Neuromorphic hardware inspired by the hippocampus

Towards more compact and efficient hardware for implantable devices

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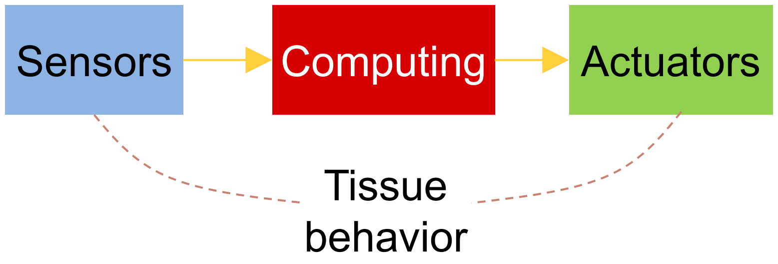
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

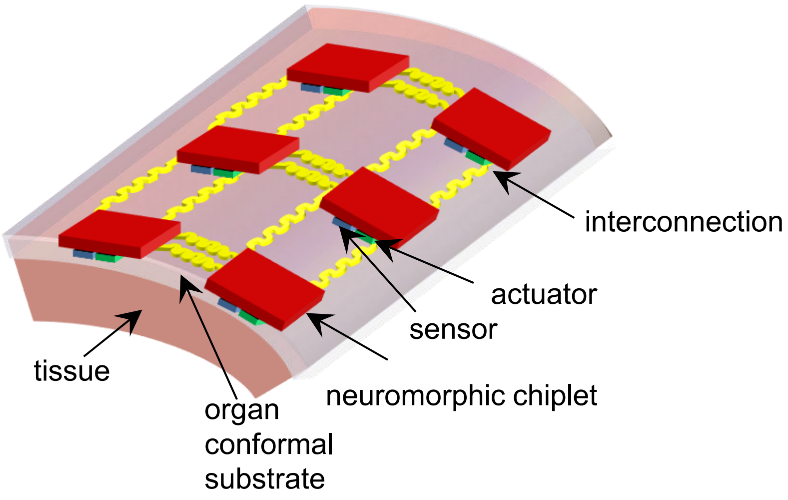
12th International IEEE EMBS Conference on Neural Engineering
NIH Brain Initiative Neuromorphic Engineering for Clinical Care Minisymposium
November 13th, 2025

12TH ANNUAL IEEE Engineering Medicine and Biology Society
International Conference on Neural Engineering
11-14 NOV 2025
SAN DIEGO
IEEE EMBS

Motivation

Organ-conformal systems with an embedded network of chiplets for distributed sensing, computing and therapy

