What can we learn from biology for computing?

Giacomo Indiveri

Institute of Neuroinformatics
University of Zurich and ETH Zurich

June 11, 2010

Outline

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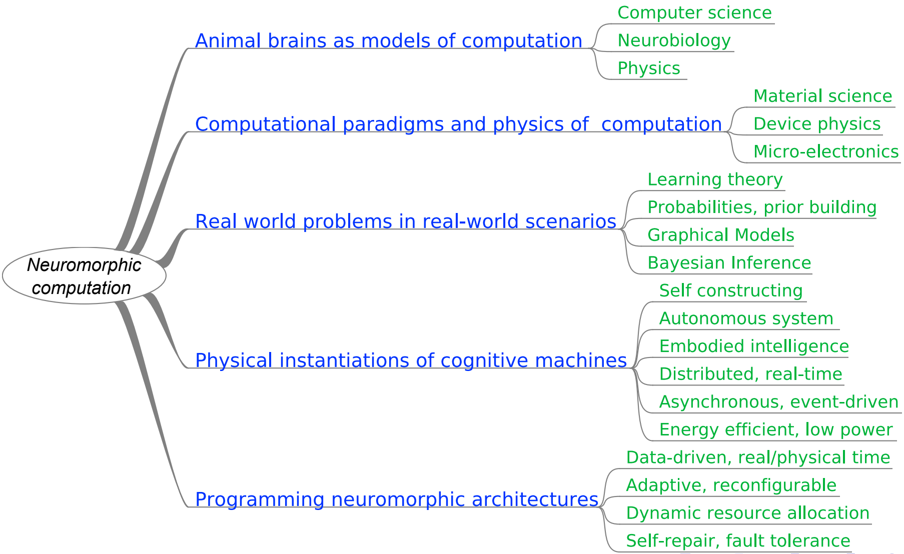
The problem: learning computing principles from the brain

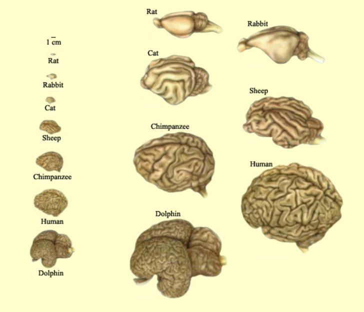
an overarching theme

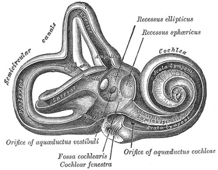


Animal brains as computational devices

(lessons from biology, for computing)

- Computation depends on the physics of the underlying computational elements.





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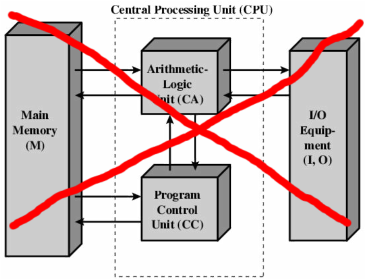
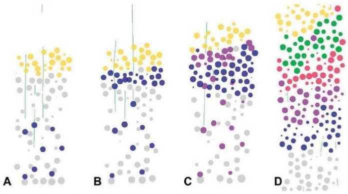
- Alternative computing paradigms alternative, *not* based on Von Neumann architectures or Boolean logic.



Animal brains as computational devices

(lessons from biology, for computing)

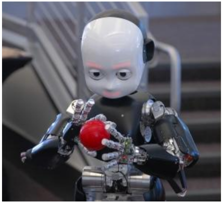
- Computation depends on the physics of the underlying computational elements.
- Alternative computing paradigms alternative, *not* based on Von Neumann architectures or Boolean logic.
- Architectures (self) constructed and evolved following a complex developmental process.



