Neuromorphic sensing for robots: towards embodiment

C. Bartolozzi

ISTITUTO ITALIANO
DI TECNOLOGIA
EVENT-DRIVEN PERCEPTION
FOR ROBOTICS

Understand biology to build better technology

From HW and circuit design....

....to computation and applications

Digital

- Largely serial computation
- Variables: "0", "1"
- Fast, precise computing elements
- Computation and memory are separate
- Clock-driven sensing
- Largely disembodied (Mainly DL)

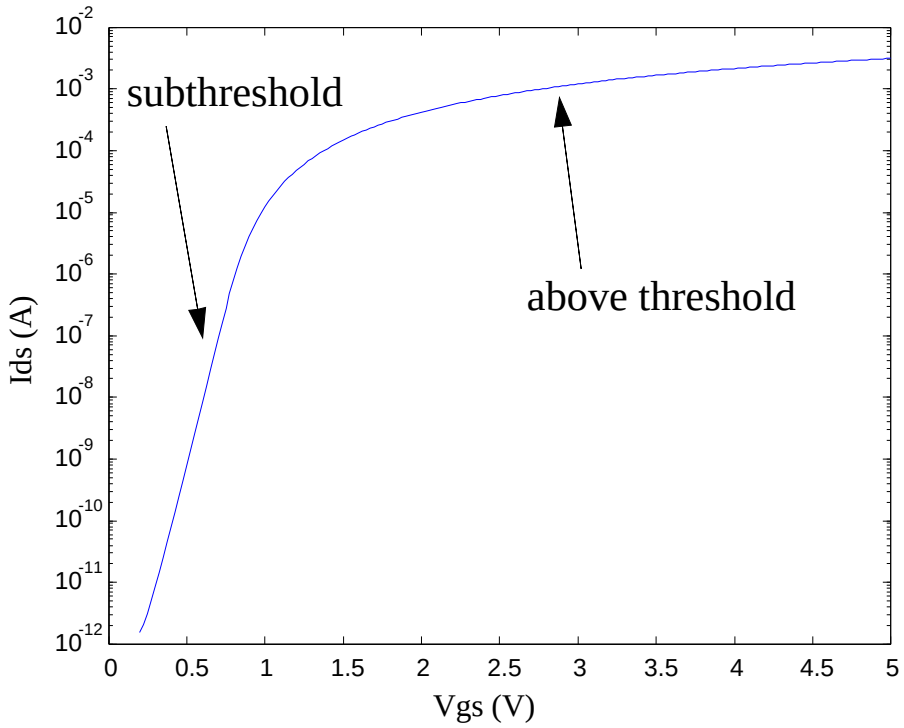
High speed numerical computation

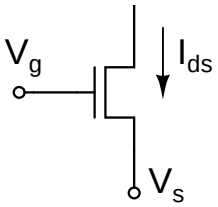
Neural

- Largely parallel computation
- Variables: analog
- Slow, imprecise computing elements (neurons, synapses)
- In-memory computing
- Event-Driven sensing
- Adaptive over different time scales, context dependent computation
- Embodiment and active sensing

Interact with the real world in 'real time'

C. Mead, M. Mahovald 90s





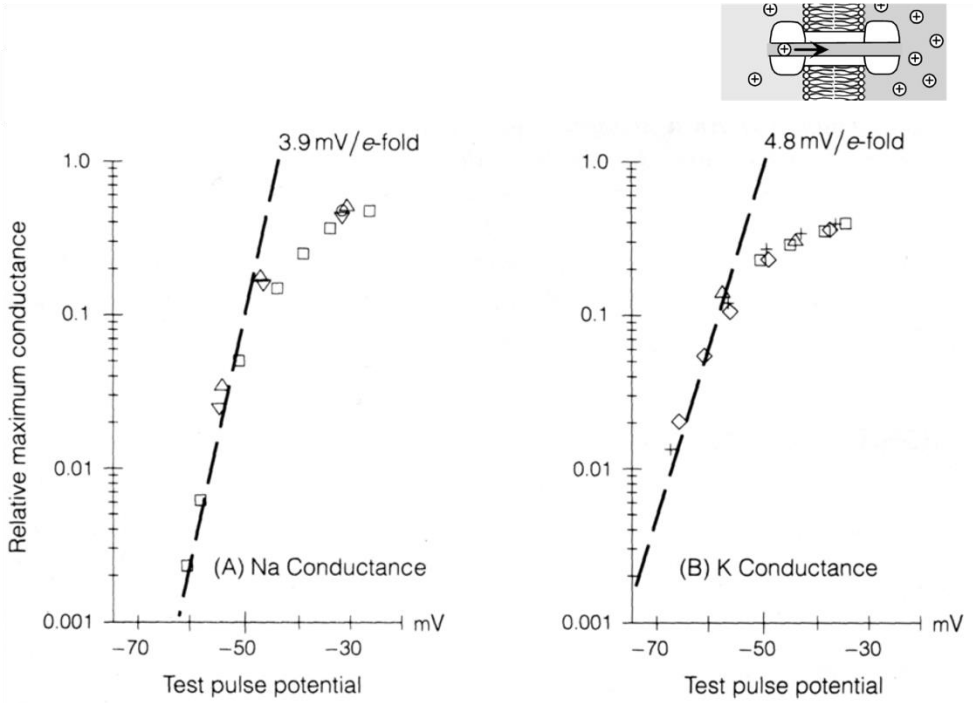
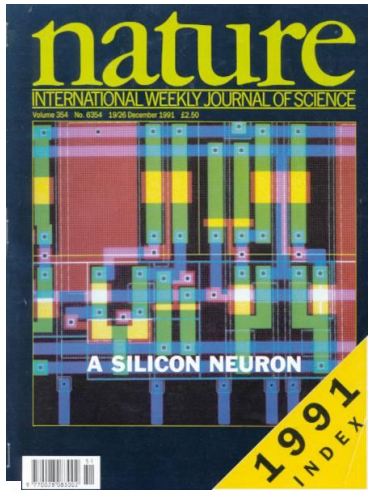
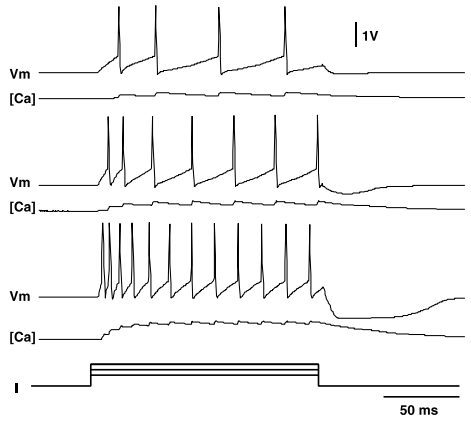
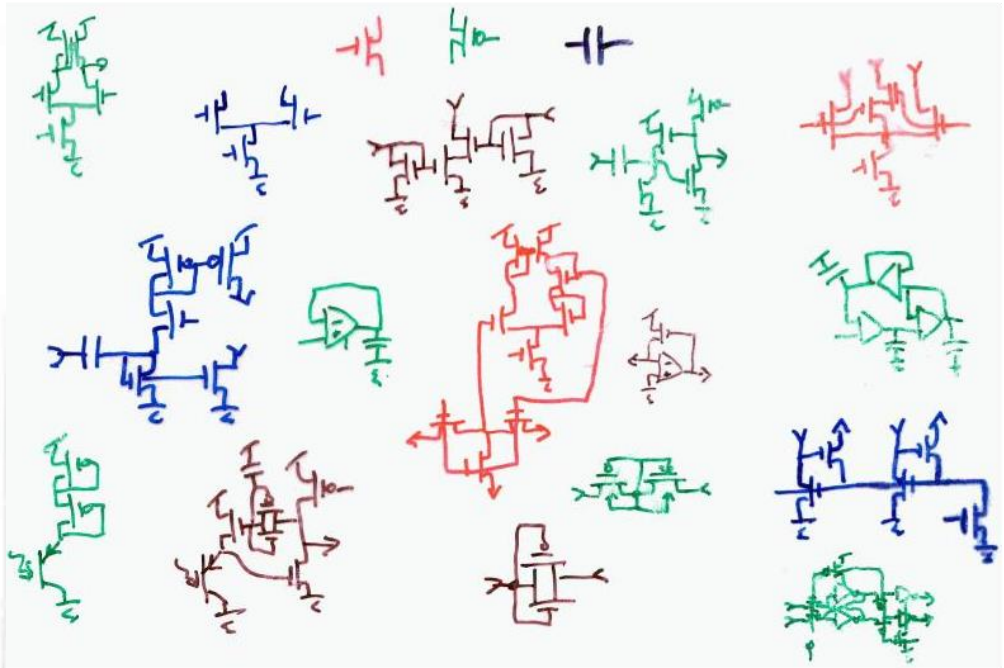


FIGURE 4.6 Exponential current–voltage characteristic of voltage-dependent channels. At high voltages, the fraction of channels that are open approaches unity, causing a saturation of the curves. (*Source:* [Hodgkin et al., 1952b, p. 464].)

C. Mead, M. Mahowald 90s







A library of neural computational primitives

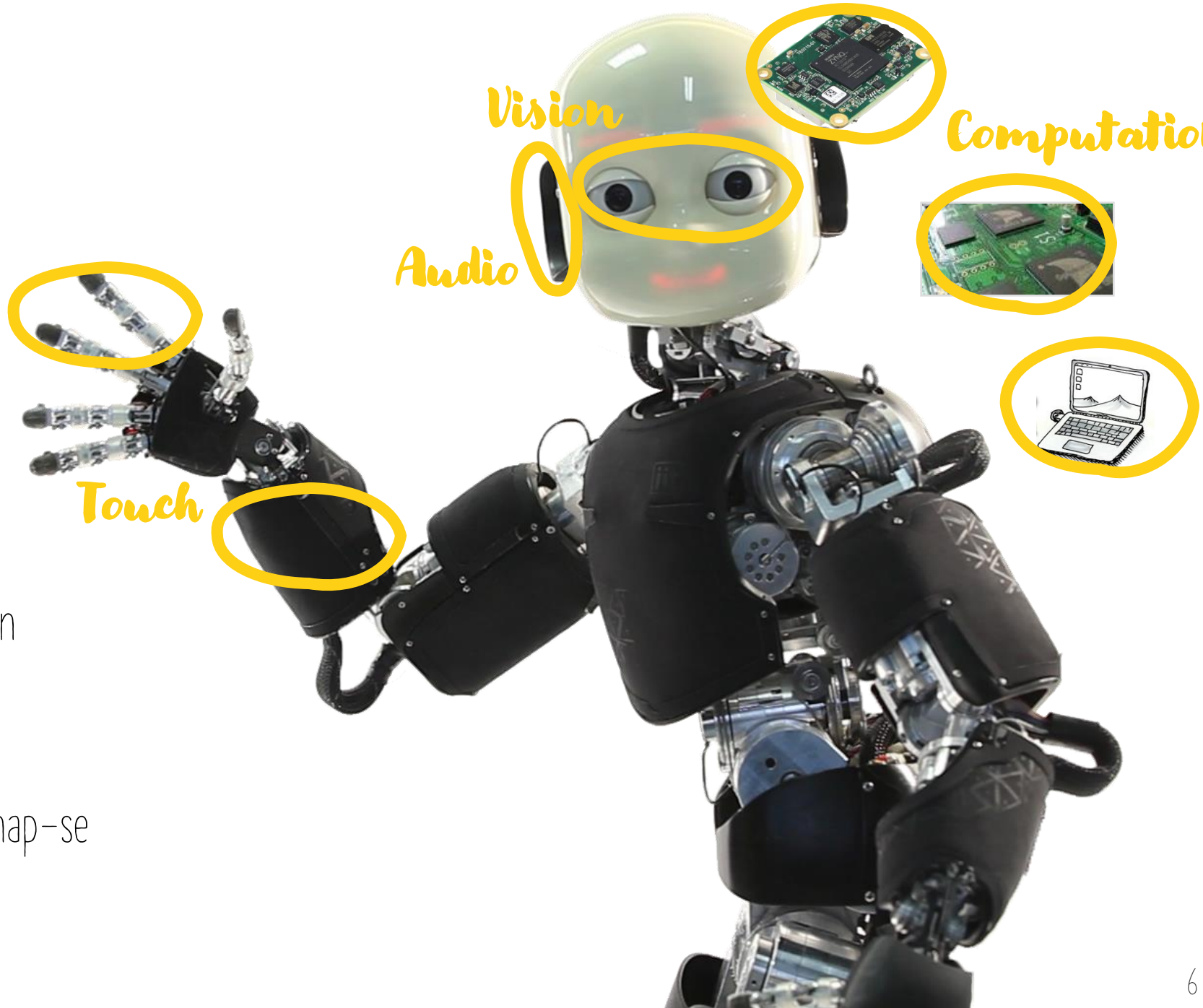
- event-driven sensors
- Short Term Depression, Short Term Facilitation, Spike Freq. Adaptation, Homeostasis, Spike-Driven Synaptic Plasticity, Balanced EI networks, etc.

