Neuromorphic Computing: Embodiment of Cognitive Neuronal Dynamics

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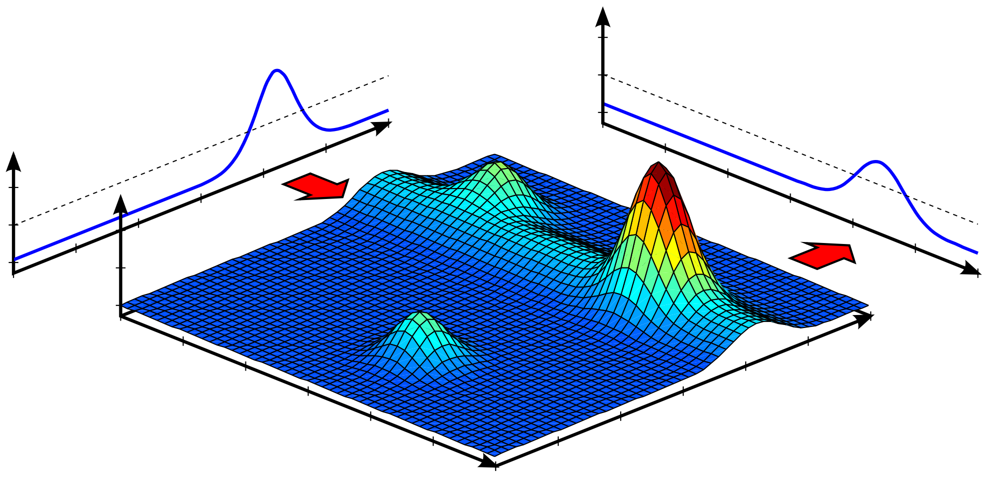


What is “Cognition”?

Cognitivity of behavior:

➡ Decisions

- defined by the sensed state
- stimulus - response

➡ Memory

- decoupling from the sensory flow

• Working memory

- Moment-to-moment memory

• Long-term memory

- habits
- skills
- controllers
- episodes
- contingencies
- semantics / language
- relations

A story of the sugar-searching bacteria

Marc Bickhard “Interactivism”

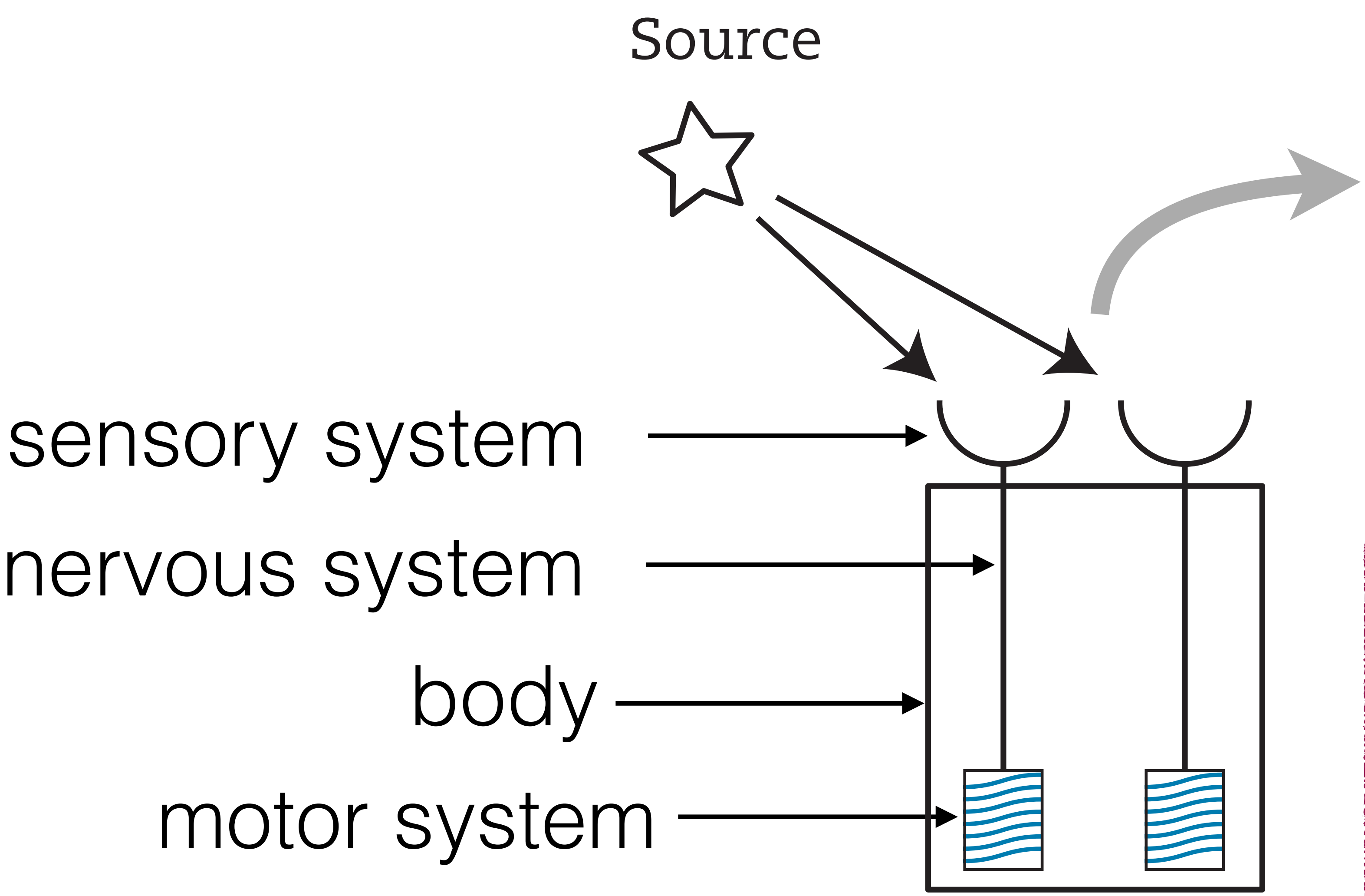
Cognitive "computing"