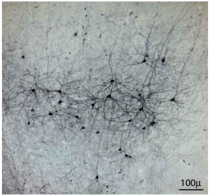
Animal brains as computational devices

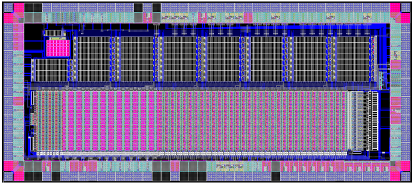
(lessons from biology, for computing)

- Computation depends on the physics of the underlying computational elements.
- Alternative computing paradigms alternative, *not* based on Von Neumann architectures or Boolean logic.
- Architectures (self) constructed and evolved following a complex developmental process.
- Solve real world problems in real-world scenarios
  - Deal with incomplete and imprecise data
  - Interact with the environment in real-time
  - Process sensory signals and produce appropriate motor actions



INI's approach





- To identify the principles of neural computation used by circuits in the brain (cat visual cortex, songbirds, etc.) through:

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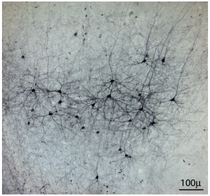

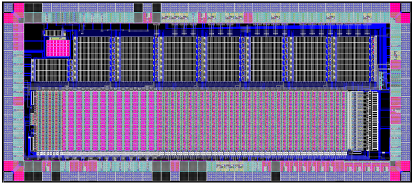

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  - *directed* neurophysiology and neuroanatomy experiments (data acquisition)

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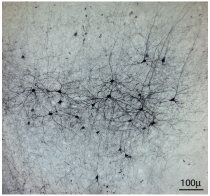

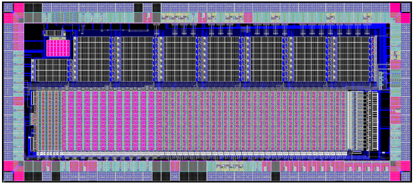

- To identify the principles of neural computation used by circuits in the brain (cat visual cortex, songbirds, etc.) through:
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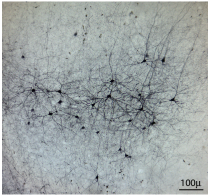

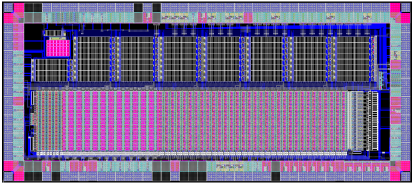

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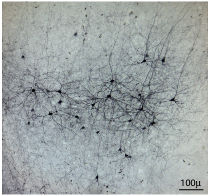

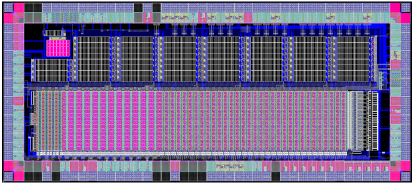

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- To reproduce the physics of neural computation using *subthreshold analog* circuits and *asynchronous digital* circuits.

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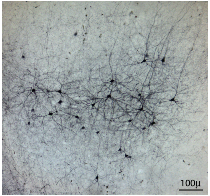

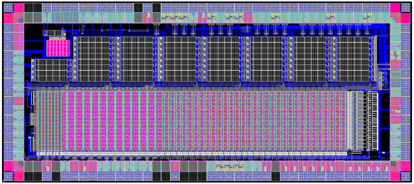

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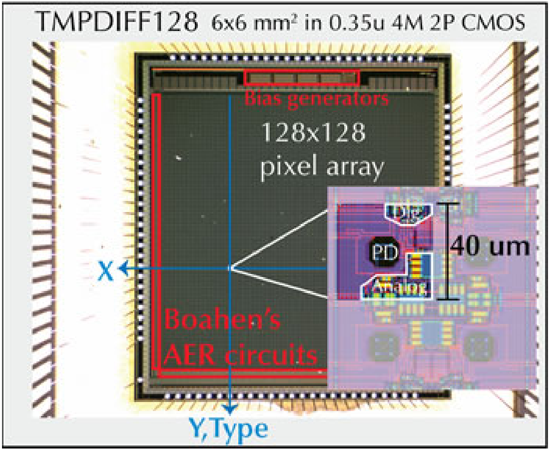
  - computing paradigms and theories compatible with anatomy, physiology and modeling results (graphical models, Bayesian inference, EM, *etc.*)
- To reproduce the physics of neural computation using *subthreshold analog* circuits and *asynchronous digital* circuits.
- To build brain-inspired, autonomous, learning, behaving systems that can interact with the environment in *real–time*.