Bartolozzi, Indiveri, Donati Nature Communications, 2022

Event-driven iCub

Neuromorphic sensing and computation

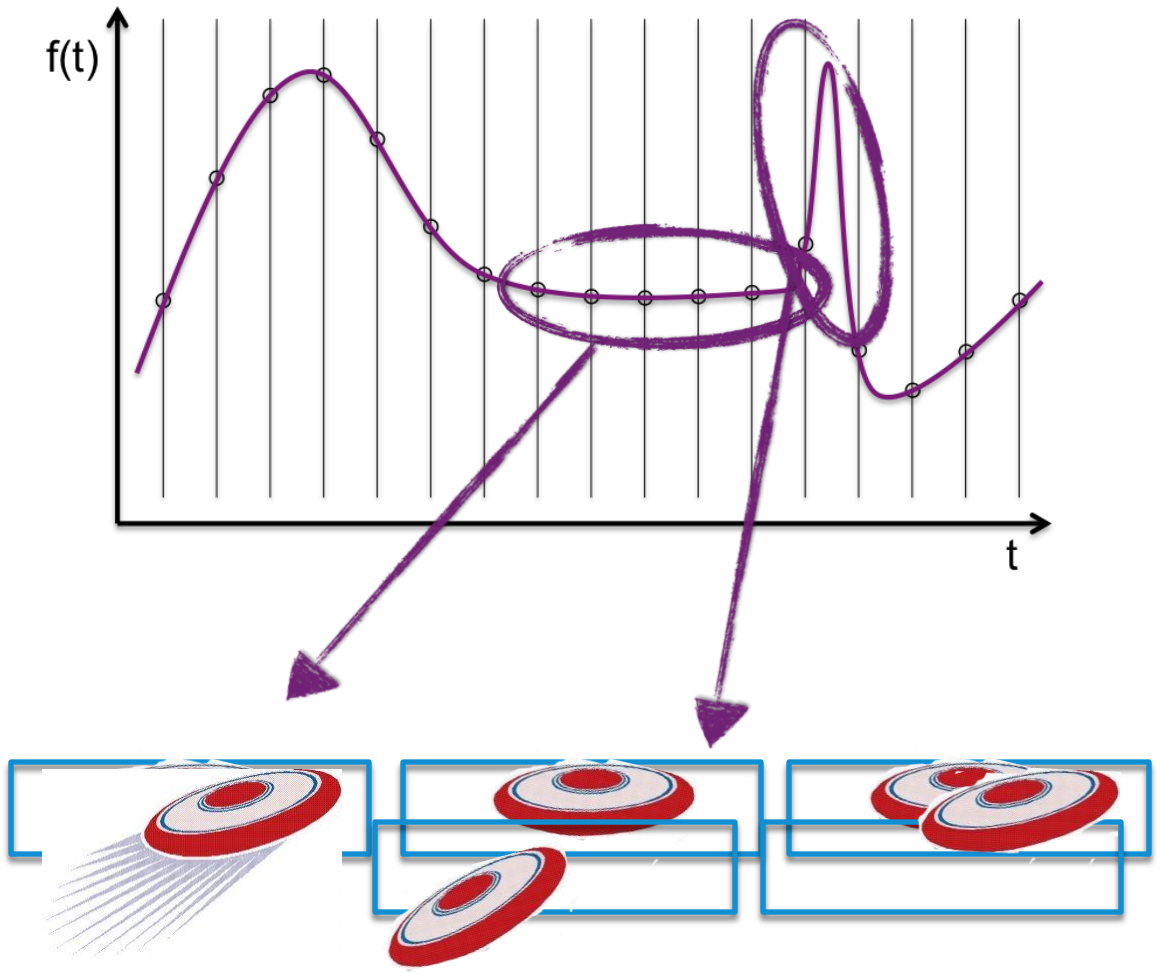
- Audio, vision, touch
- SpiNNaker, Loihi, GPUs, FPGAs, Dynap-se