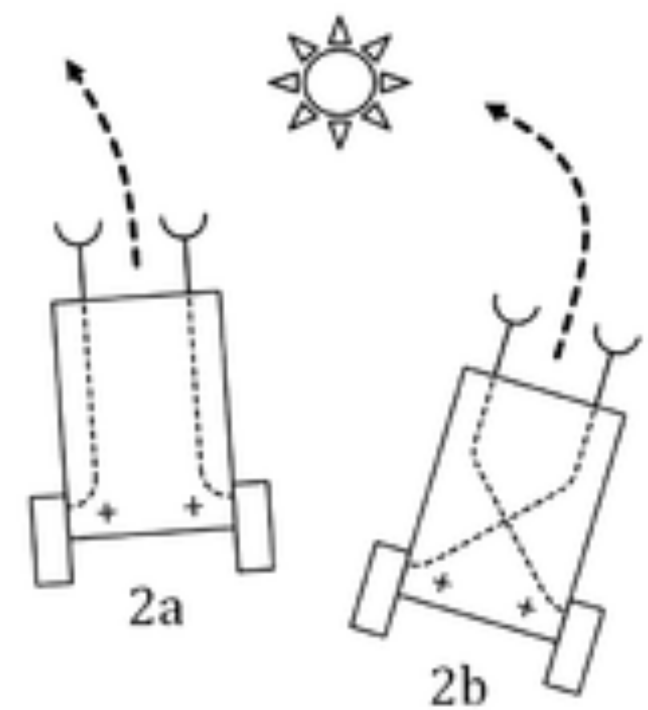



- biological neural systems evolved to produce behavior
- amazing perception, adaptivity, control, learning capabilities
- efficient, robust, and powerful with "noisy" biological elements