Outline

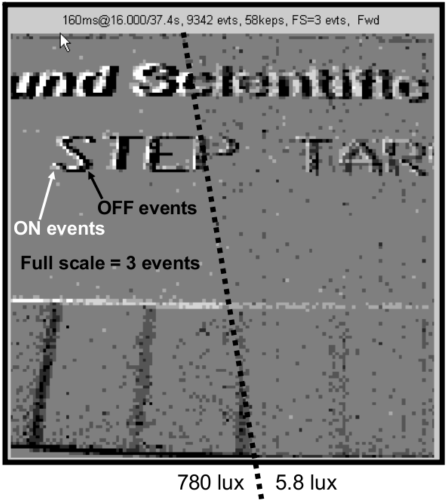
AER silicon retinas

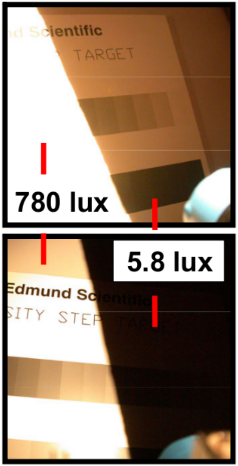
Tobi Delbruck



Silicon retina properties

http://siliconretina.ini.uzh.ch





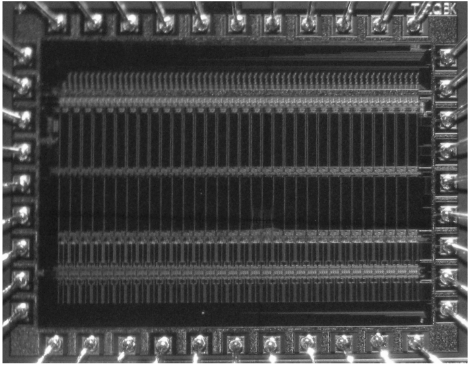
Edmund 0.1 density chart
Illumination ratio=135:1

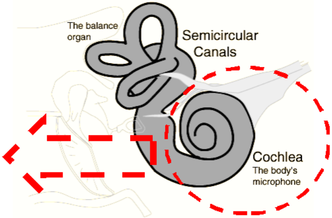
An AER silicon cochlea

Shih-Chii Liu

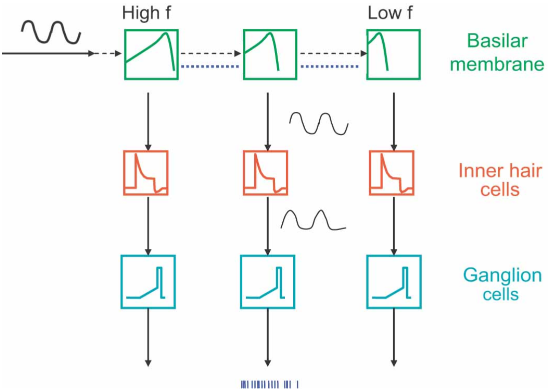
AER EAR: A Matched Silicon Cochlea Pair With Address Event Representation Interface

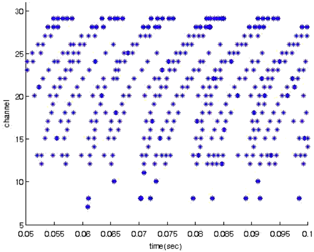
Vincent Chan, *Student Member, IEEE*, Shih-Chii Liu, *Member, IEEE*, and André van Schaik, *Senior Member, IEEE*