Event-Driven Sensing

Clock-Based Sampling

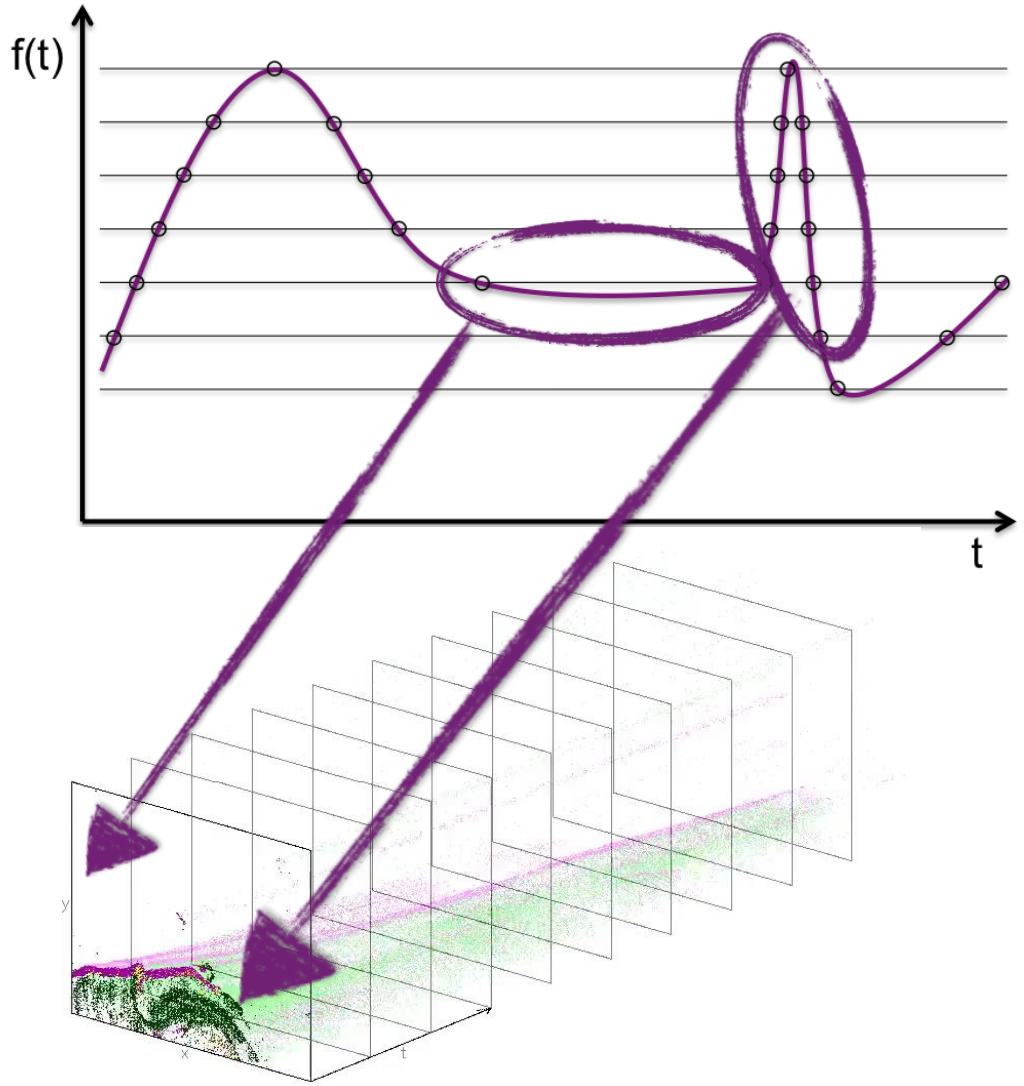
fixed **Δ**t



Event-Driven Sensing

Data-Driven Sampling

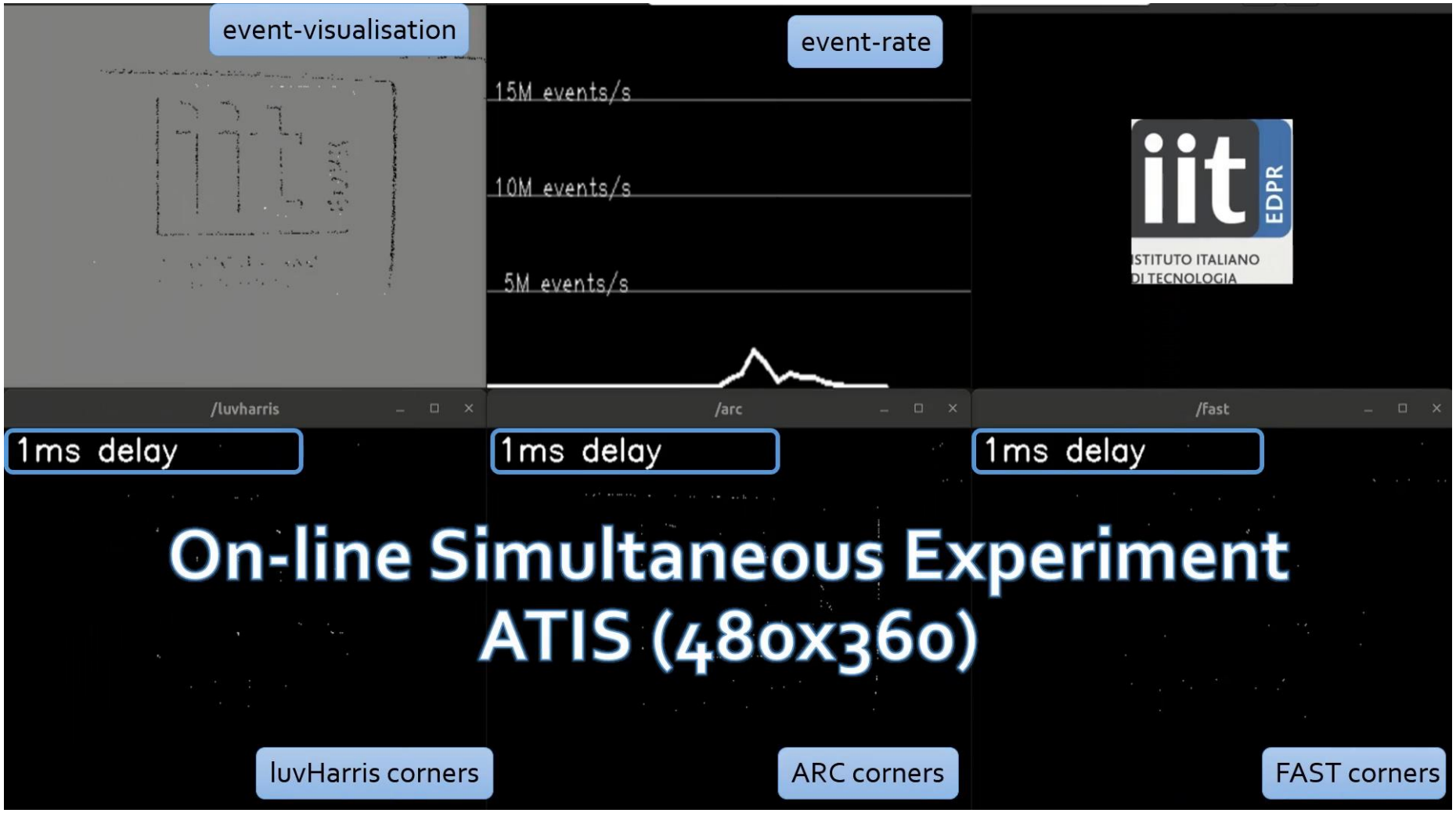
fixed **Δ**f



Corner detection

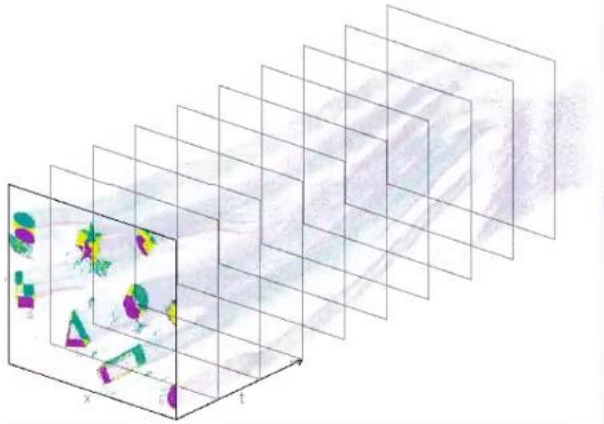
Event-Driven Computer Vision

Low-latency



Glover et al TPAMI 2021

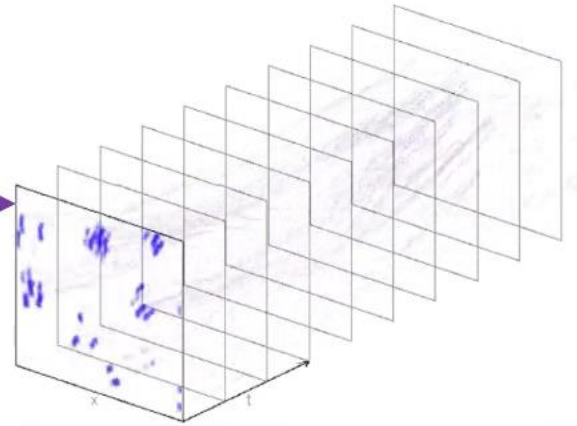
Look-up event-Harris



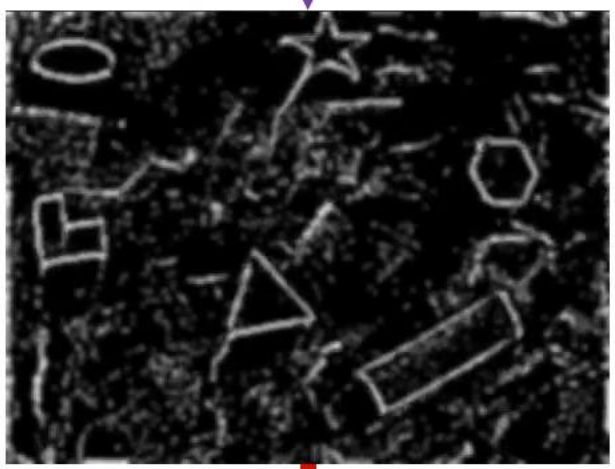
Event-throughput is decoupled from corner detection algorithm

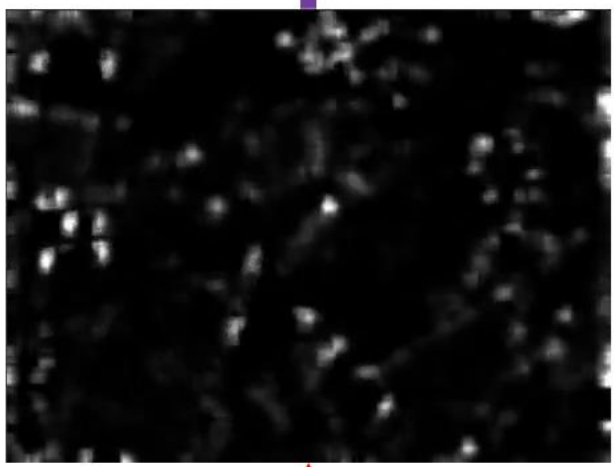
Fast Asynchronous TOS update

Corner Assigned by score in LUT



event stream





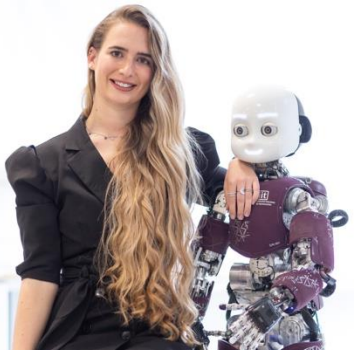
corner stream

Threshold Ordinal Surface (TOS)

corner score Look-up Table (LUT)