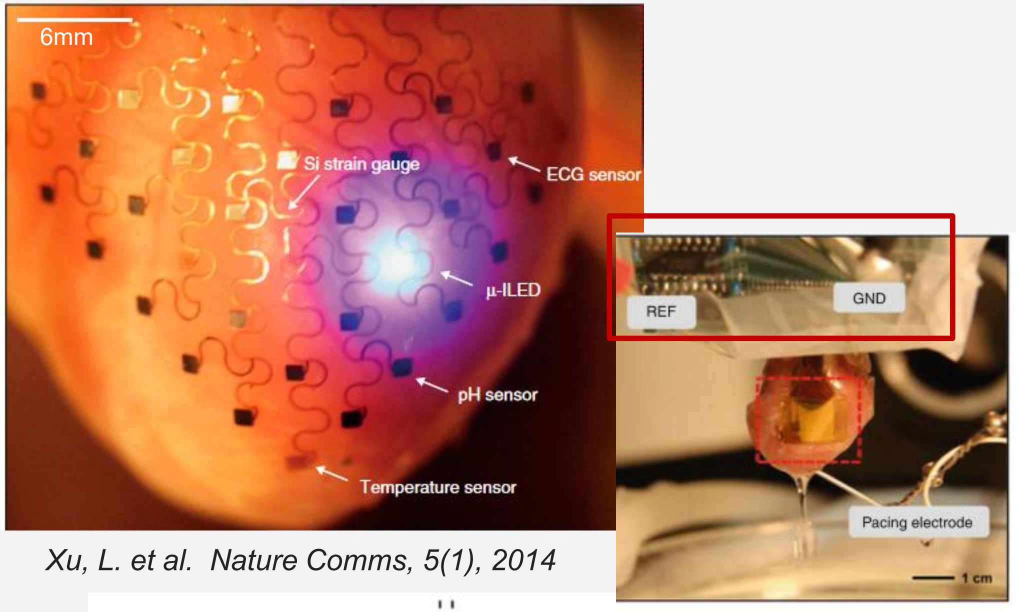




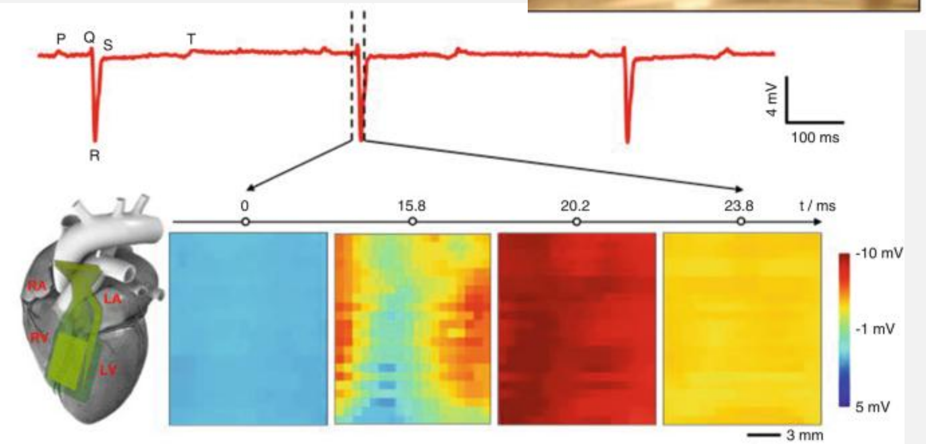
State-of-the art

Cardiac applications

Sensor fabrics integrated in conformal heart sleeve

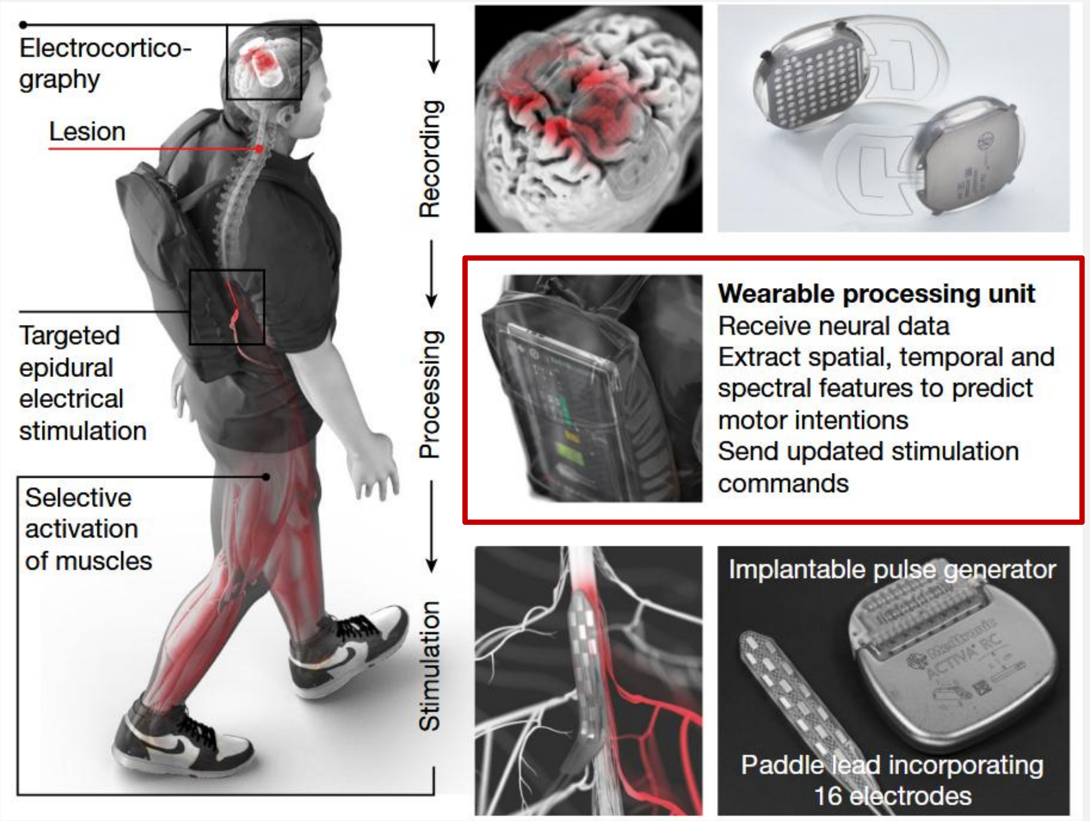


Xu, L. et al. Nature Comms, 5(1), 2014



Fang, H., et al. Nature biomedical engineering 1.3, 0038, 2017

Neuro applications



Lorach, H., et al. "Walking naturally after spinal cord injury using a brain–spine interface." Nature 618.7963: 126-133, 2023.

Challenge: Compact and energy efficient computing hardware!

Emerging hardware for compact and efficient computing

Leverage of novel analog hardware technologies
that promise major improvements in efficiency

	Digital			
	CPU 2.66 GHz	GPU 1 GHz	FPGA 200 MHz	ASIC 400 MHz
Time (s)	~8×10^{-3}	~3×10^{-4}	~1.5×10^{-4}	~5×10^{-5}
Power (W)	~30 to 40	~40	~10	~3
Energy (J)	~3×10^{-1}	~1×10^{-2}	~1×10^{-3}	~1×10^{-4}

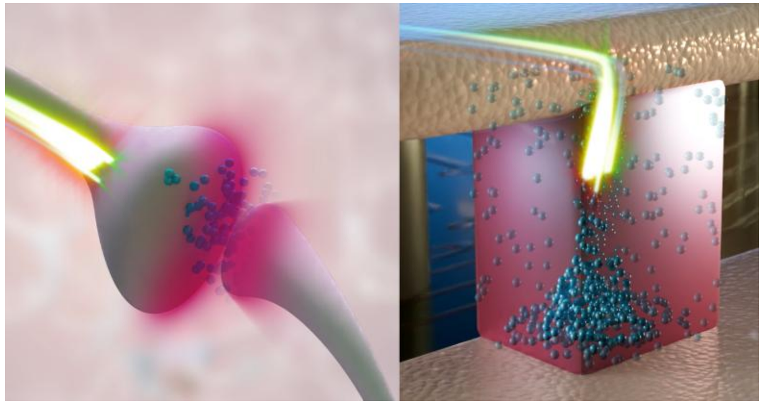
	Analog			
	NOR 180 nm	NOR 55 nm	Memristors 200 nm	3D memristors 10 nm
Time (s)	~2×10^{-6}	~7×10^{-7}	~5×10^{-8}	~1×10^{-8}
Power (W)	~1	~1	~1	~0.1
Energy (J)	~2×10^{-6}	~7×10^{-7}	~5×10^{-8}	~1×10^{-9}

Energy efficiency and performance comparison for a 64×64-pixel neural network image classification

Ceze L. et al., DRC, 2016

memristors

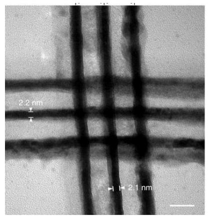
Synaptic inspiration | *Memristor functionality*



! Change filament shape to change device memristance state → **learning**

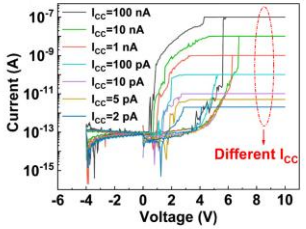
! Retain filament shape in absence of applied voltage → **memory**

Ultra-scaling (~2nm)



Pi, S. Nature Nano 14.1, 35-39, 2019

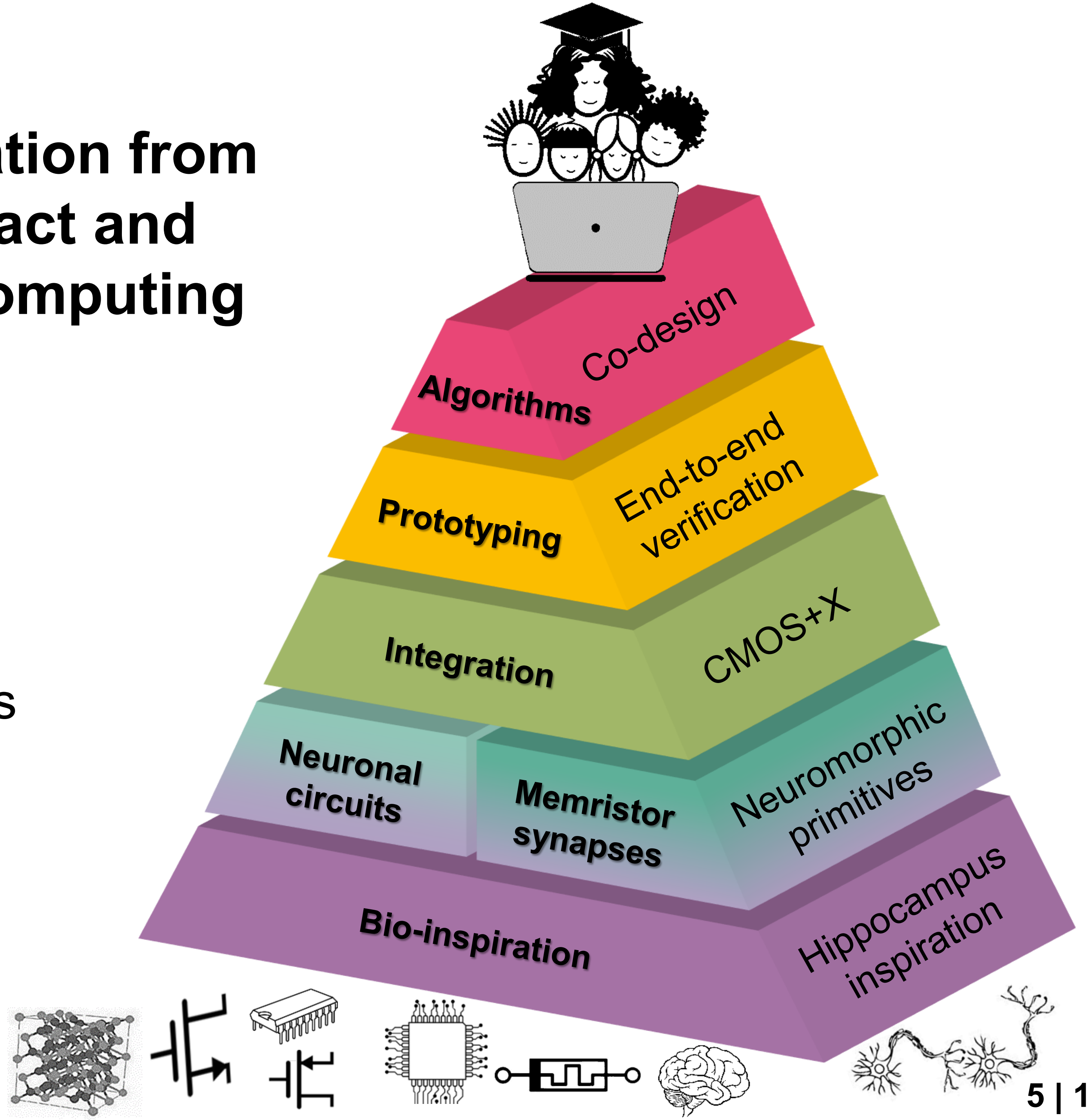
Ultra-low currents (~2pA)