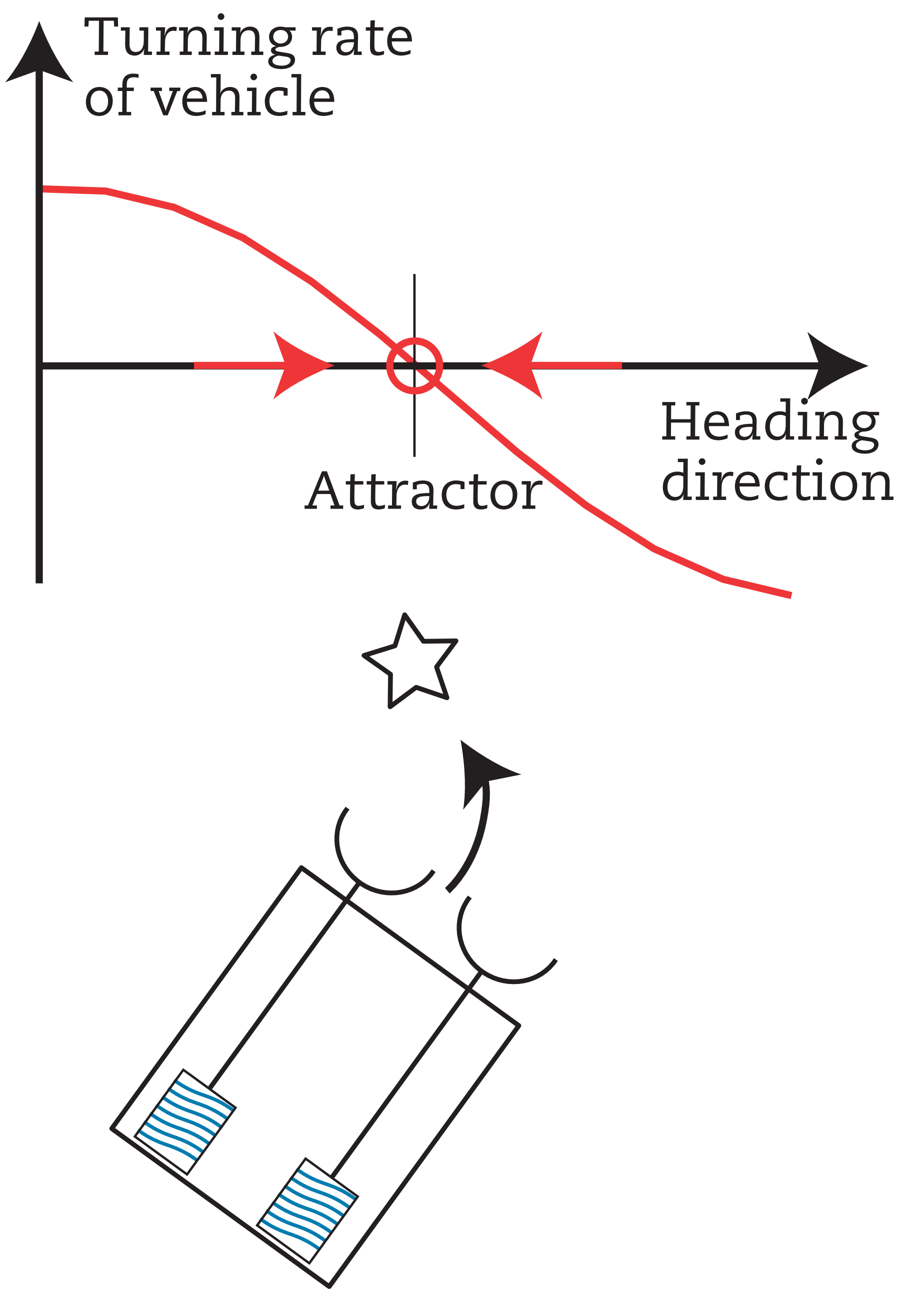
Neuronal mechanisms: Braitenberg Vehicle



Different behaviours:



