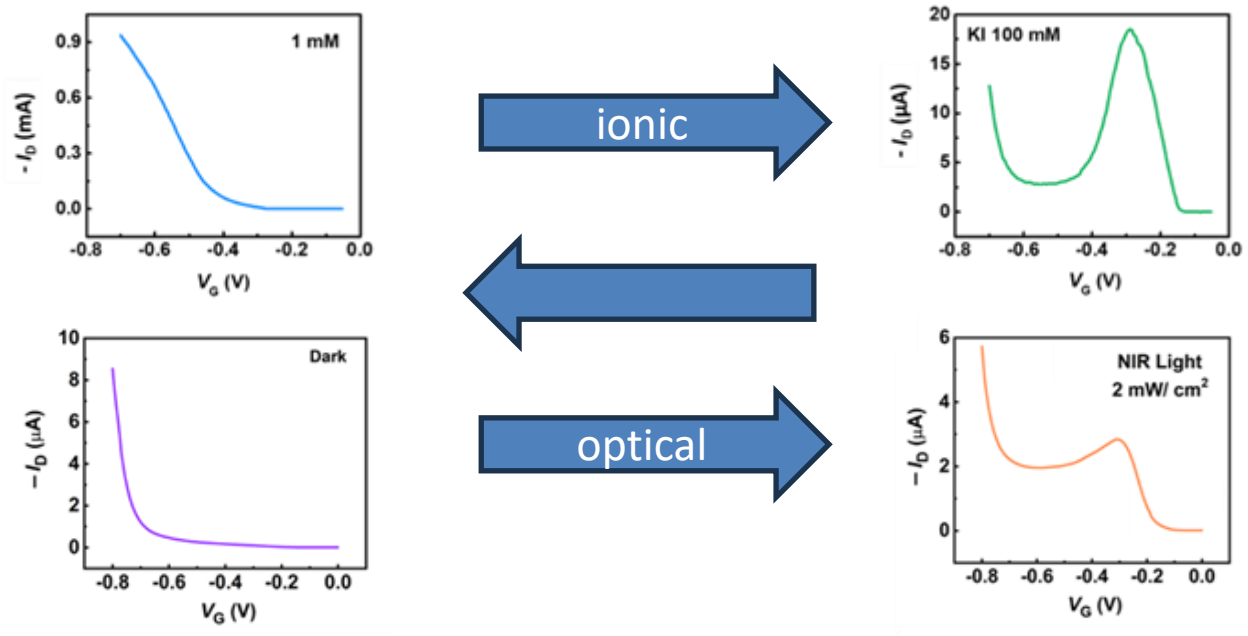
Cross - bar array

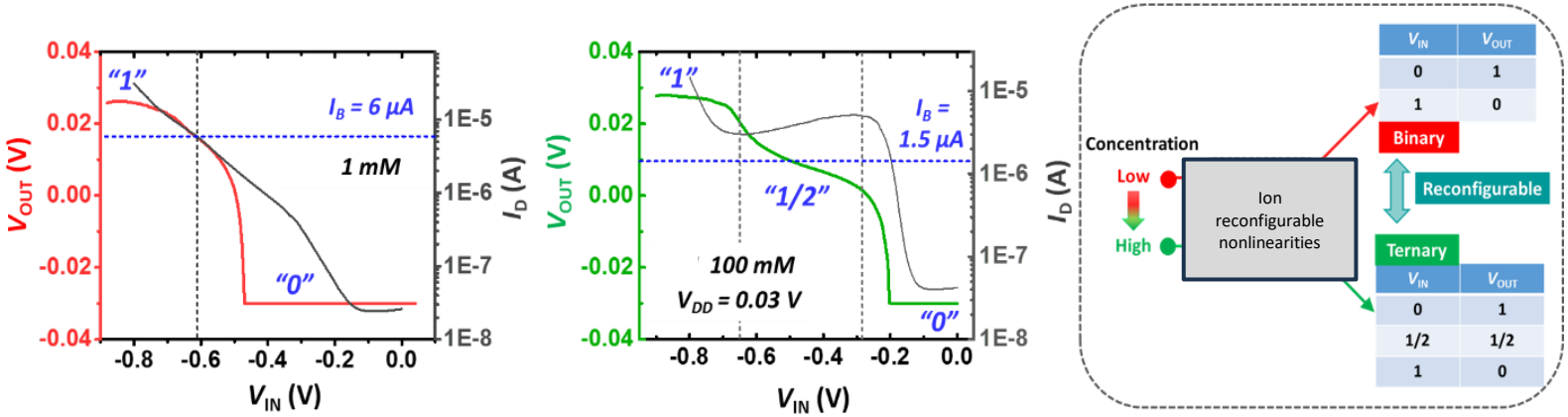


$$I_m = \sum_n G_{n,m} \cdot V_n$$

Y. van de Burgt et al., Nat. Mater. 16, 414 (2017). | E. J. Fuller et at., Science (364) 6440, 570 (2019).

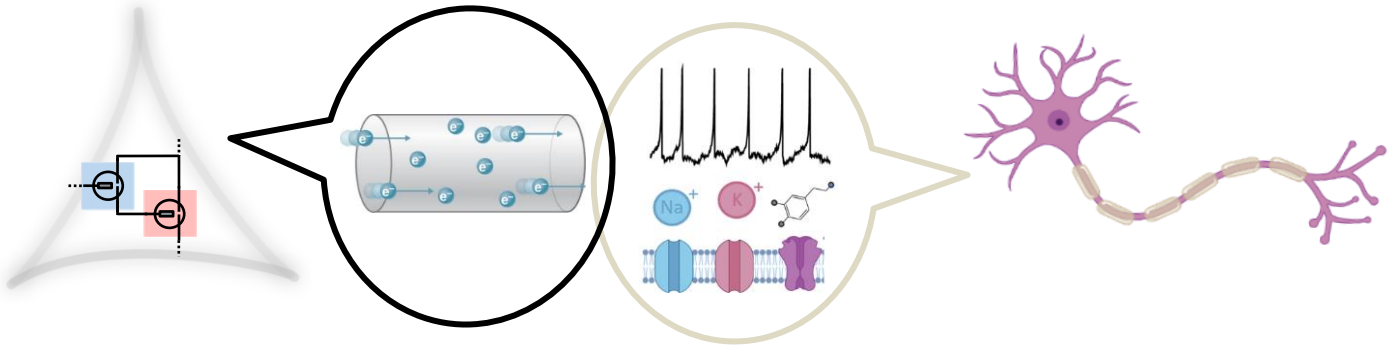
Ion-reconfigurable nonlinearities





D. Panigrahi et al., Adv. Mater. e16684 (2026). | D. Panigrahi et al., Adv. Funct. Mater. 36 (27), e25271 (2026).