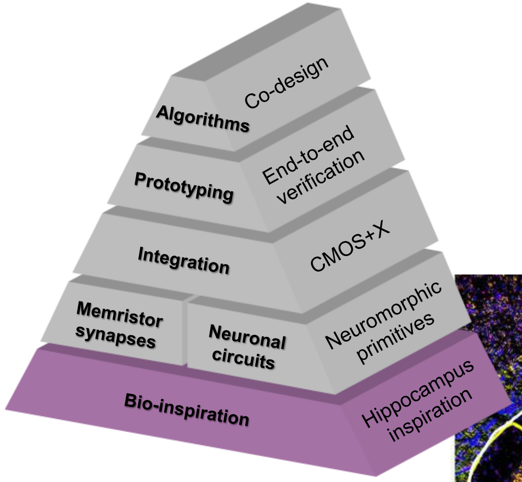


Ren, S.G., et al. IEEE Trans Electron Devices 69.2, 838-842, 2021

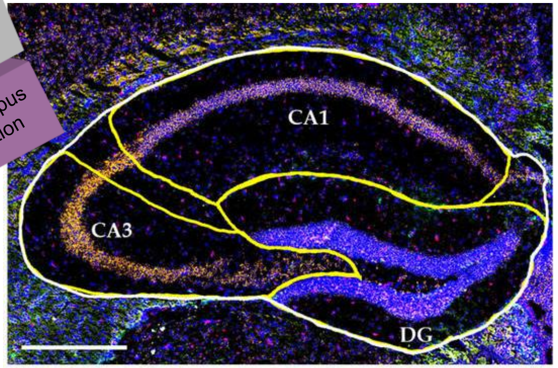
Our vision to draw inspiration from the brain to build compact and efficient neuromorphic computing

Vertical integration across the stack
from bio-inspiration to hardware and algorithms



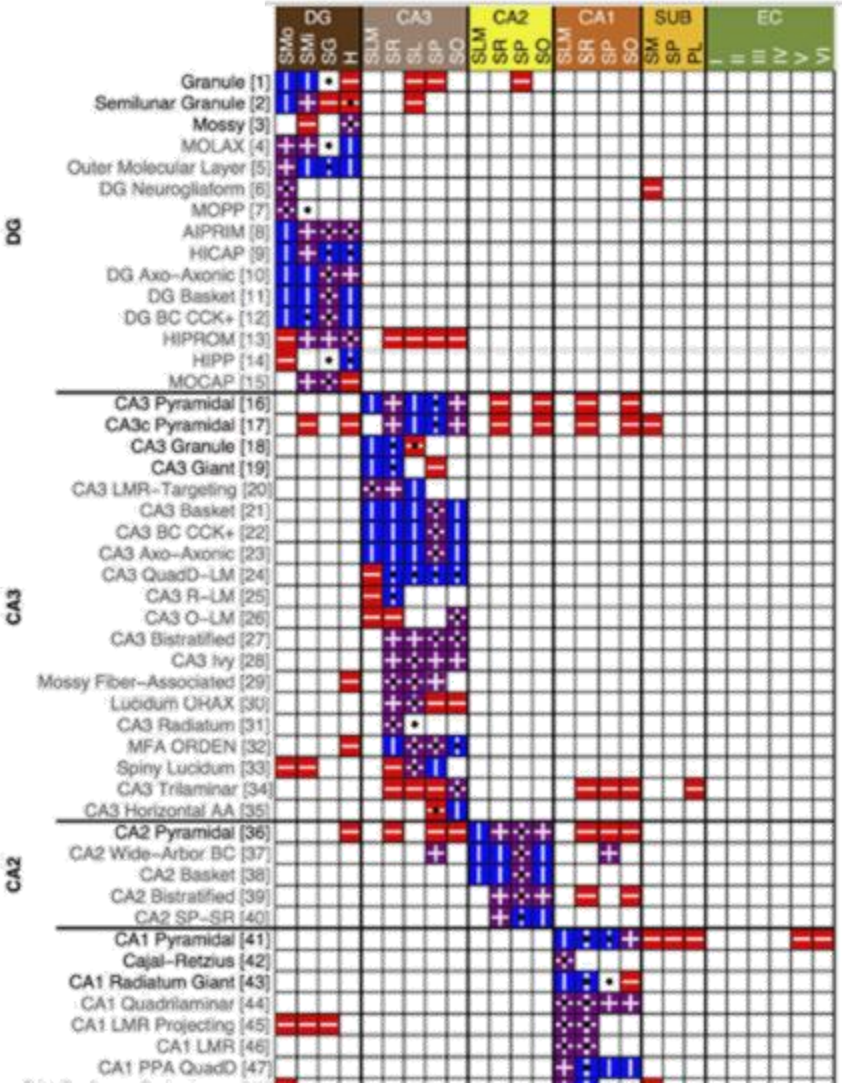


Drawing inspiration from the rodent hippocampus



Hippocampome inventory

~120 neuron types with diverse spiking patterns and connection probabilities from experimental neuroscience data