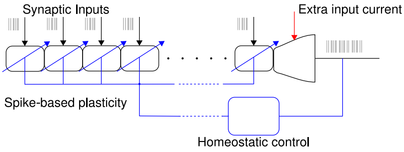
Silicon cochlea properties

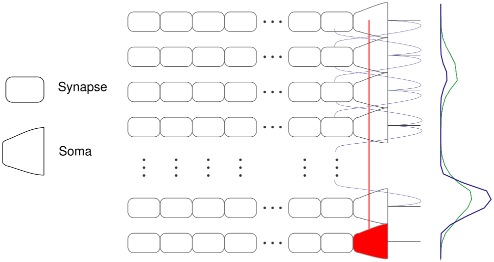


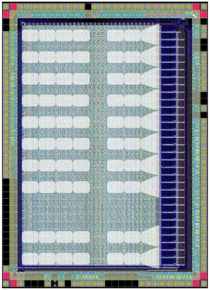


Spiking multi-neuron architectures

Giacomo Indiveri



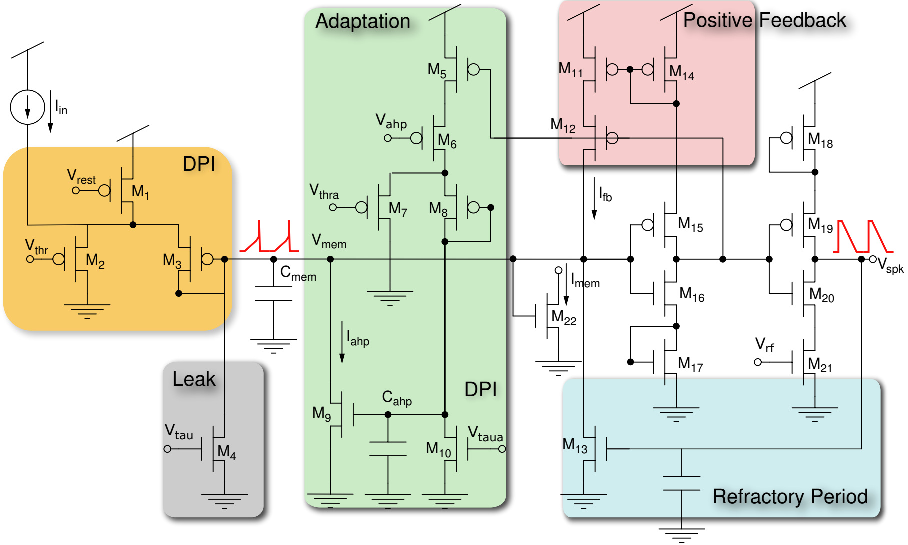




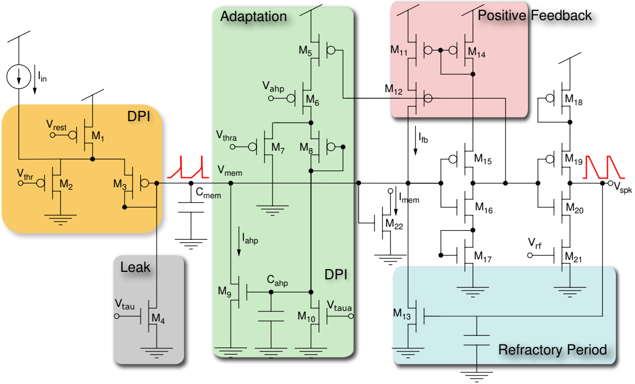
- Networks of I&F neurons with adaptation, refractory period, *etc.*
- Synpases with realistic temporal dynamics
- Winner-Take-All architectures
- Spike-based plasticity mechanisms

Outline

An ultra-low power generalized adaptive I&F circuit



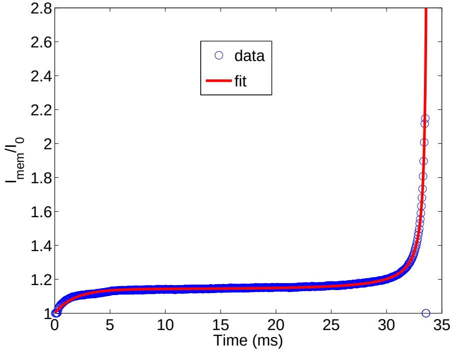
Circuit subthreshold equations

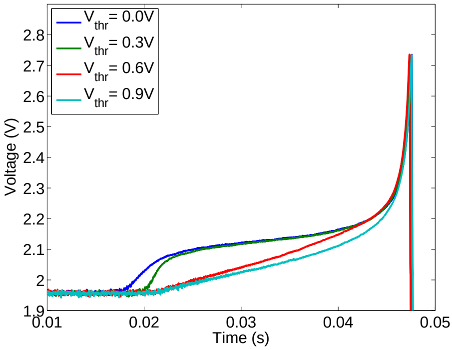


$$C_{mem}\frac{d}{dt}V_{mem} = (I_{dpi} - I_{\tau}) - I_{ahp} + I_{fb}$$

$$I_{fb} = I_0^{\frac{1}{\kappa+1}} I_{mem}^{\frac{\kappa}{\kappa+1}} \frac{1}{1+e^{-\alpha(I_{mem}-I_{th})}}.$$