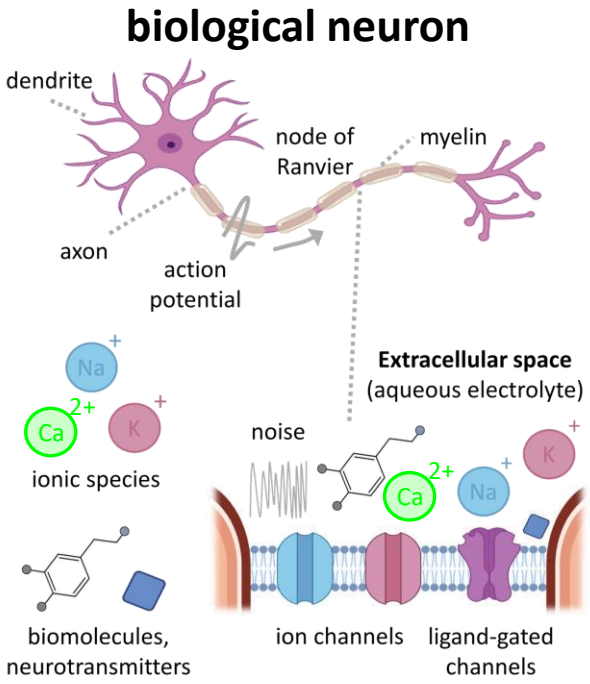
Seamless bio-interfacing

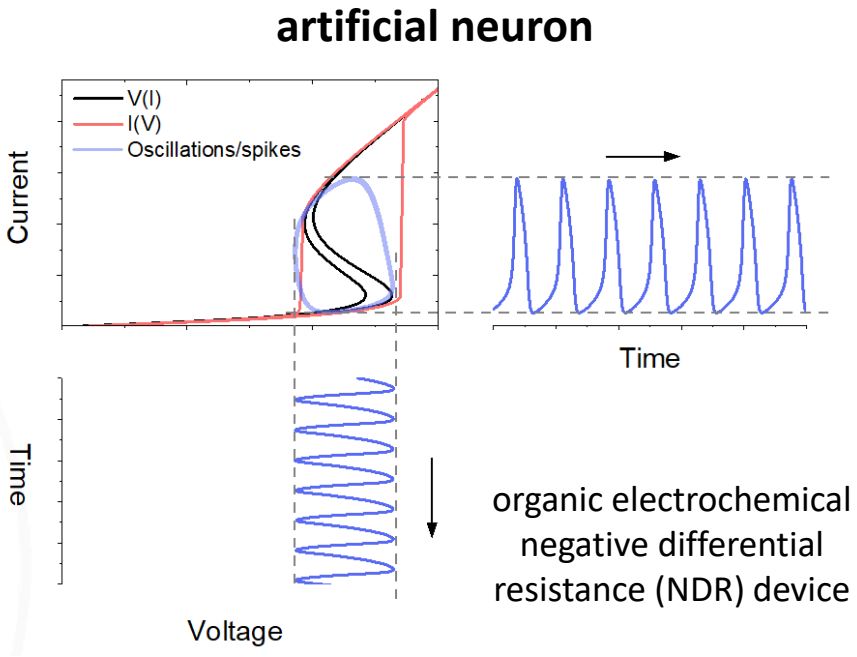


Need for naturalistic communication: electronics that speak the biological language

E. R. W. van Doremaele et al., J. Mater. Chem. C (2019). 2020). | Y. van de Burgt et al., MRS Bull. 8, 631 (2020).
C. Lubrano et al., MRS Commun. 10, 3 (2020). | P. Gkoupidenis, Nat. Electr. 5, 721 (2022).