Prof. Giorgio Ascoli (GMU)

rodent hippocampus

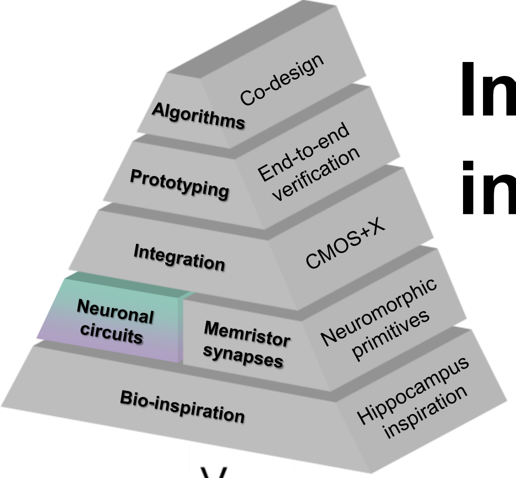
one of the most studied brain regions

rich experimental neuroscience data

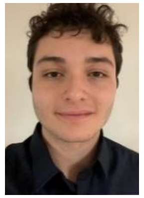
has several subregions

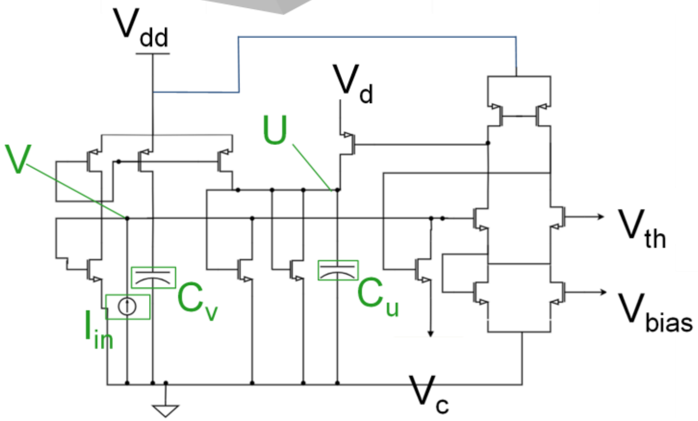
- **dentate gyrus** (DG) – role in pattern separation
- **cornu ammonus** (CA)
  - CA3 – potential role in pattern completion
  - CA1 – role in novelty detection

Financial support from: DOE CRCNS grant (collab with George Mason Univ.)



Implementing neuronal functionality in analog circuitry


Susmita Karmaker

Aral Balsari



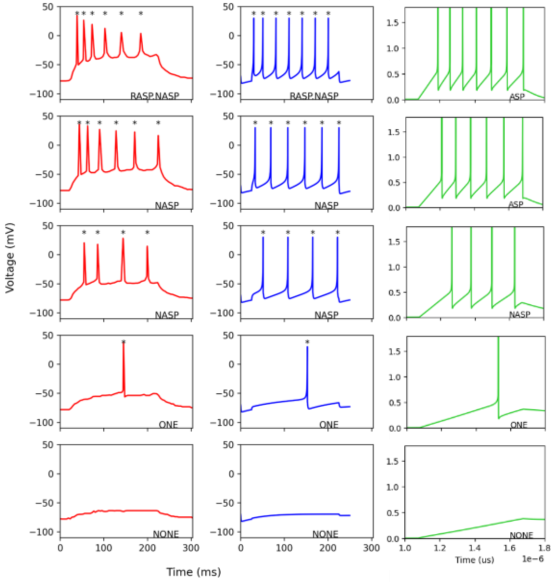
Izhikevich model behavior of different neurons can be successfully implemented by changing the circuit parameters

- Two of these parameters (C_u and C_v) are fixed after fabrication
- On-going work: Tape-outs for experimental validation

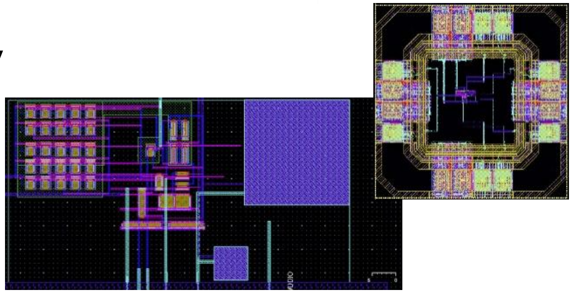
young granule cell behavior

experimental current level | Izhikevich model | circuit current level

90pA, 70pA, 50pA, 30pA, 10pA



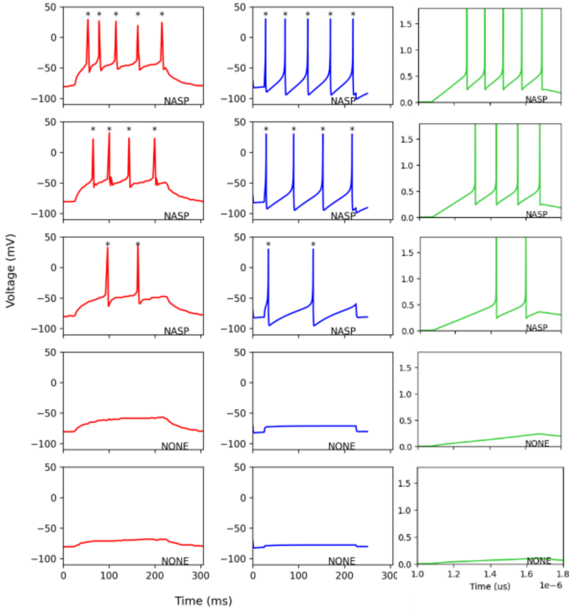
V_c=200mV
V_d=0V
C_u= 1pF
C_v=100fF



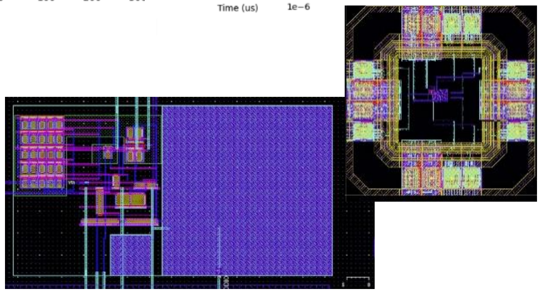
mature granule cell behavior

experimental current level | Izhikevich model | circuit current level

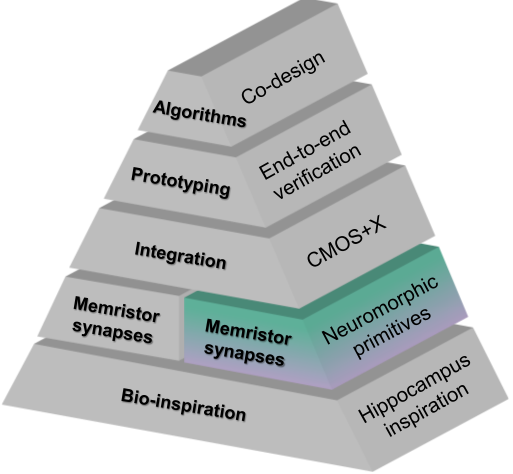
60nA, 50nA, 35nA, 15nA, 10nA



V_c = 250mV
V_d = 0V
C_u= 3pF
C_v=170fF

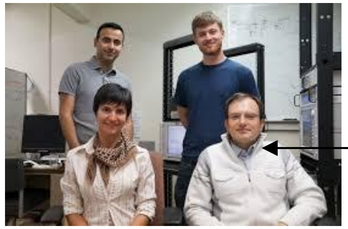


Financial support from: DOE Early Career Award, AFOSR YIP



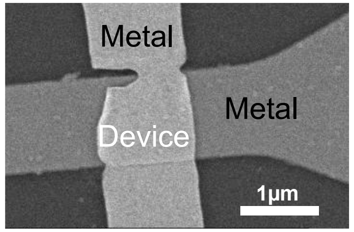
Optimizing memristors for synaptic behavior