LUT is calculated "as-fast-as-possible"

```
LUT = cv::cornerHarris(TOS)
```



4DoF tracking

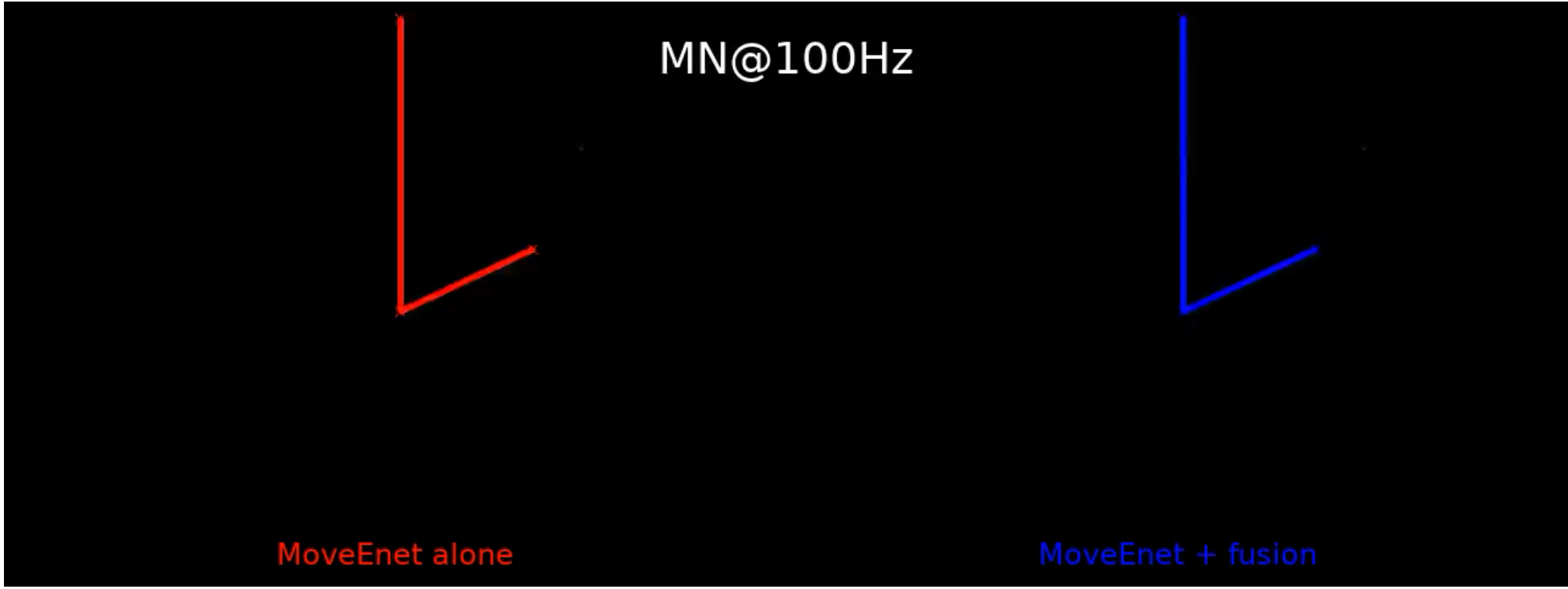
Event-Driven Computer Vision

Low-latency

Eye tracking

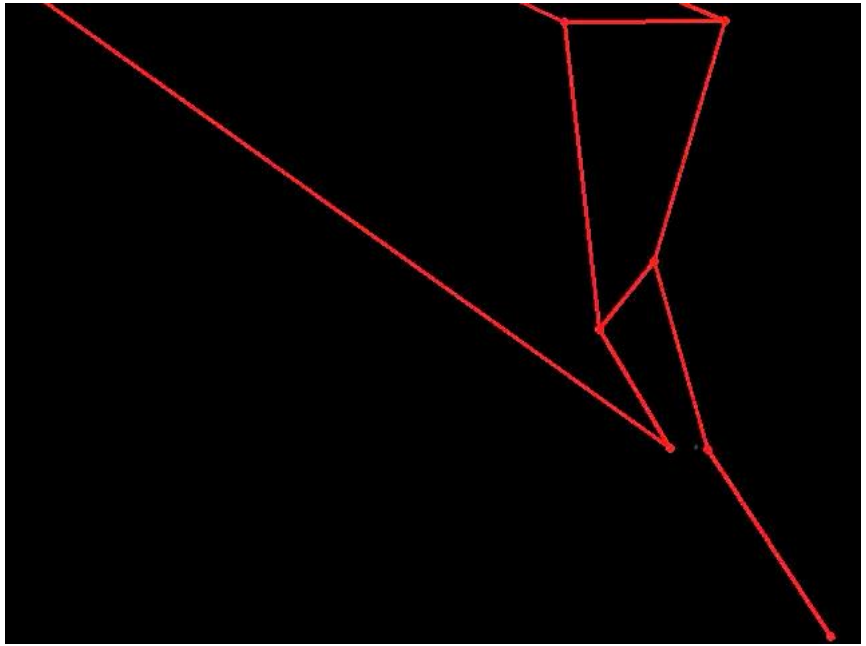
Event-Driven Computer Vision

Low-latency Feature detection, Tracking



HPE

Event-Driven DNN



Event-driven touch

4k sensors

10ms sampling period

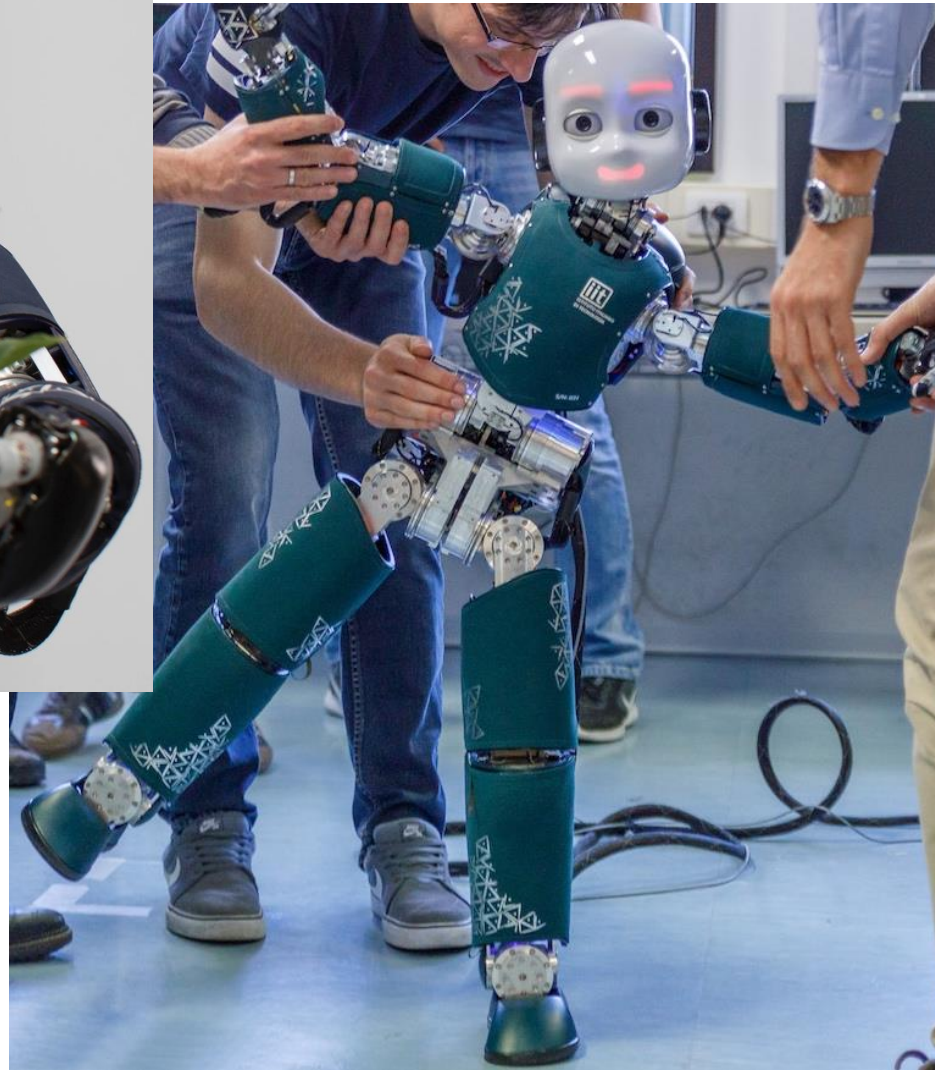
Localised in space & time

Grasping &

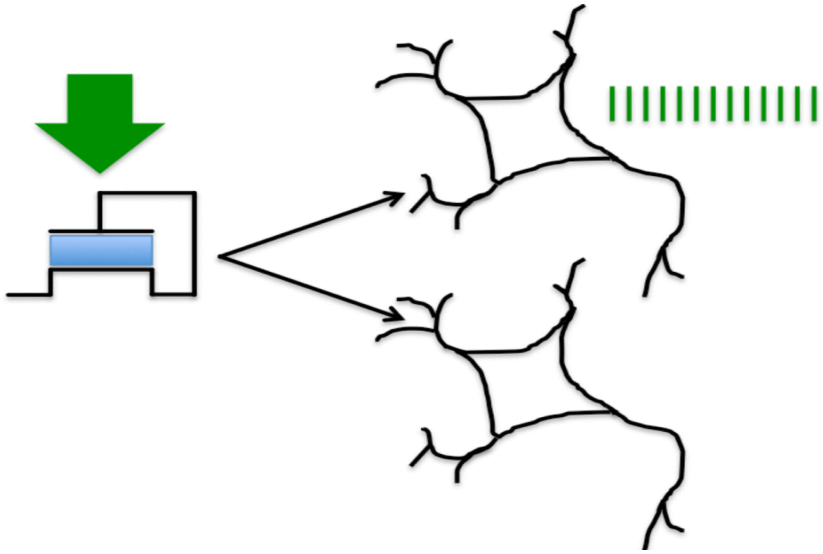
Object manipulation

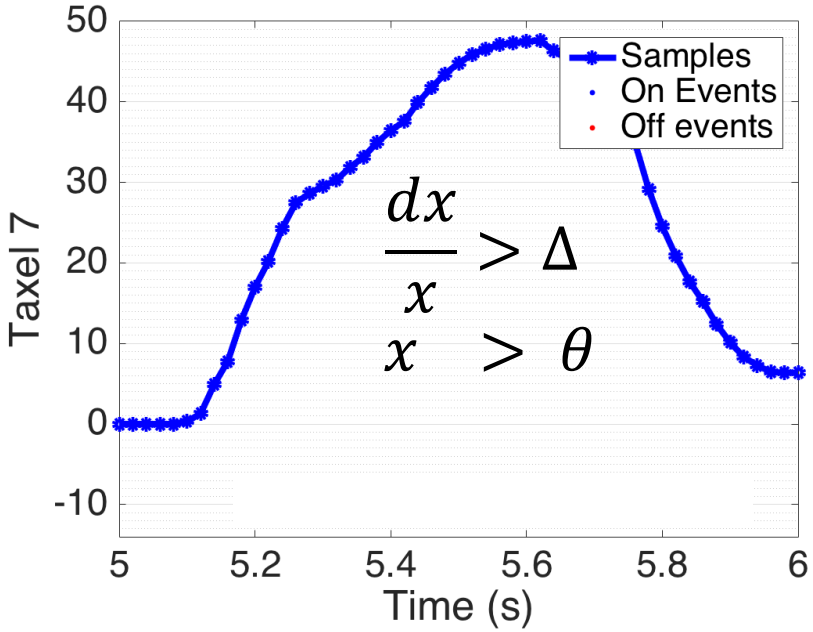
Safety &

Physical HRI

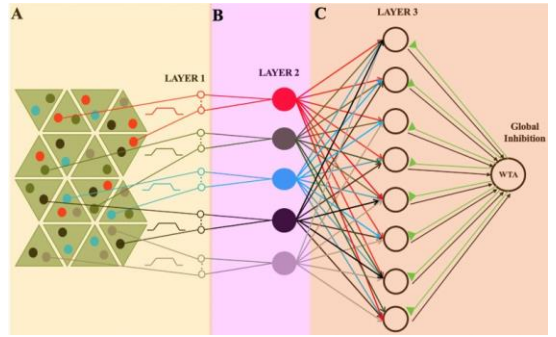


Event-driven touch

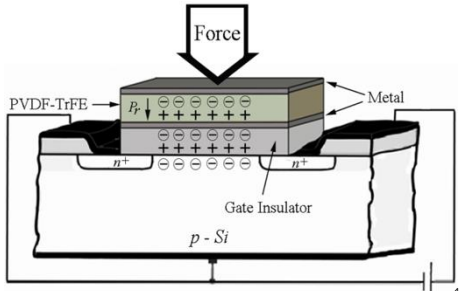




SNN-based tactile perception

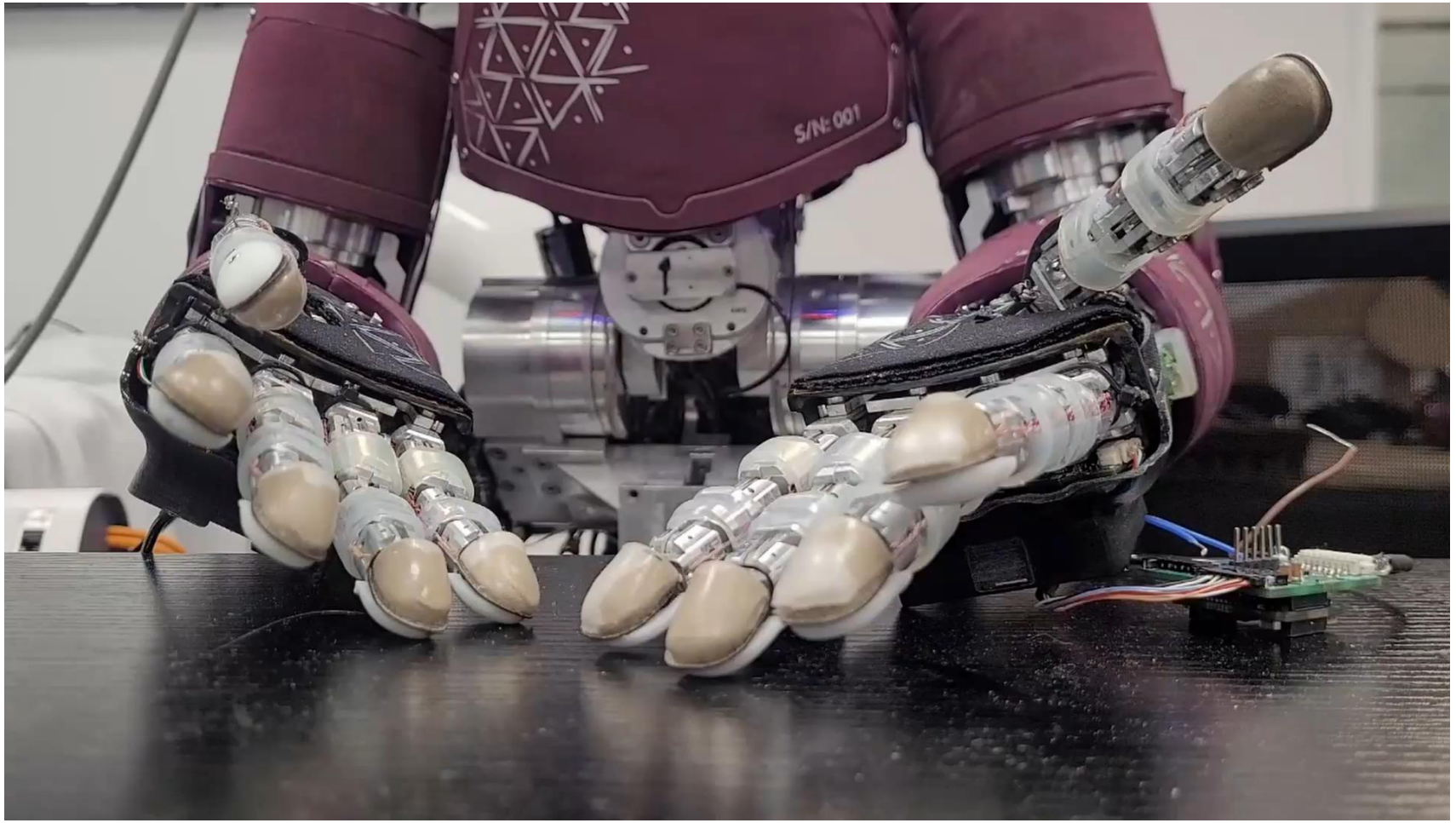


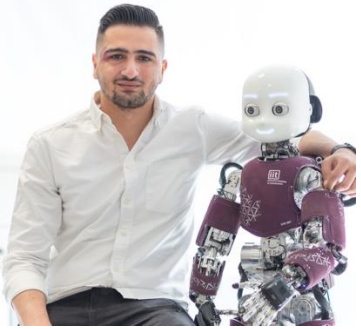
Neuromorphic sensing (Silicon CMOS)