Diversity in organic artificial neurons



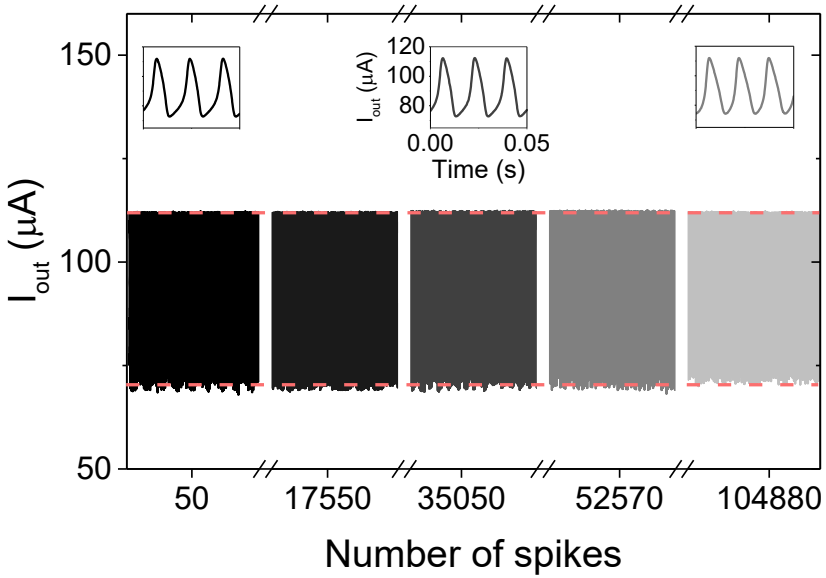


- *In situ* operation in biological environments; **electrolytes, ions, neurotransmitters…**
- Diverse spiking
- Biocompatibility

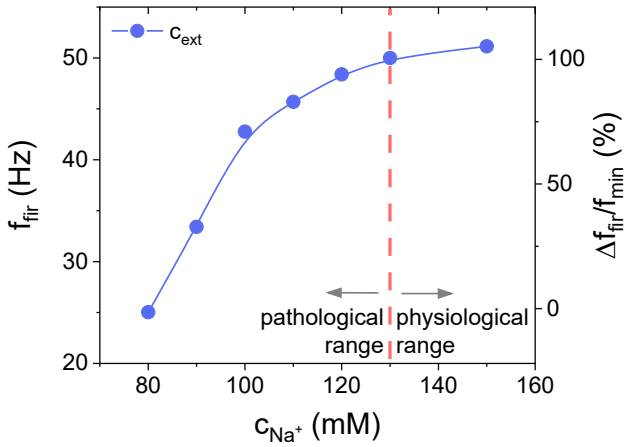
P. Romele et al., Nat. Commun. 11, 3743 (2020). | T. Sarkar et al., Nat. Electr. 5, 774 (2022). | P. Gkoupidenis, Nat. Electr. 5, 721 (2022).