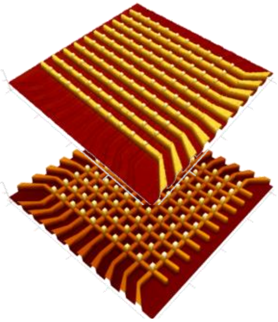
me as a PhD student



Dmitri Strukov (my PhD advisor)

When I started by PhD
Damaged memristor, but still working

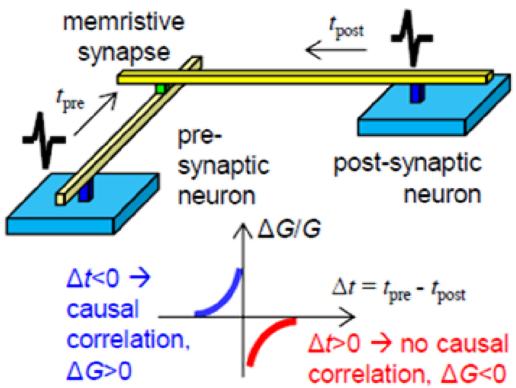




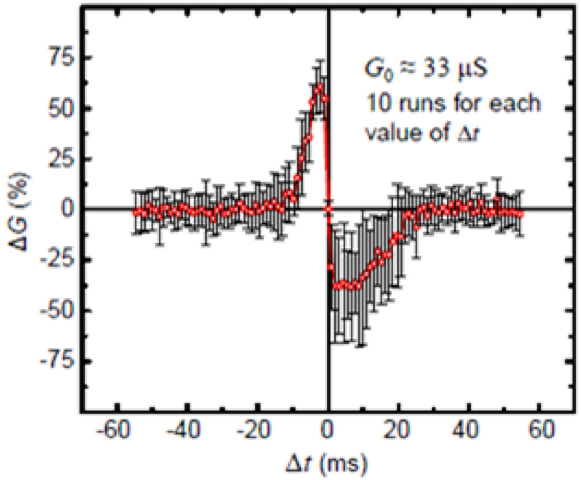
At the end of my PhD
200 damage-free memristors integrated three-dimensionally

Adam, G. C., Hoskins, … Strukov, D. B. IEEE Transactions on Electron Devices, 64(1), 312-318, 2016

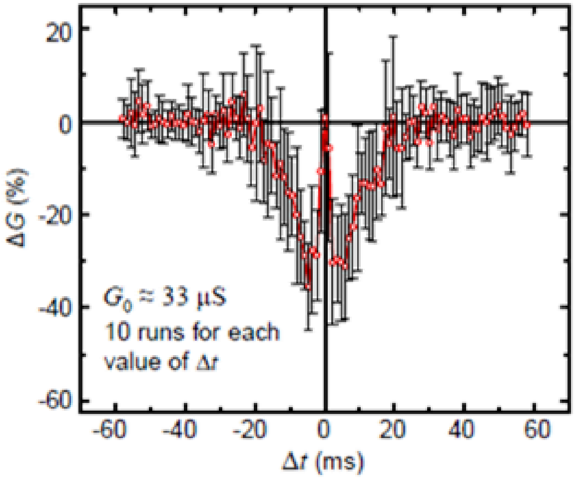
Spiking timing dependent plasticity in memristors similar to those in neuroscience



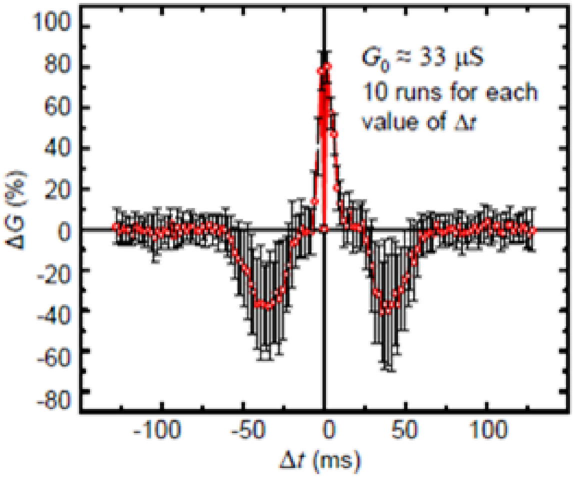
layer 5 neocortex



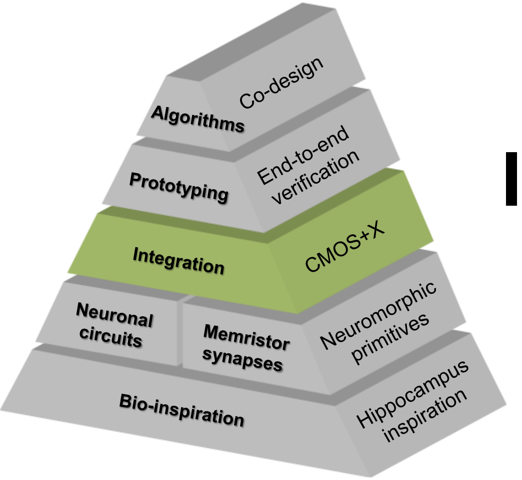
layer 4 neocortex



GABAergic synapses



Prezioso, M., Zhong, Y., Gavrilov, D., Merrikh-Bayat, F., Hoskins, B., Adam, G., ... & Strukov, D. IEEE International Symposium on Circuits and Systems (ISCAS), pp. 177-180, 2016.

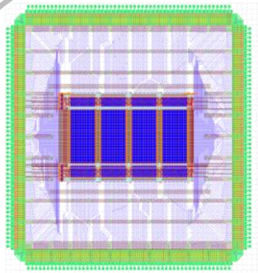


Integration of memristors on transistor chips at scale

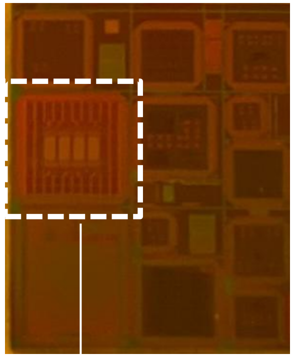
Shweta Joshi

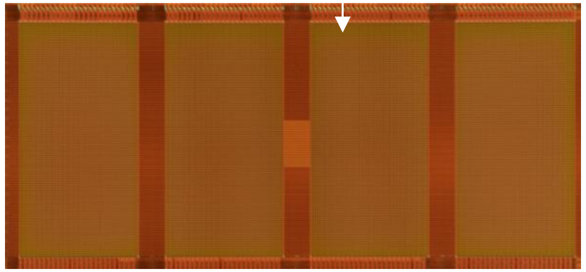
Imtiaz Hossen

Foundry – sourced circuitry with open vias

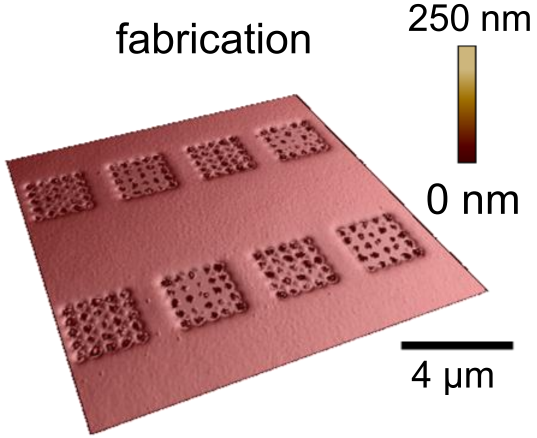


Designed by
Advait Madhavan @NIST





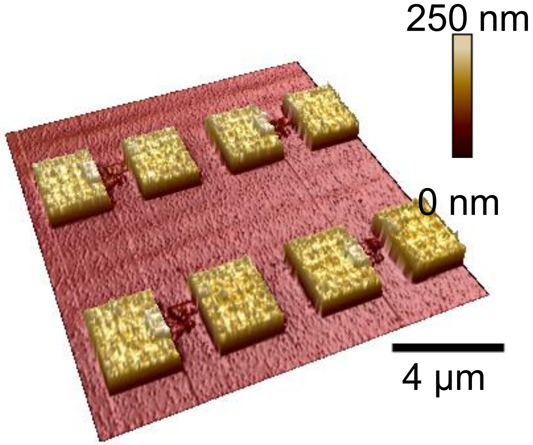
Planar interface
= ideal for add-on memristor fabrication