Circuit closed form solution

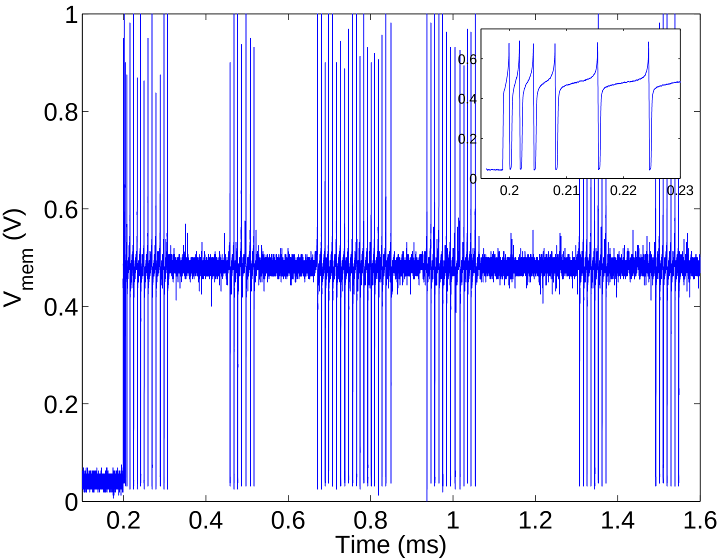




$$I_{mem}(t) = I_0 + \frac{I_g I_{in}}{I_\tau}(1 - e^{-t/\tau}) + I_{fb0}\left(\frac{e^{\alpha(t-t_0)}}{1 + \beta e^{\alpha(t-t_0)}}\right)$$

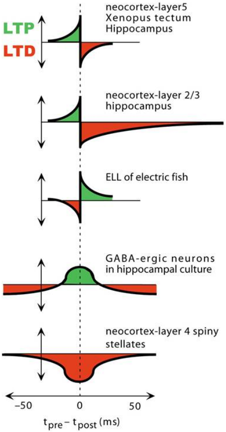
(Brette & Gerstner 2005)

Spike frequency adaptation



Outline

Spike timing based learning: beyond STDP



Spike timing and analog voltages

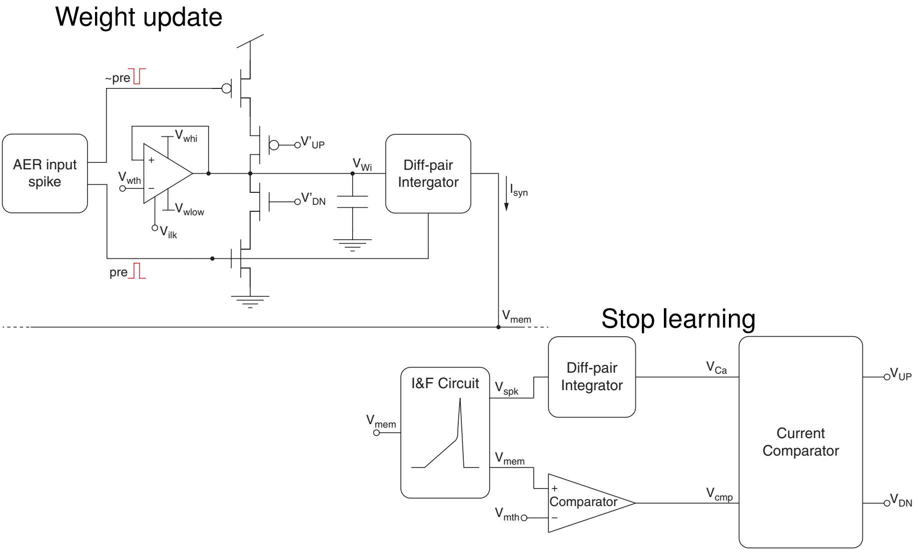
Weight change depends on the timing of the pre-synaptic spike, on the value of the post-synaptic neuron's membrane potential, and on its past spiking activity.