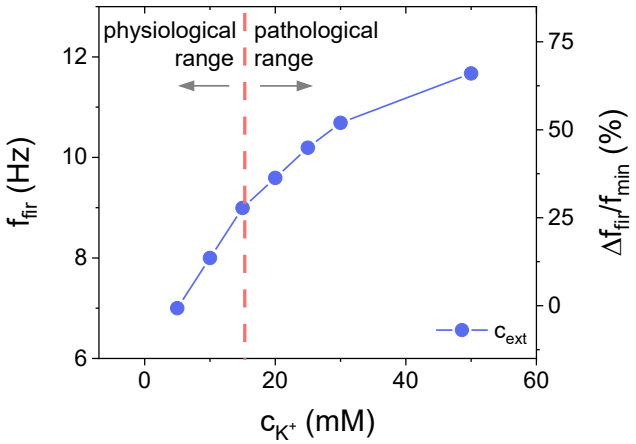
Basic spiking properties

- Spiking and endurance (>10^5 spikes)



- Common physiopathological conditions



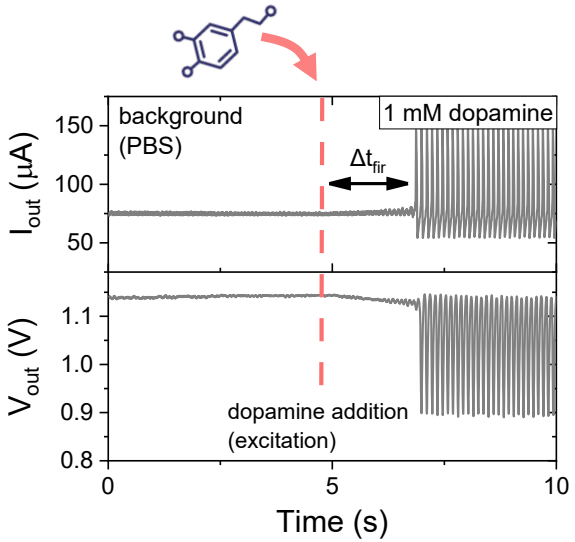


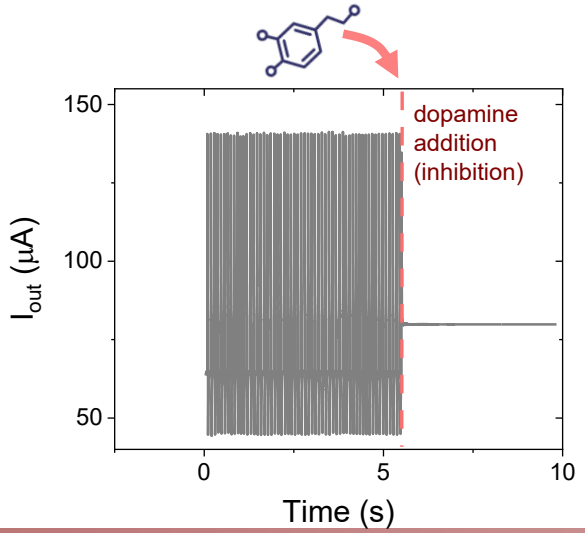
- Stable iono-electronics with metrics close to the biological regime