Touch on iCub

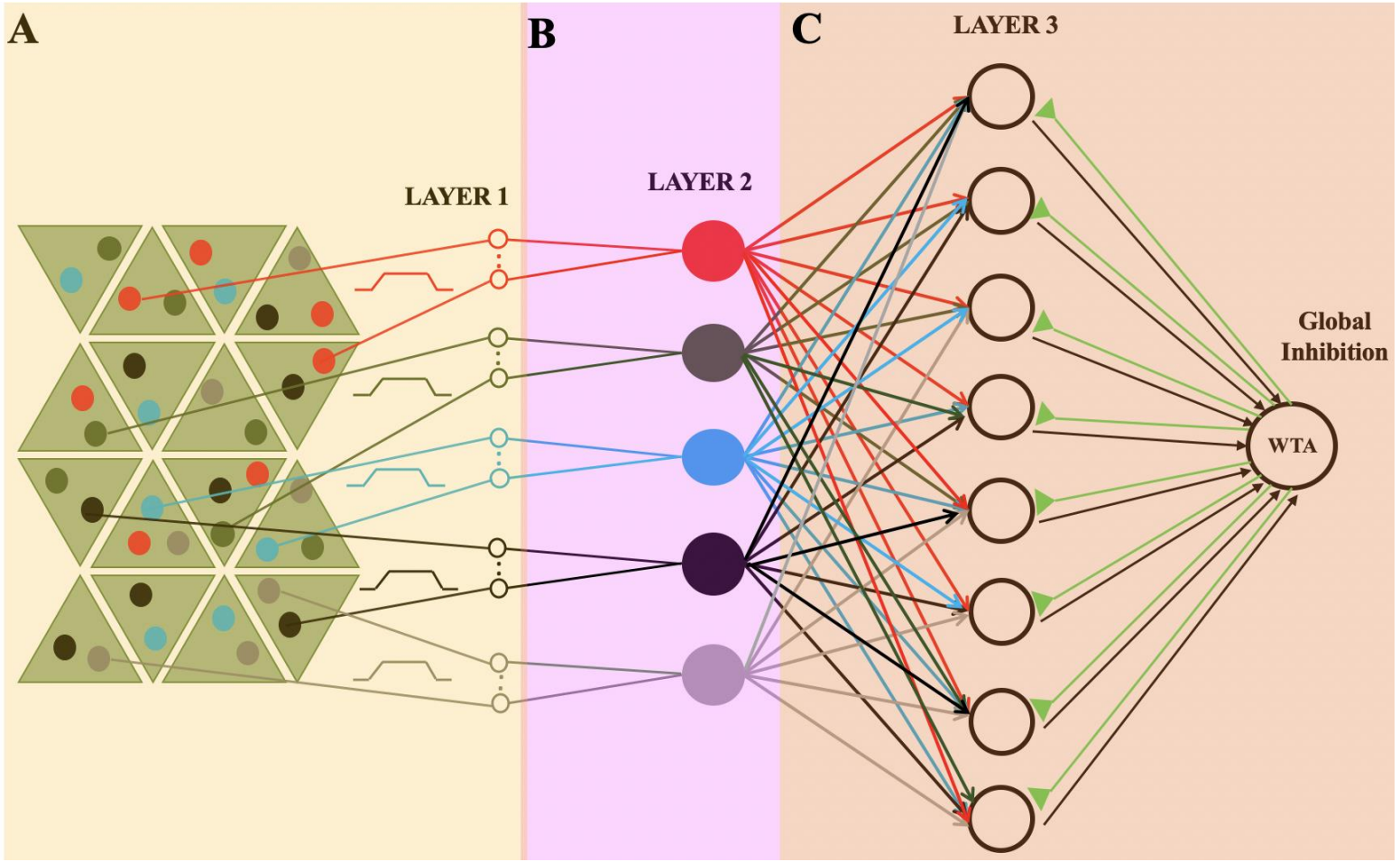
FPGA sigma-delta encoding



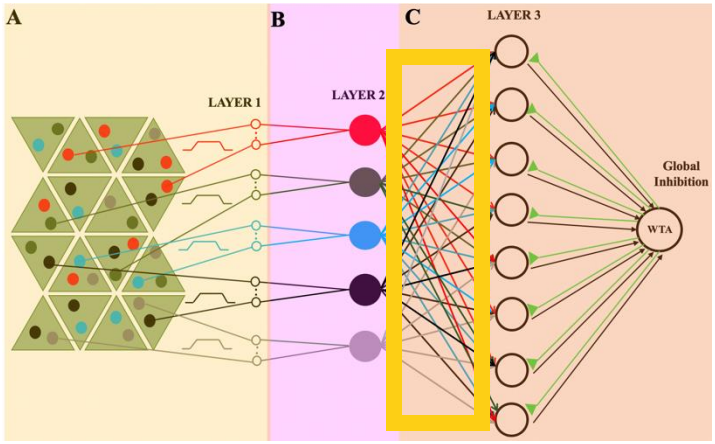


Edge orientation tuning

Capacitive sensing, soft neuromorphic



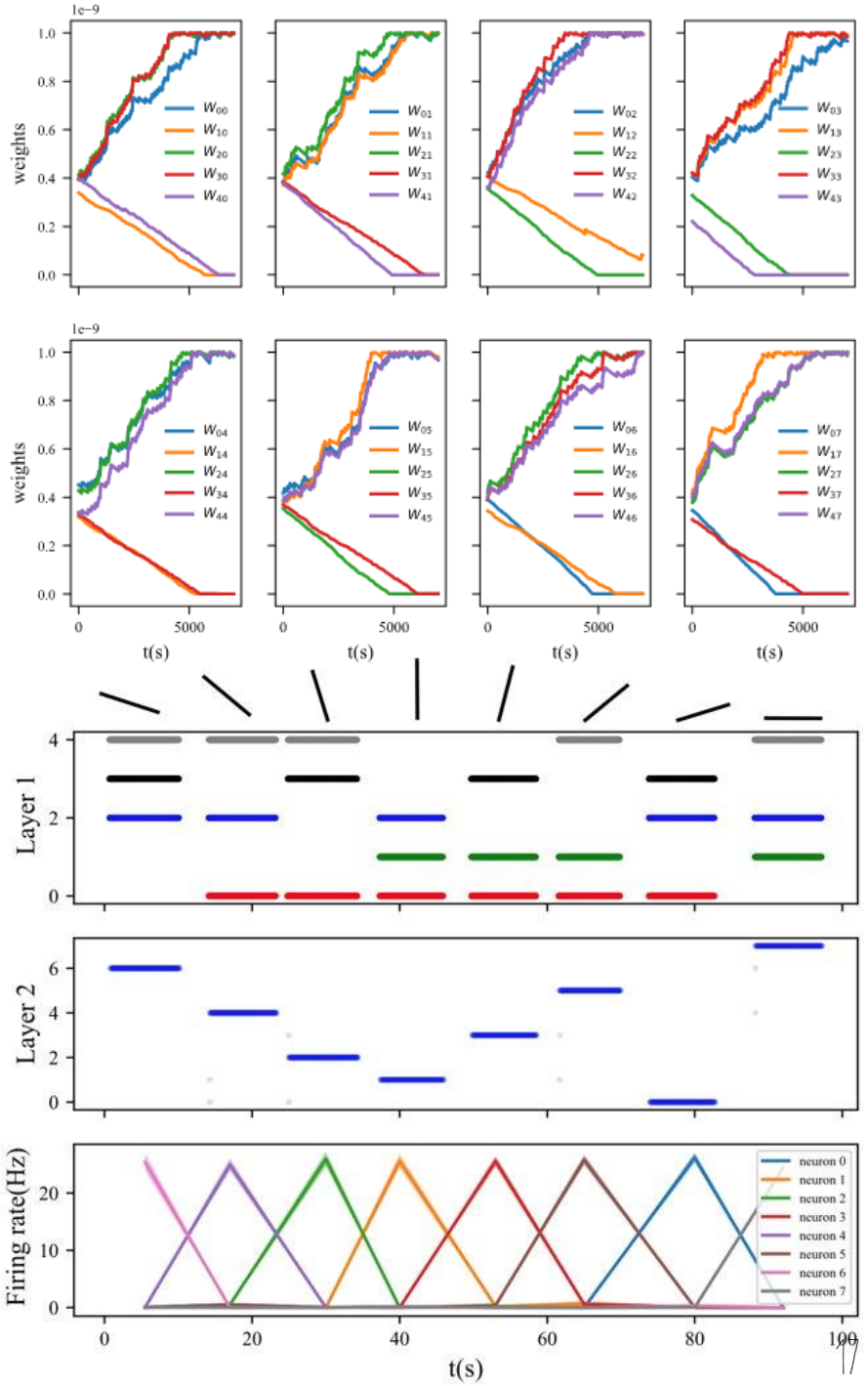
Edge orientation tuning



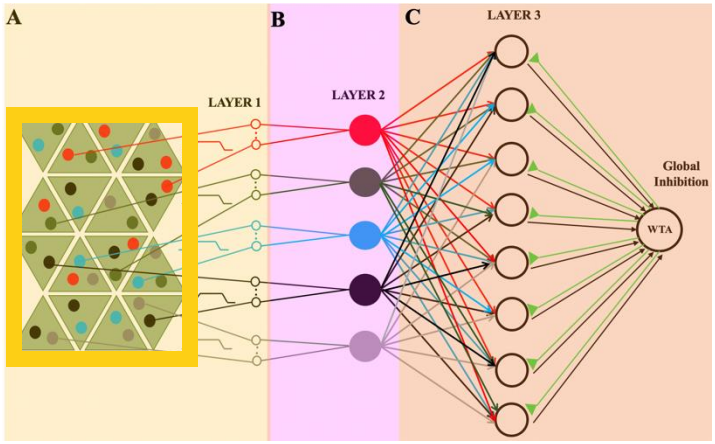
Spike Driven Synaptic Plasticity (Brader, Senn, Fusi)