Fusi et al. 2000; Gutig & Sompolinsky 2006; Brader et al. 2007

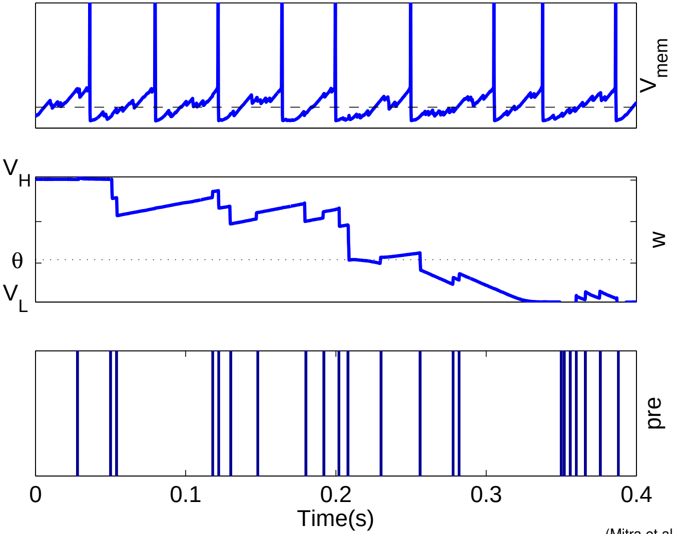
Theoretical prescription

1. Bistability: use two stable synaptic states;
2. Redundancy: implement many synapses that see the same pre- and post-synaptic activity.
3. Stochasticity: update only random a subset of stimulated synapses.
4. Stop-learning: stop updating weights if the output rate sufficiently high (or low).

Weight update circuits

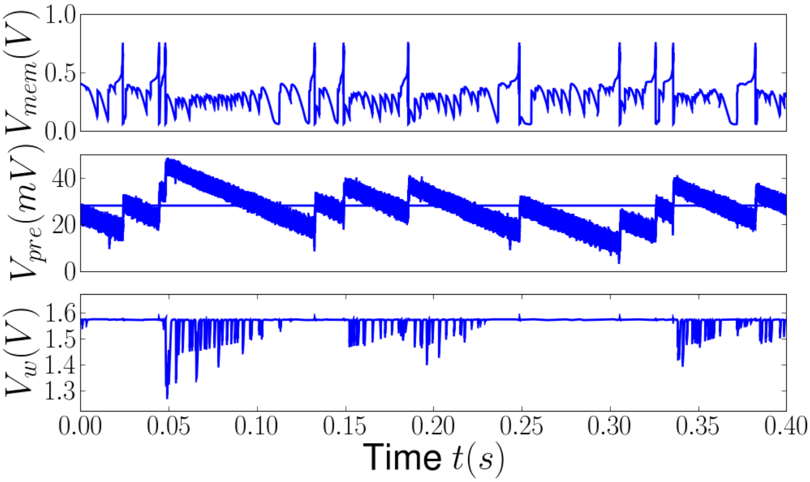


Weight updates



(Mitra et al., TBCAS, 2009)

Stop Learning



Outline

What we learned

- The brain is a very complex computational engine. "If the brain finds a successful strategy to get something accomplished, it does it at all levels, from the molecular structure of proteic channels, to the full network and development level" (Matteo Carandini).
- It's not hopeless: it is possible to find common strategies used by neural circuits, common classes of cells, connectivity patterns, coding schemes.
- It is possible to build silicon devices that faithfully reproduce the biophysics of their neural counterparts, and use them for practical applications.
- Building *cognitive* neuromorphic systems, that go beyond basic sensory processing (*e.g.* with learning) is non-trivial...

What we need to do

- Combine the process of hypothesys building with that of observation making: i.e. computer science with experimental neuroscience, physics and engineering with biology.
- Validate the computational theories, models and algorithms developed on neuromorphic real-time behaving systems (analogous to fabricating a chip, to validate the TSPICE simulations).
- Start an FET Flagship Initiative :)

Acknowledgments

The Institute of Neuroinformatics

- Tobi Delbruck
- Shih-Chii Liu
- Elisabetta Chicca
- Rodney Douglas
- Kevan Martin
- Richard Hahnloser

Funding sources

- SCANDLE EU project
- eMorph EU project
- SoundRec Swiss NSF project
- nAttention Swiss NSF project

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