T. Sarkar et al., Nat. Electr. 5, 774 (2022). | P. Belleri et al., Nat. Commun. 15, 5350 (2024).

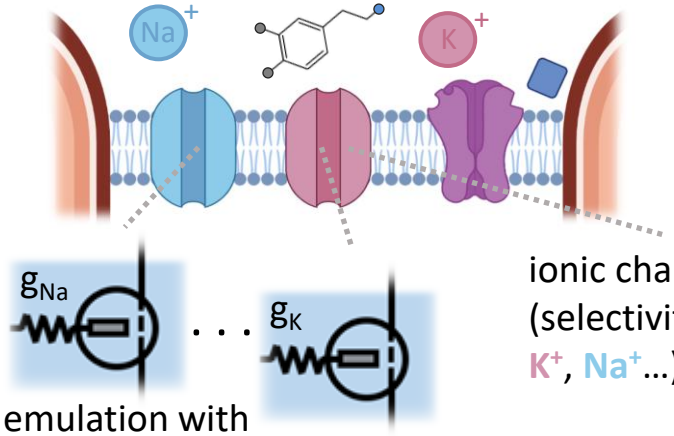
Biophysical realism: NTs & ion channels

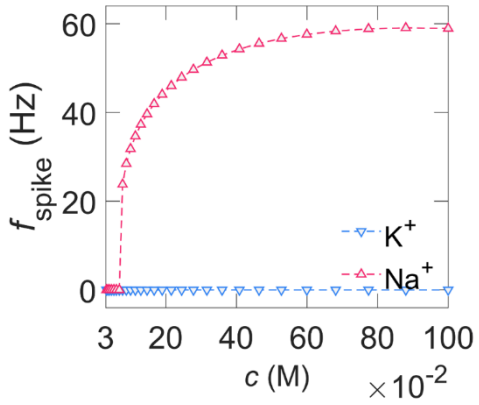
Dopamine (NT) excitation/inhibition



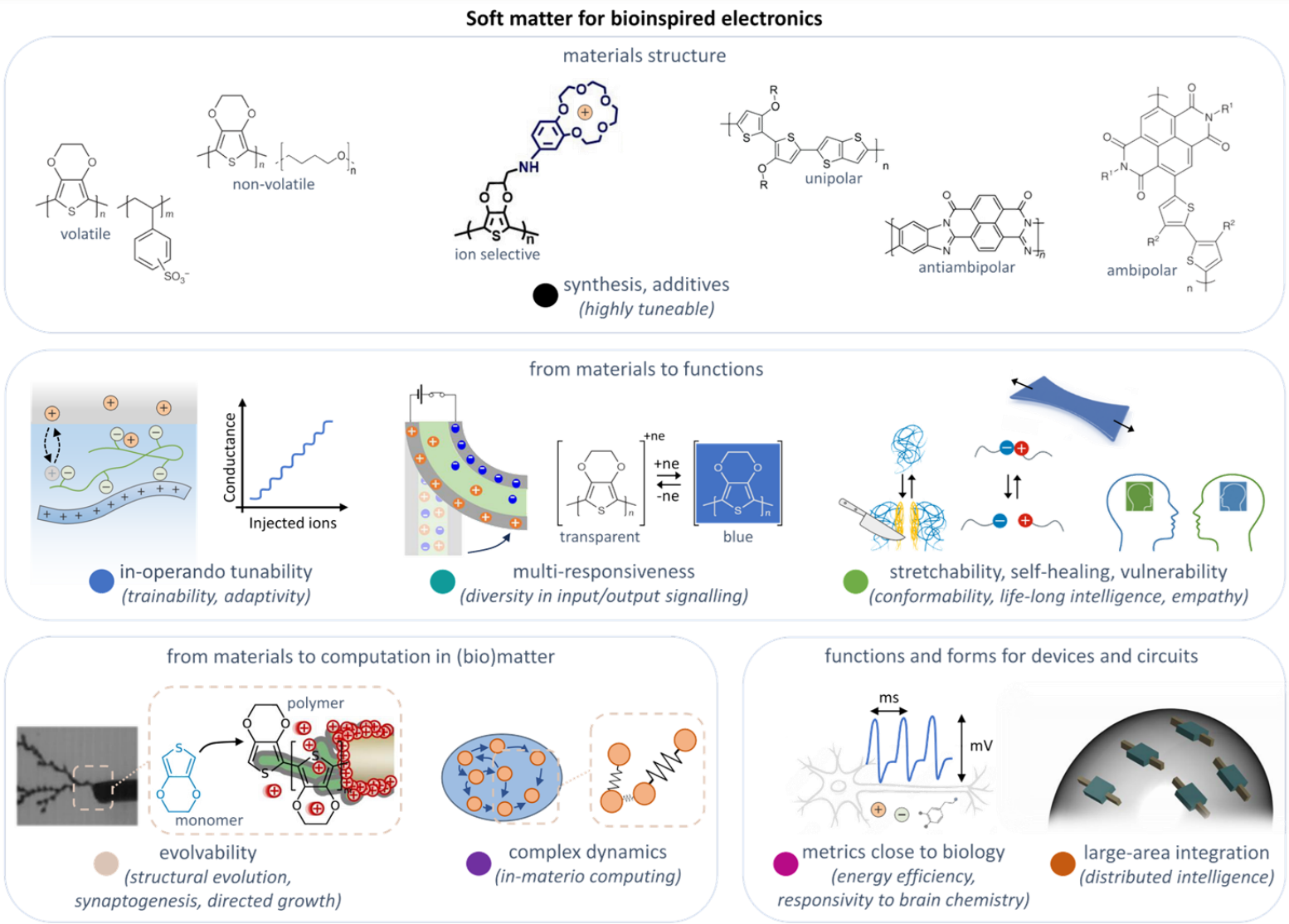


Ion channel dynamics





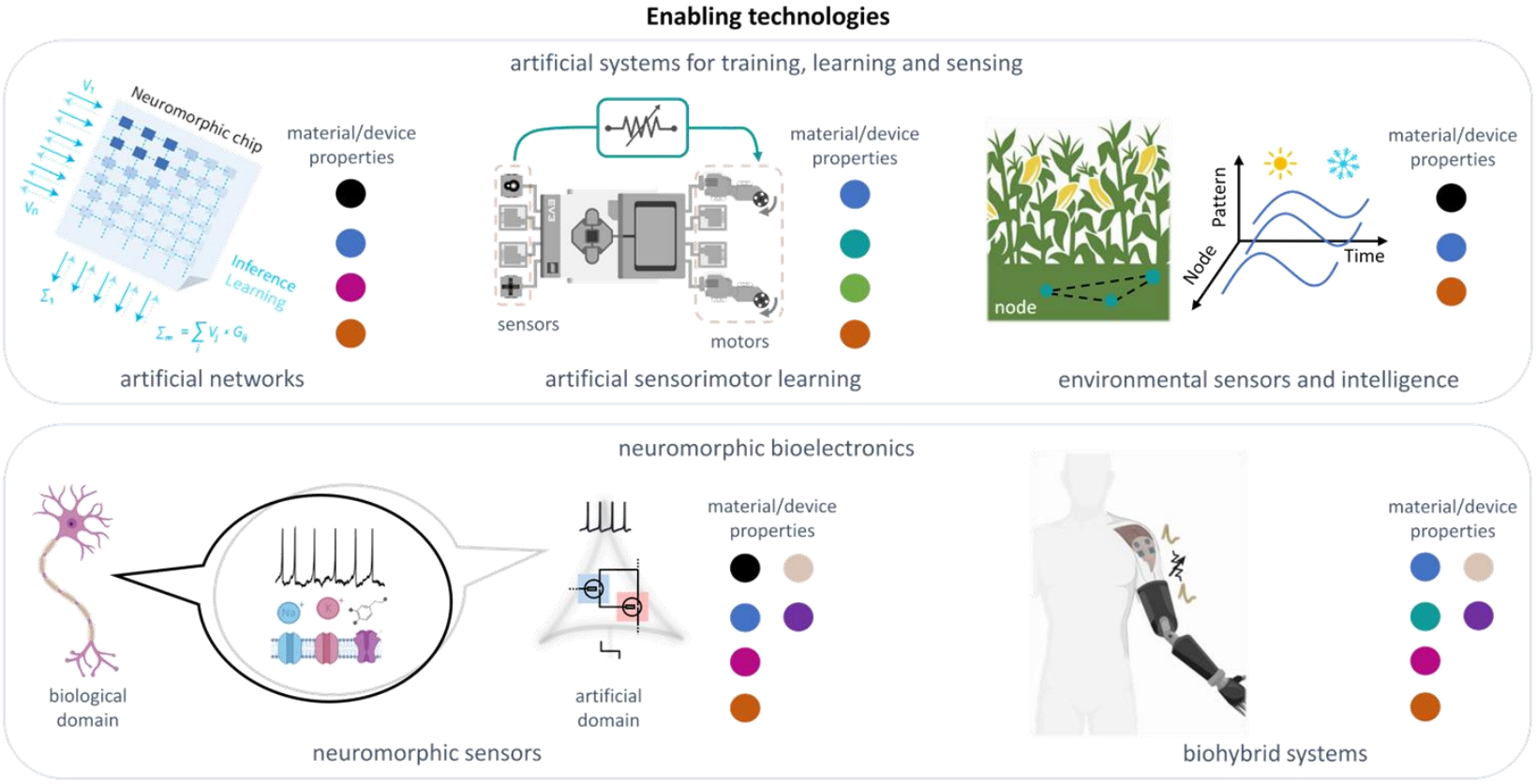
Future



P. Gkoupidenis et al., Nat. Rev. Mater. 9 (2), 134-149 (2024).

Future

- Applications: diverse forms of intelligence everywhere



P. Gkoupidenis et al., Nat. Rev. Mater. 9 (2), 134-149 (2024).

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Emergent Algorithmic Intelligence

Carl Zeiss Stiftung

DARPA

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MAX PLANCK INSTITUTE FOR POLYMER RESEARCH

ICMS INSTITUTE FOR COMPLEX MOLECULAR SYSTEMS

TU/e

Thank you for your attention!

email: pgkoupi@ncsu.edu