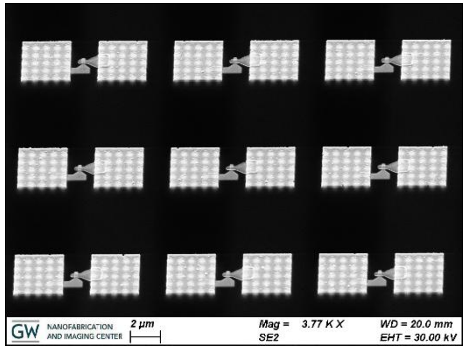
Underlying vias to 20,000 memristor array

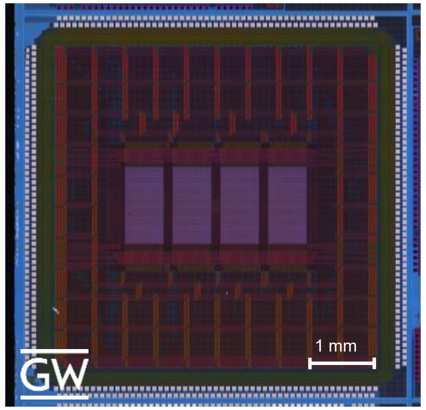
Add-on integration of memristors in house (@GW)

TiO_{2-x} memristor-based devices



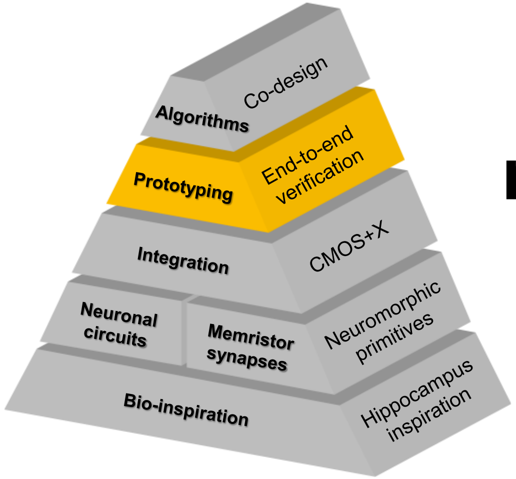
yield ~85%



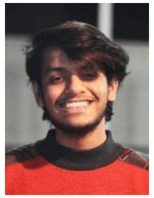


Hossen I. … Adam G.C. IEEE NMDC 2022
Hossen I., Joshi S….Adam G.C, Advanced Electronic Materials, 2500203, 2025

Financial support from: NSF CAREER, DOD DEPSCoR, DARPA/ONR



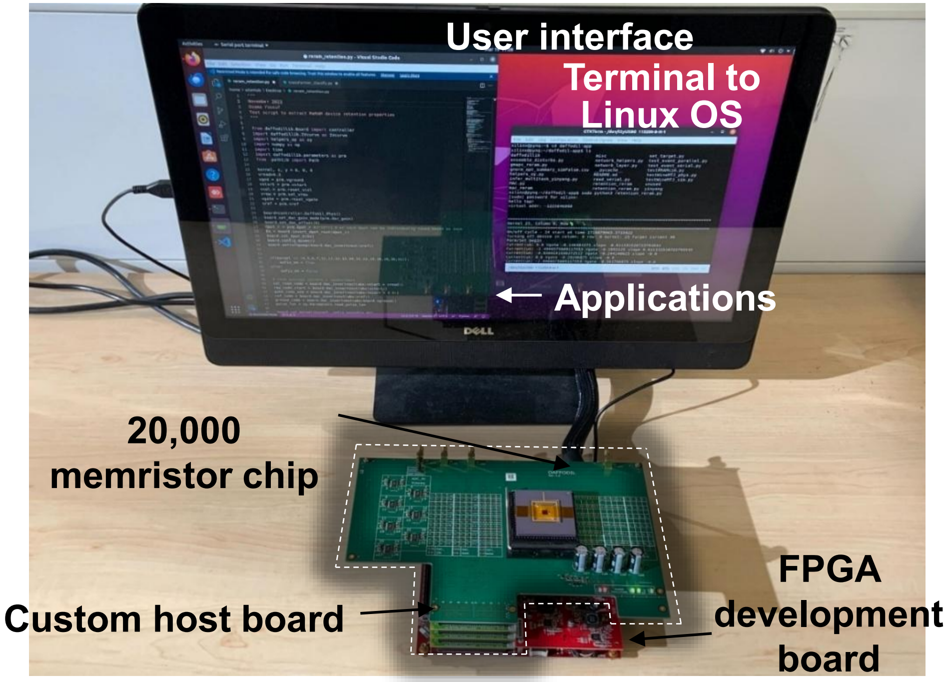
Prototyping small spiking neural networks on integrated memristor chips

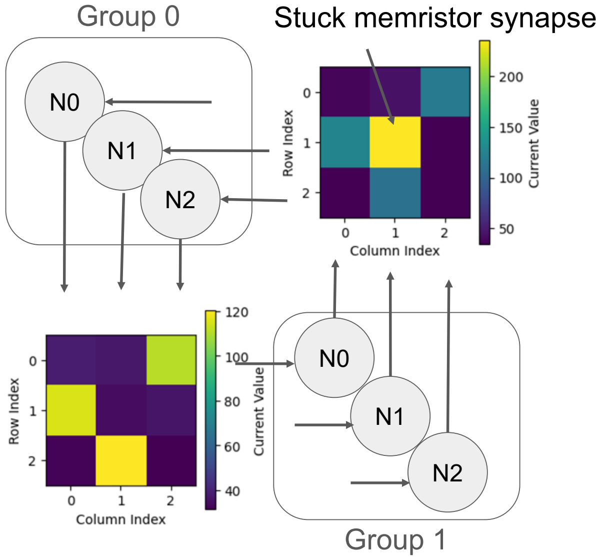


Osama Yousuf (now at Western Digital)