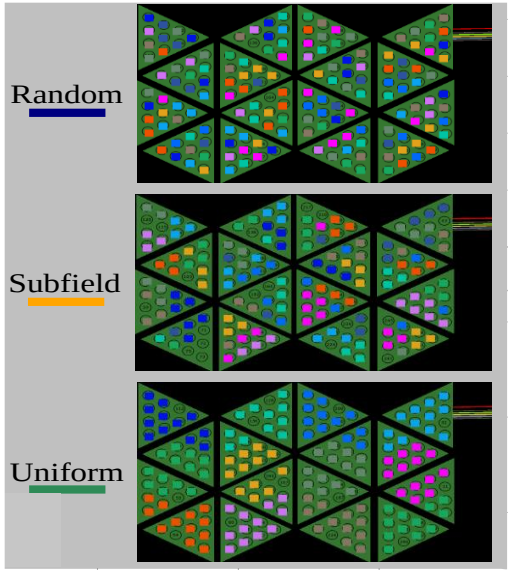
Winner-take-all

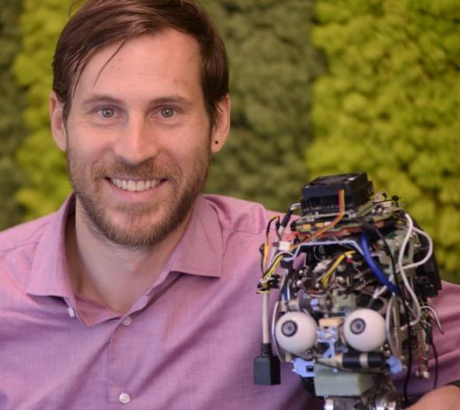
Synaptic Normalisation



Edge orientation tuning



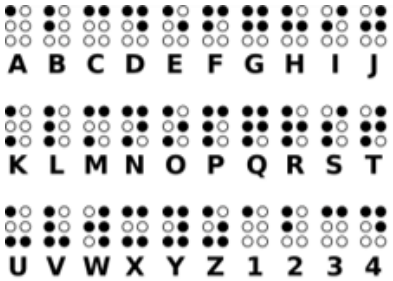


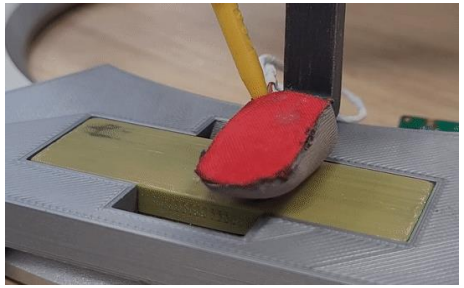


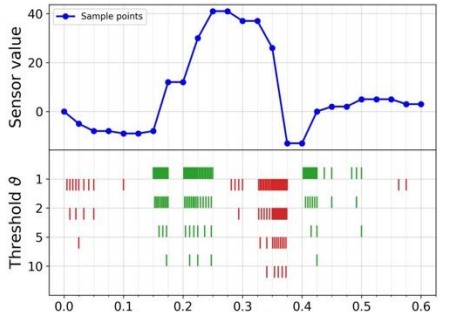
Braille reading

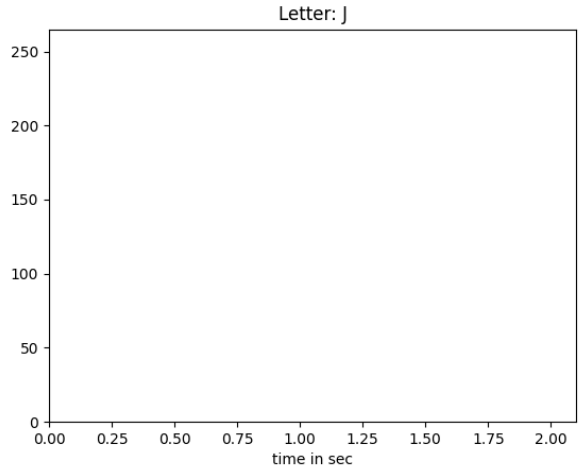
Recurrent Spiking Neural Network

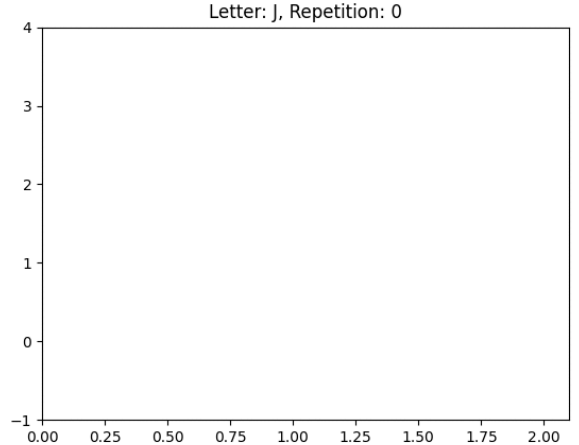
Back Propagation Through Time

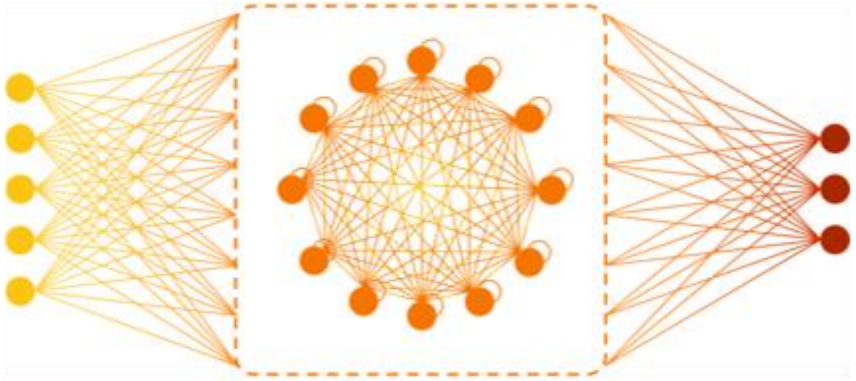












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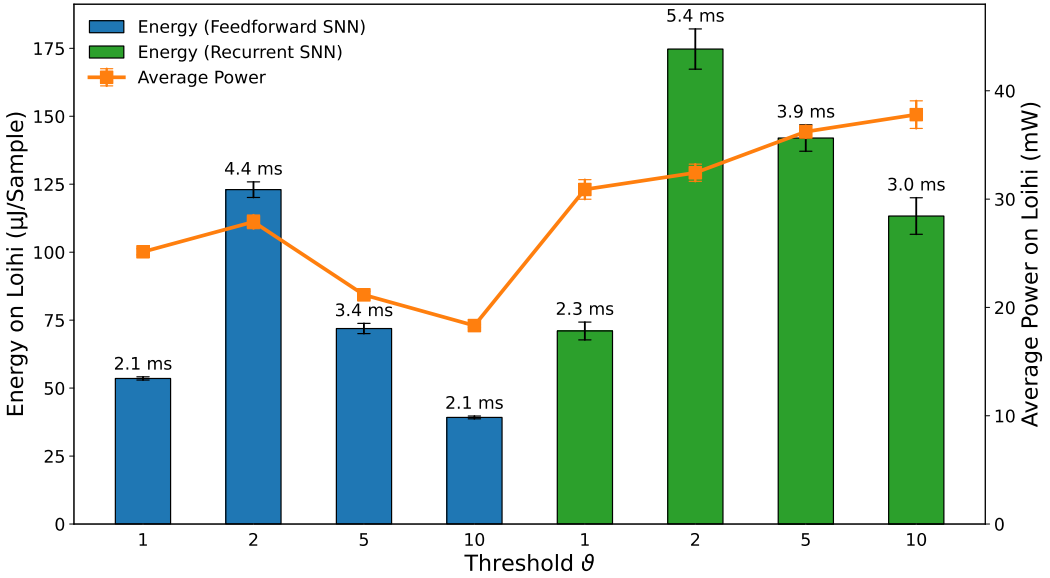
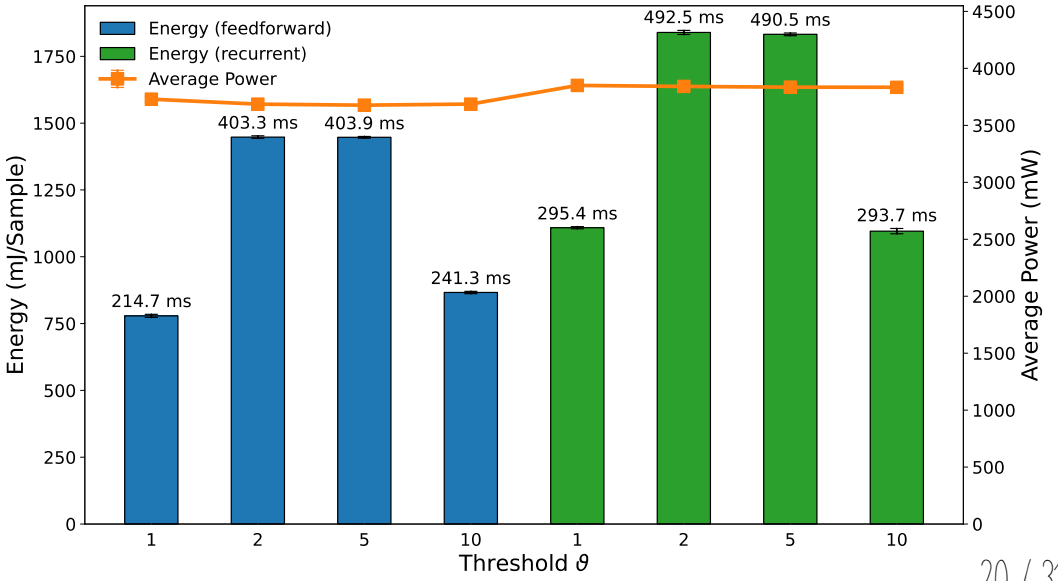
Neuromorphic HW vs GPU

Neuromorphic – INTEL Loihi



GPU – NVIDIA Jetson



Müller-Cleve et al Frontiers in Neuroscience 2022

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Neuromorphic HW vs GPU

Metric	RSNN on Loihi	RSNN on Jetson	LSTM on Jetson	RSNN on Loihi gain vs. RSNN on Jetson	RSNN on Loihi gain vs. LSTM on Jetson
Accuracy (%)	78.32	79.90	92.56	-1.58	-14.24
Total power (mW)	31	3.8k	7.4k	125x	240x
Total energy per sample (uJ)	71	1.1M	16.8M	15.6k x	237 x
Delay per sample (ms)	2.30	295.38	2.30	129x	1x

Energy and timing measurements were obtained on Nahuku 32 board ncl-ext-ghrd-01 with an Intel(R) Xeon(R) CPU E5-2650 0 @ 2.00GHz and 4GB
RAM running Ubuntu 20.04.4 LTS and NxSDK v1.0.0

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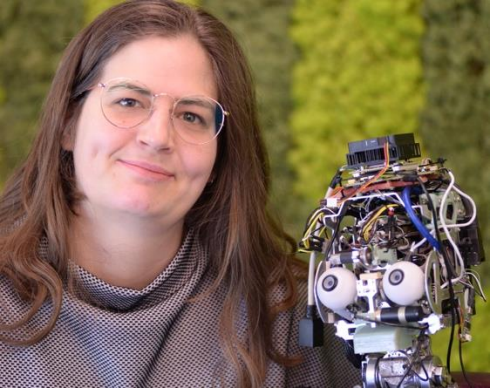
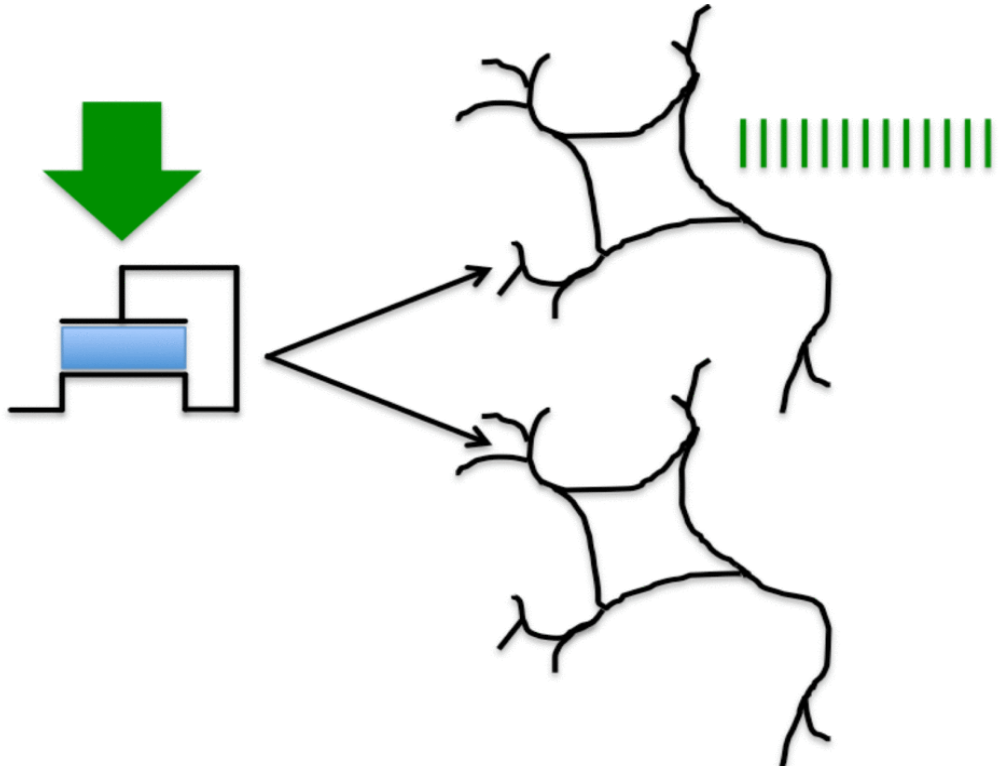
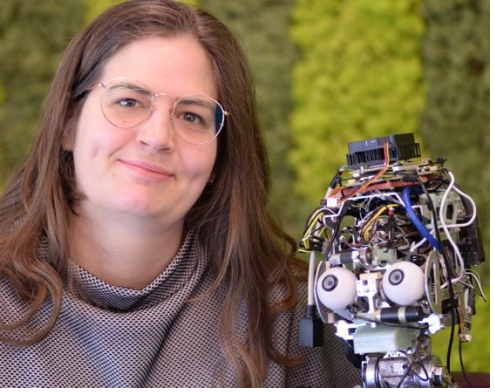