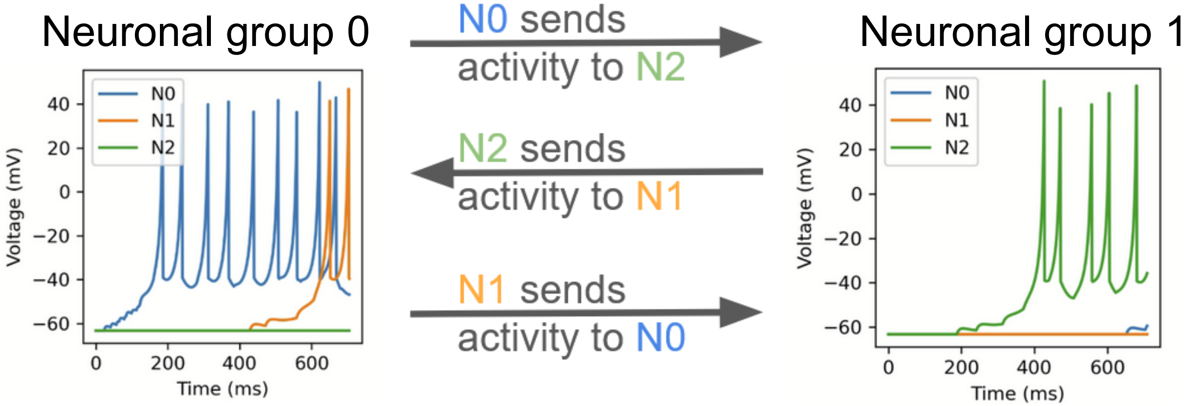
Joey Kilgore

end-to-end prototyping platform with 20,000 synaptic memristors and FPGA integration



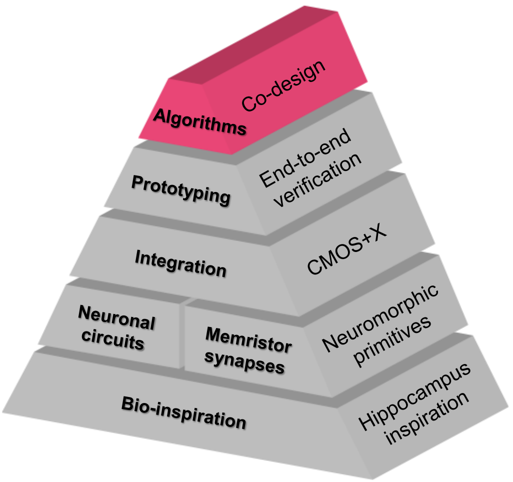


- Small 3 x 3 network
- Neuron model represents biologically realistic CA3 pyramidal cells
- All activity passed through the memristor array determines postsynaptic current



Adam G., Hoskins B., Lueker-Boden. M. DARPA ERI Summit, 2020
Hoskins B.... Adam G., Lueker-Boden M. International Conference on Neuromorphic Systems, 2021
Yousuf O., Hoskins B., Ramu K., Fream M., Borders W. A., ... , Adam G. Nature Communications, 16(1), 1250, *2025*

Financial support from: DARPA/ONR, NIST, Western Digital, NSF, AFOSR, DOE



Scaling a bio-realistic CA3 hippocampal model for hardware

Joey Kilgore

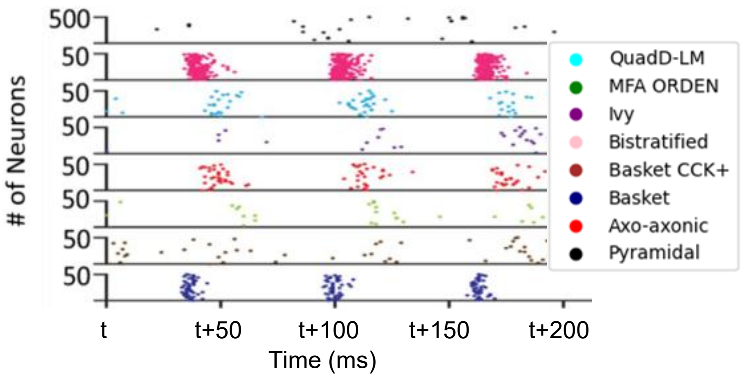
Zahin Ahmed

The networks were scaled down in terms of population, type of neurons, and number of connections utilizing optimization algorithms and biologically derived scaling factors

Scaled 0.1 and 0.01 models exhibit **realistic continuous periodic behavior** with several neuron subtypes retaining biologically realistic firing rates to full scale model

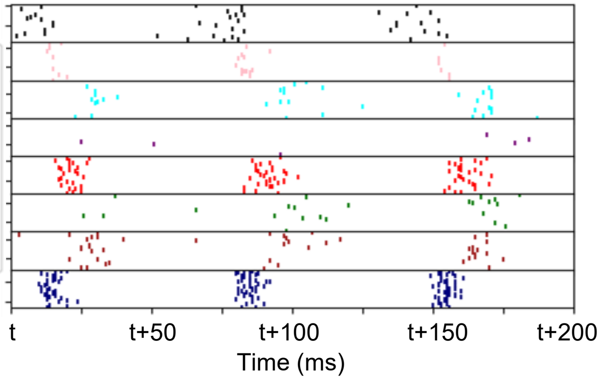
The 0.0001 scale network is currently being tuned for realistic periodic behavior

Full-scale model
89,000 neurons



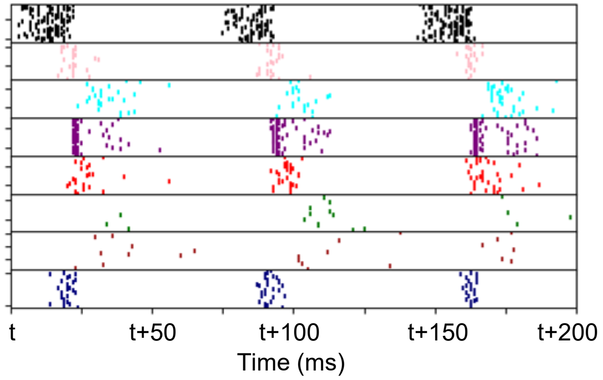
8 neuron types
51 connection types
89k neurons
250M connections
83:17 E:I Ratio

0.1 scale model
19,000 neurons



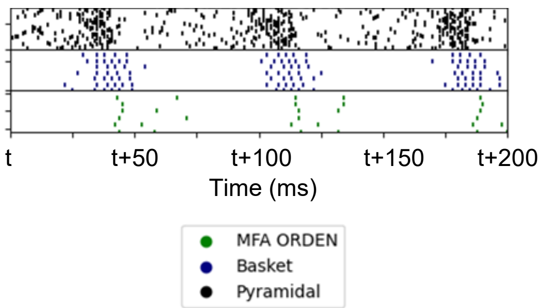
8 neuron types
51 connection types
19k neurons (77% reduction)
32M connections (82% reduction)
83:17 E:I Ratio

0.01 scale model
4,000 neurons



8 neuron types
51 connection types
4k neurons (85% reduction)
1.7M connections (99% reduction)
83:17 E:I Ratio