Neuromorphic touch

Spike encoding of analog signals from different physical transducers

- capacitive, piezoelectric
- Slow- Fast- Adaptive

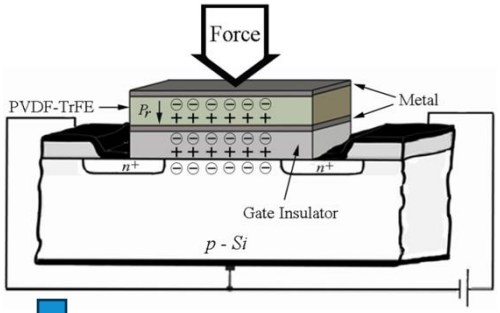


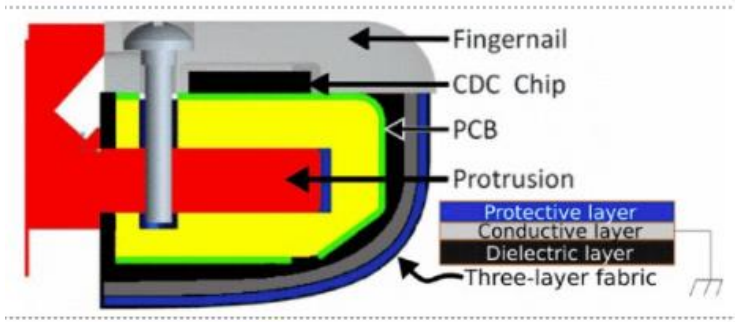


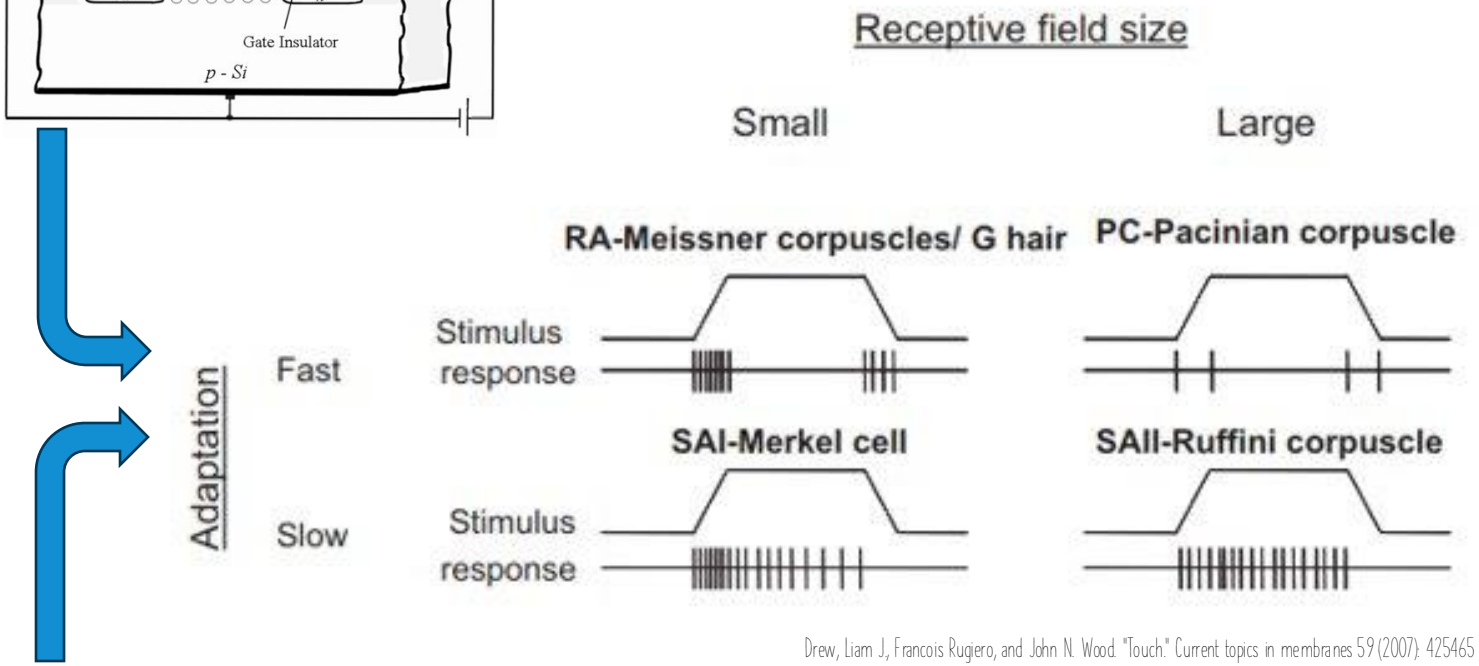
Neuromorphic touch

Spike encoding of analog signals from different physical transducers

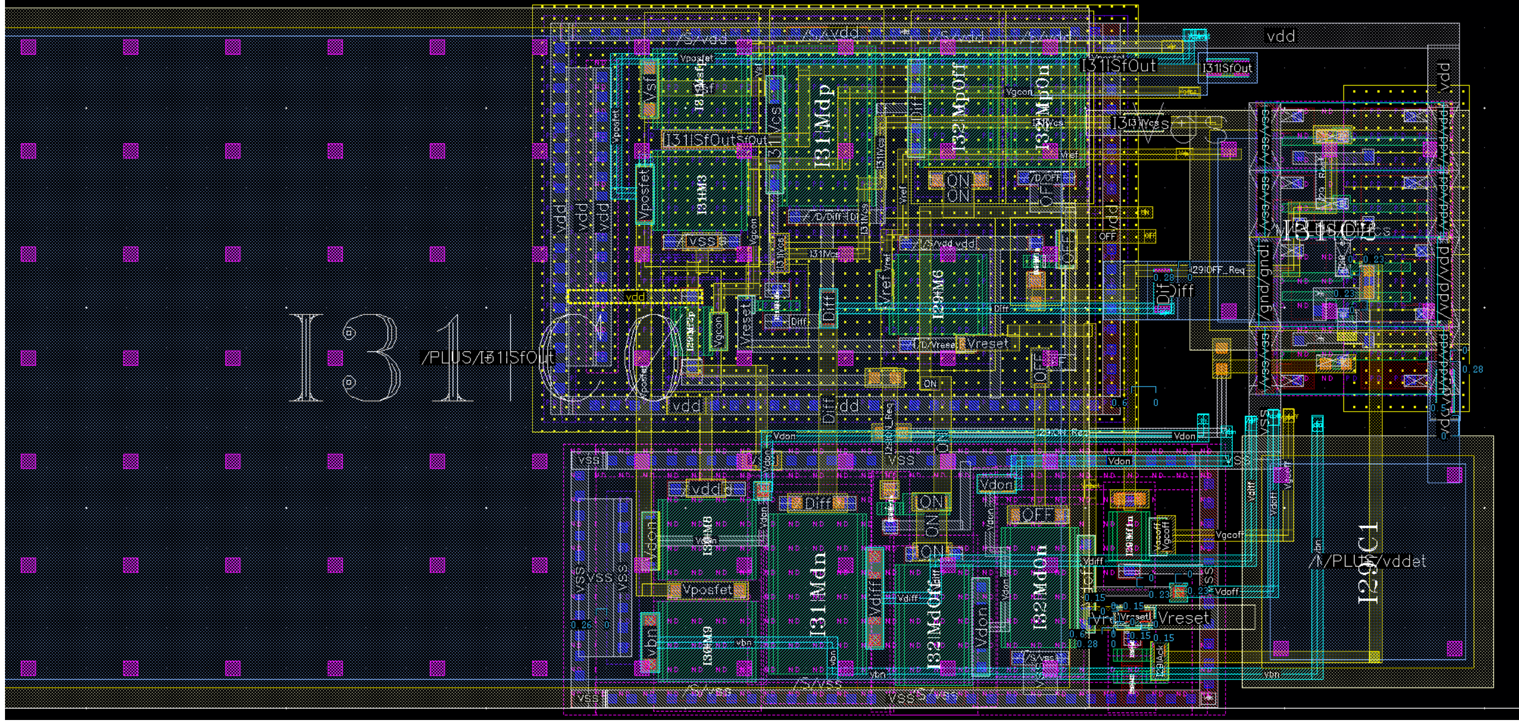
- Which transducer?
- Which encoding?





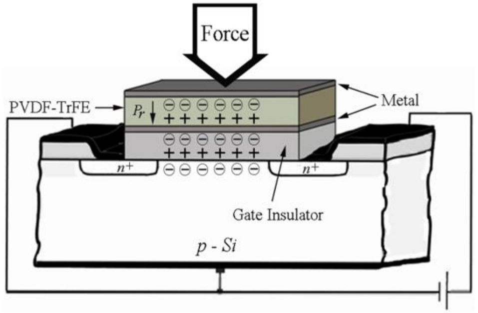


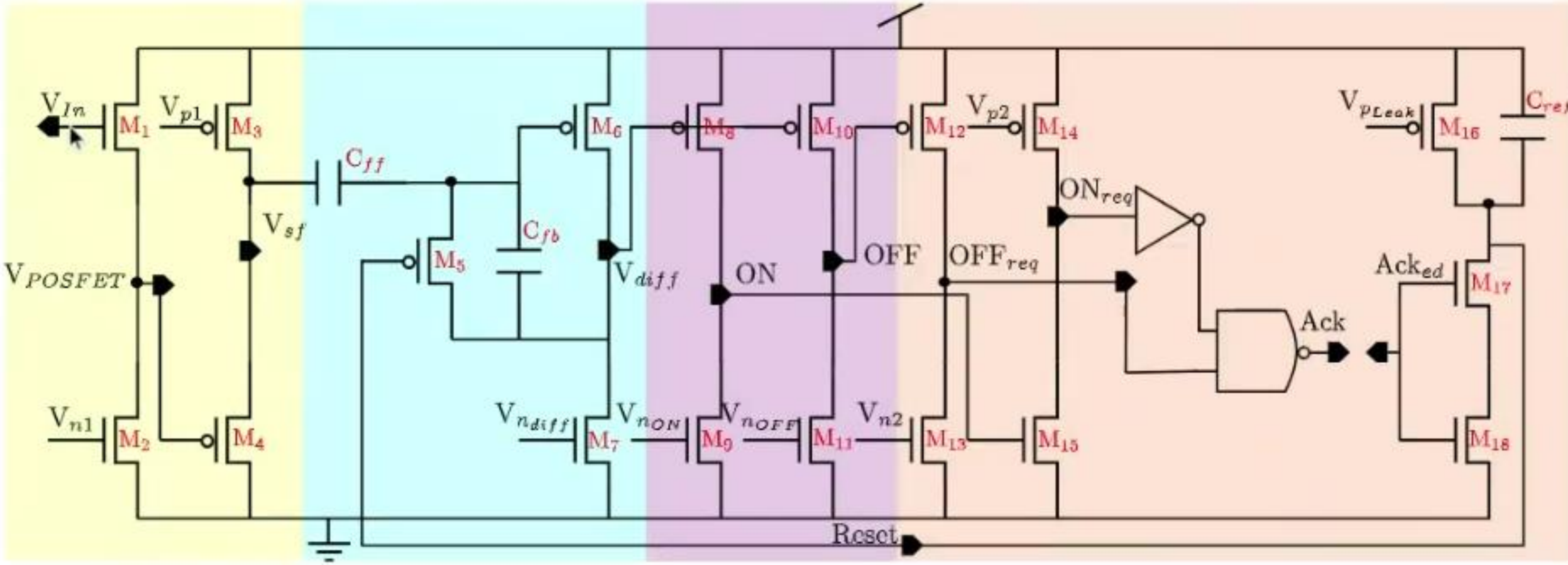
Drew, Liam J., Francois Rugiero, and John N. Wood. "Touch." Current topics in membranes 59 (2007): 425465

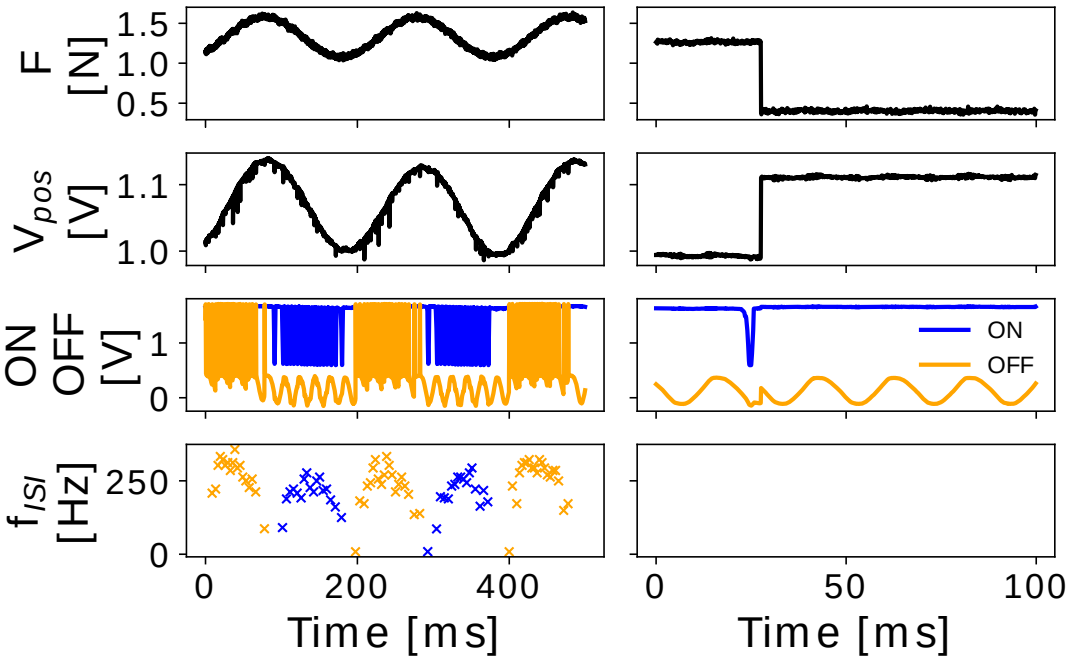


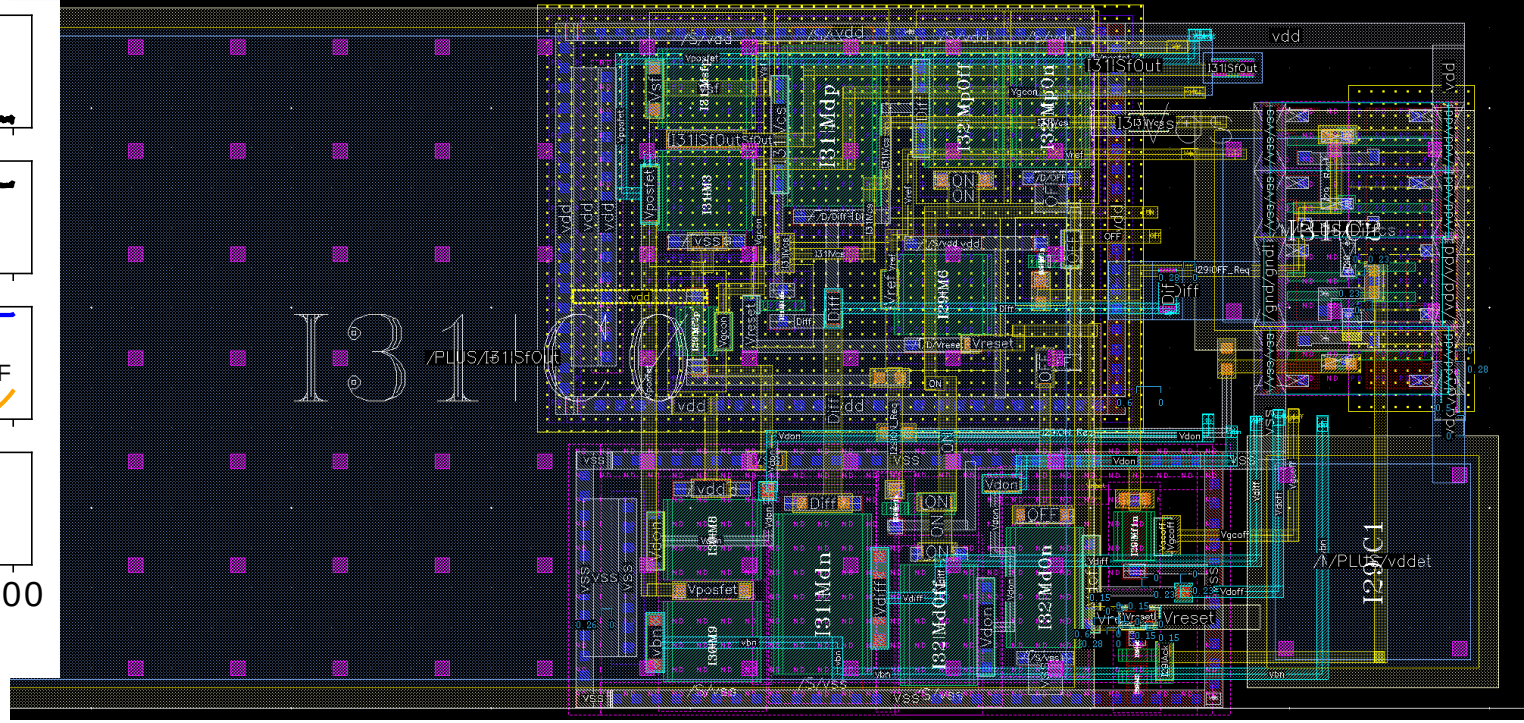
Piezoelectric

XFab 180nm, 700μm^2









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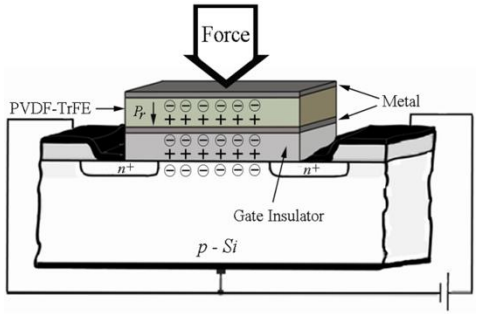
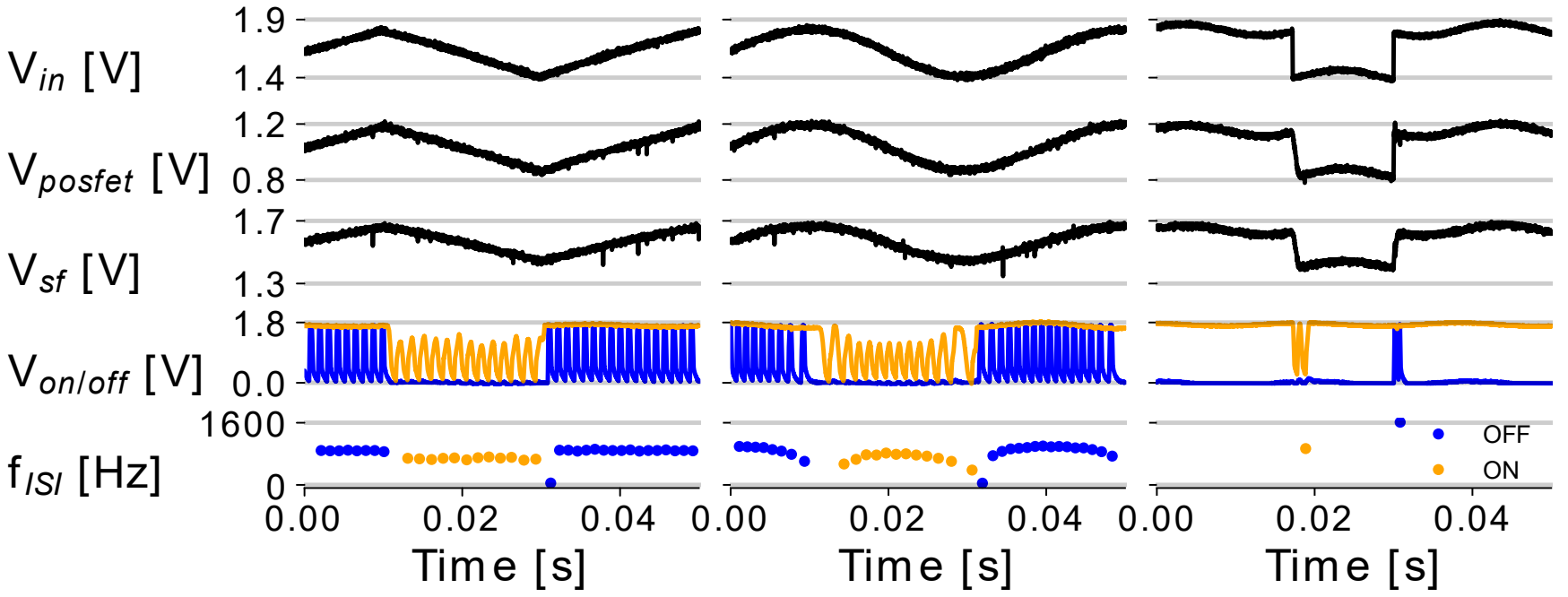
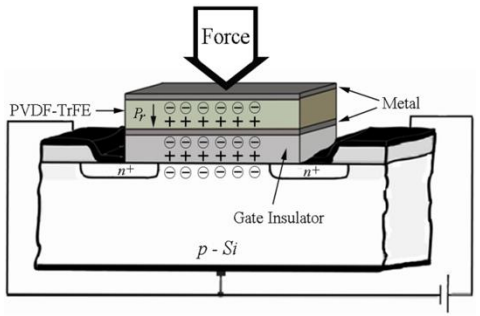
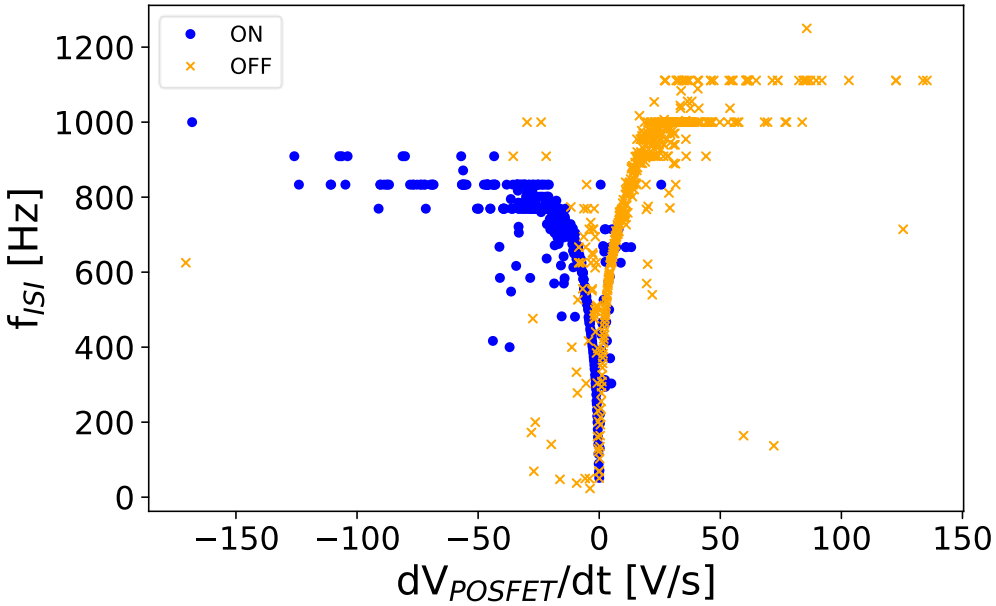


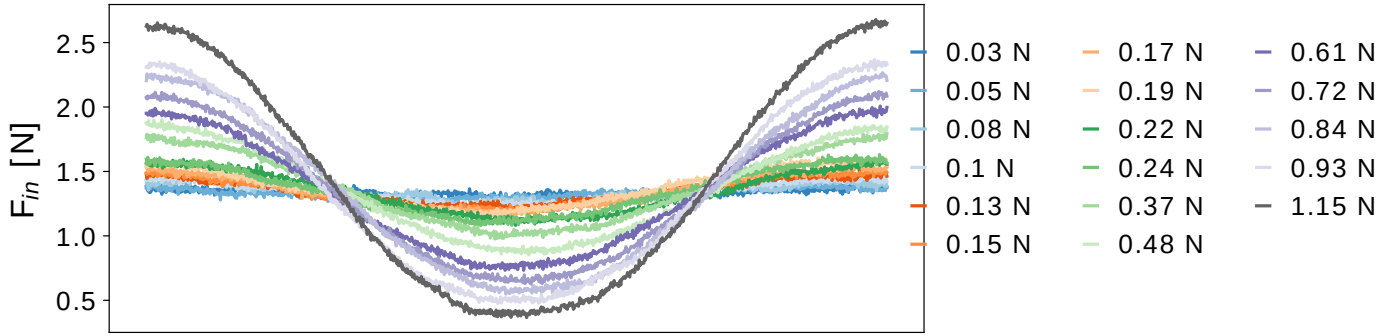


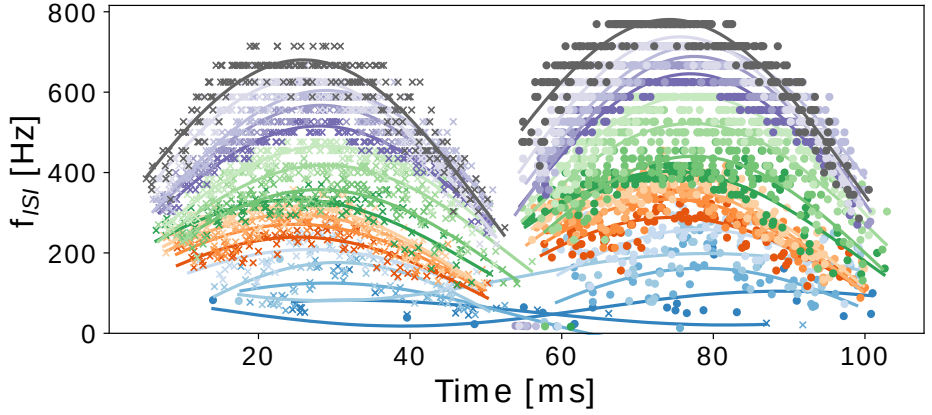
Piezoelectric

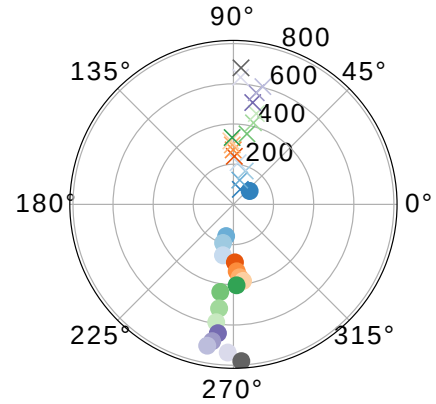
XFab 180nm





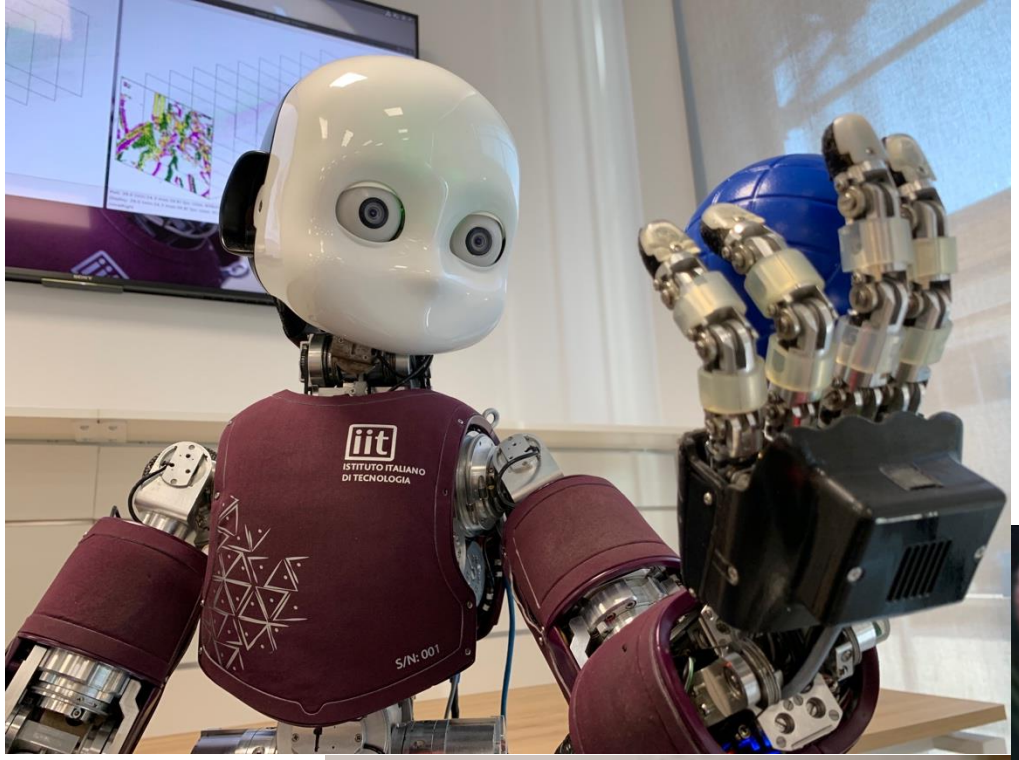






Next?

Flexible neuromorphic sensing, Embodiment, Edge applications, Neuromorphic computing HW!



Thanks!

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