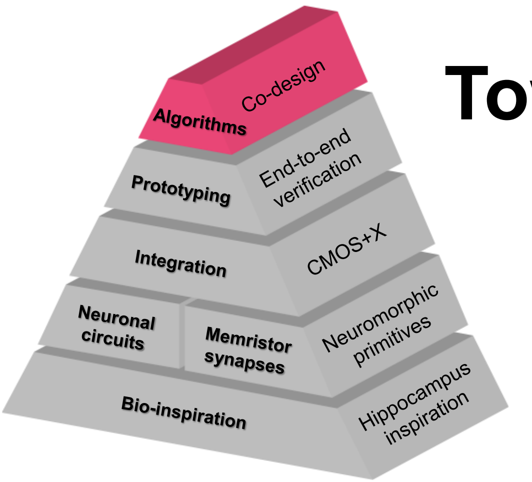
0.0001 scale model
173 neurons



3 neuron types
9 connection types
173 neurons (99.8% reduction)
17k connections (99.99% reduction)
92.5:7.5 E:I ratio
sufficiently small scale

On-going work: testing these reduced models for pattern completion and implementing them in hardware

Kilgore, J. A., manuscript in preparation



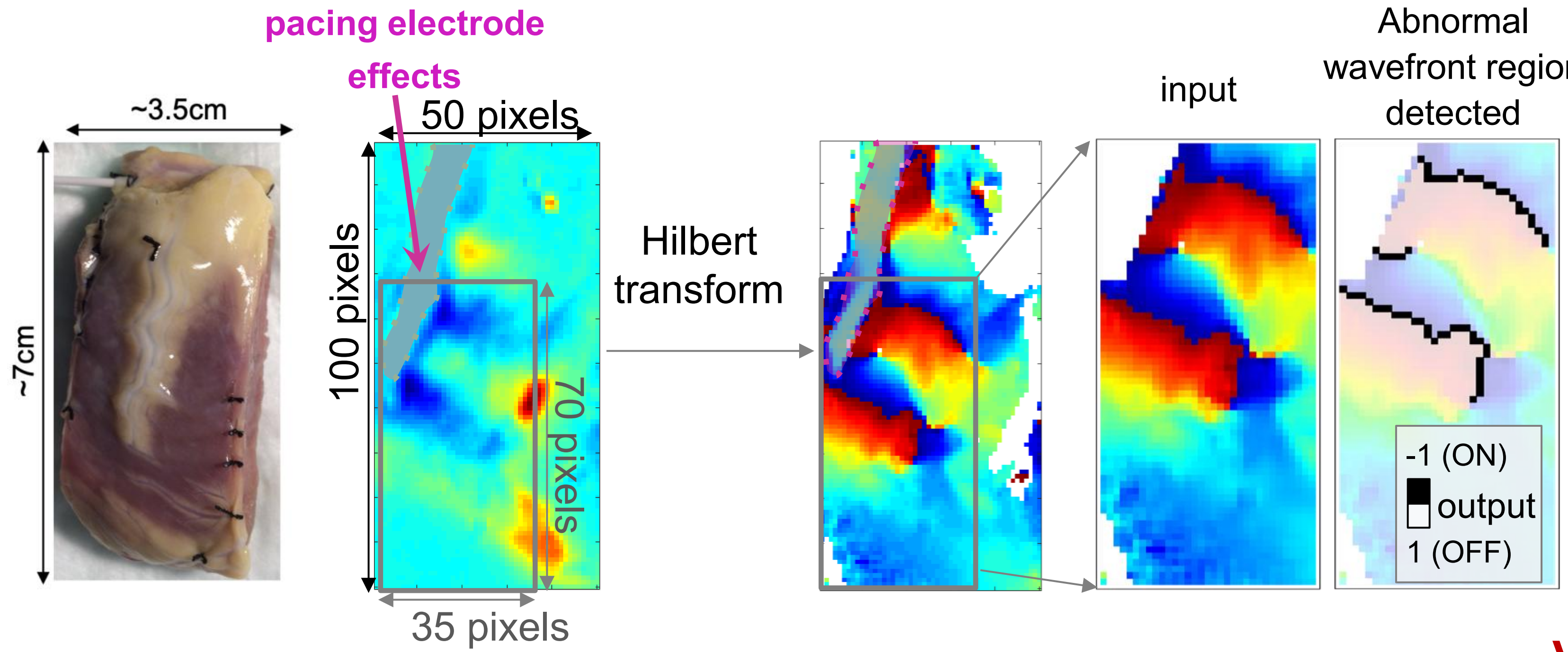
Towards using memristor neuromorphic chiplets in practical applications

Zhuolin Yang

Lei Zhang (now at Micron)

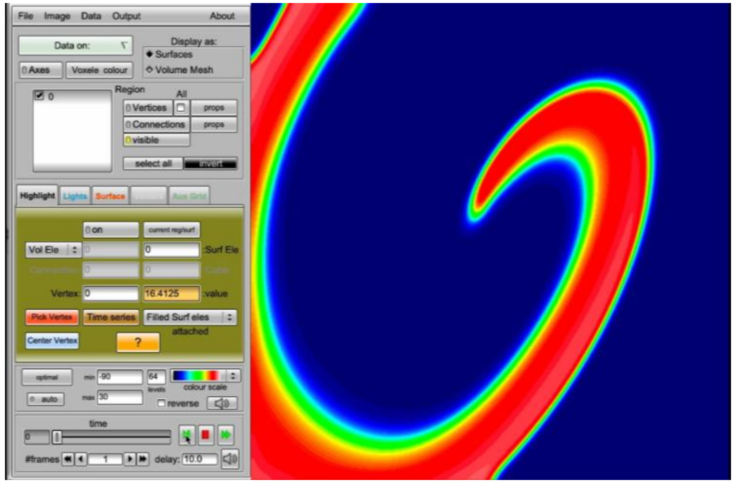
Memristor-based neural networks for smart cardiac implants

+ Prof. Igor Efimov (Northwestern Univ.)
+ Prof. Kedar Aras (Univ. at Buffalo)
+ Prof. Karli Gillette (Univ of Utah)



Yang, Z., Zhang, L., Aras, K., Efimov, I.R. , Adam, G. C. Advanced Intelligent Systems, p. 2200032, 2022

Simulation of local termination of ventricular arrythmia using memristor-based chiplets



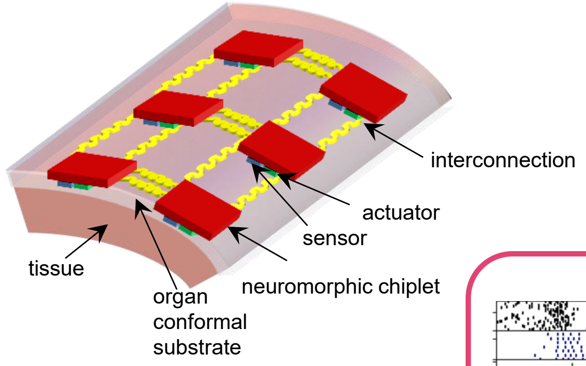
Yang Z. et al – paper in preparation

Vision for the future

Memristive neuromorphic chiplets distributed in a fabric of sensing/computing/therapy for implants

Financial support from NSF CRII

Summary



- Computing is a key bottleneck in the development of organ-conformal systems with an <u>embedded network of chiplets for distributed sensing, computing and therapy</u>

- <u>Emerging analog neuromorphic hardware, e.g. memristors,</u> can be used for compact and energy-efficient computing applications

- Scaling up and prototyping new neuromorphic hardware requires a <u>vertical approach</u> from neuroscience to emerging devices and circuits to novel architectures and algorithms