Mathematical formalisation: attractor dynamics

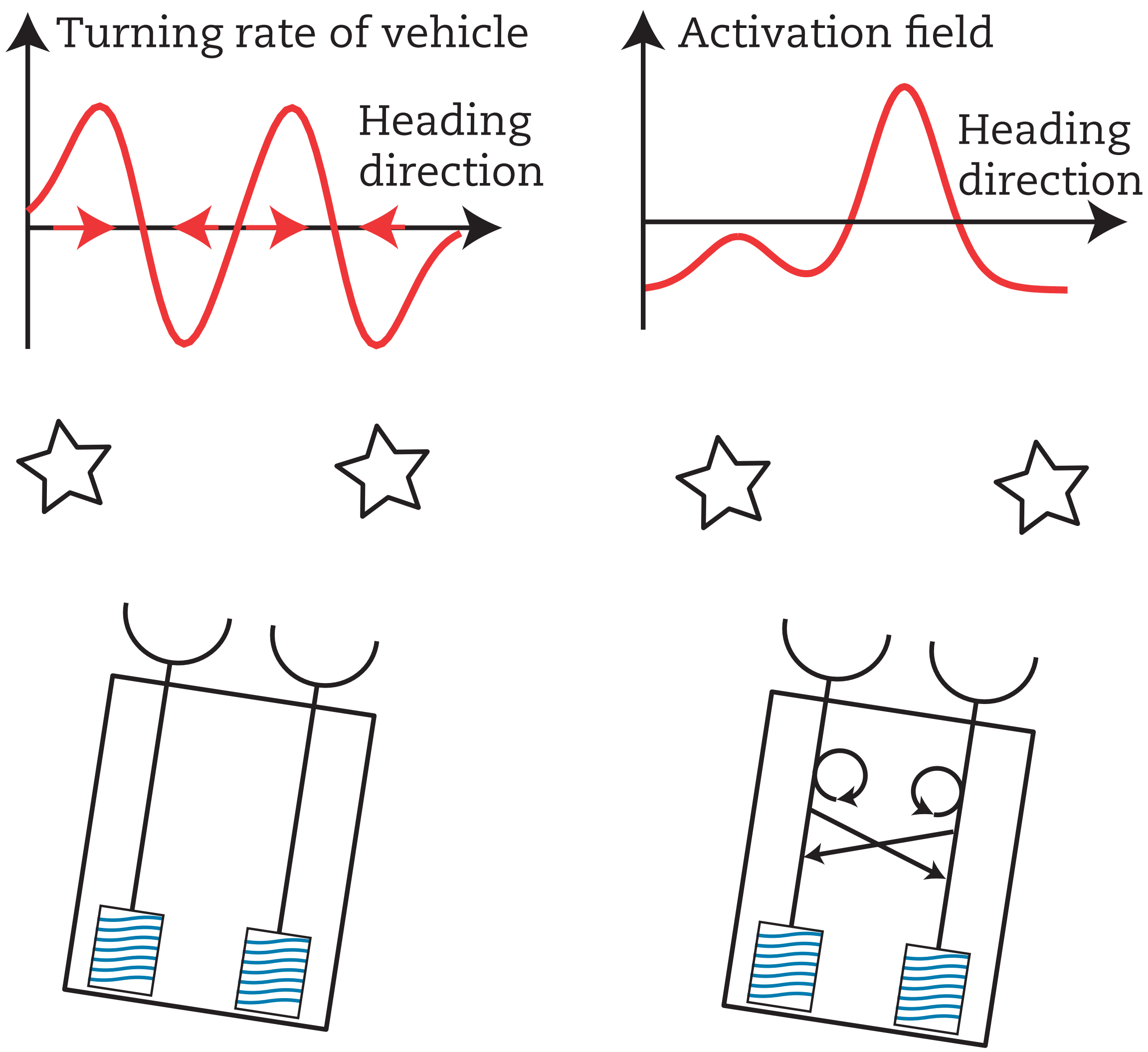


- "behavioral variable"
  - describes the behavior
- its rate of change:

$$\tau\dot{\phi}(t) = -\phi(t) + A(t)$$

  - determines its dynamics
- overt behavior corresponds to attractors
  - stability

Multiple targets



- represent “utility” of options
- stabilise decisions

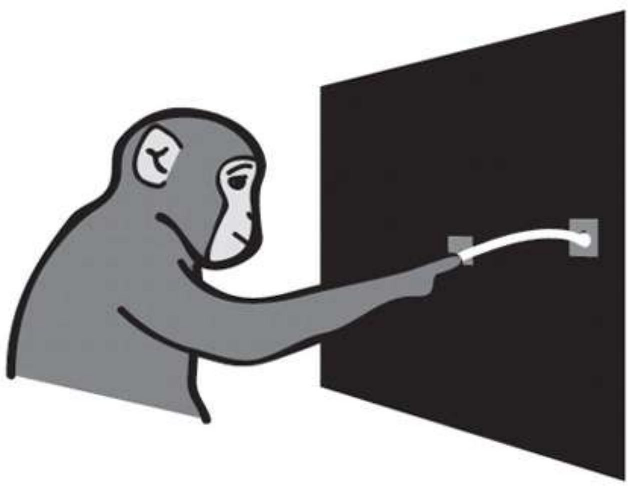
$$\boxed{\dot{\phi}(t) \rightarrow \dot{u}(\phi, t)}$$

“activation” and its dynamics

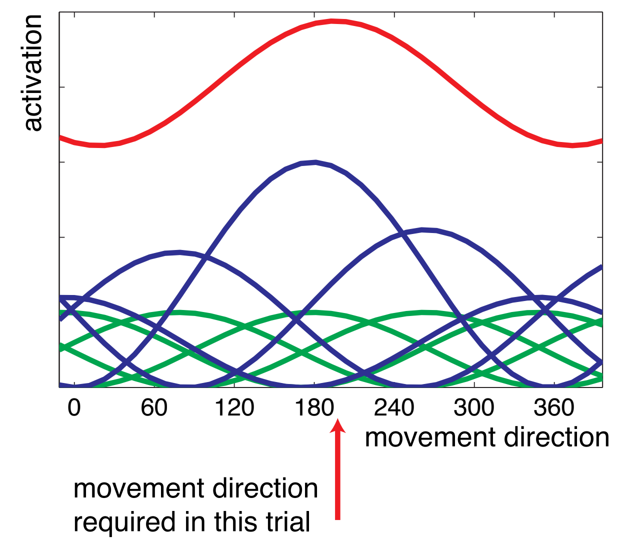
➔ Neural dynamics

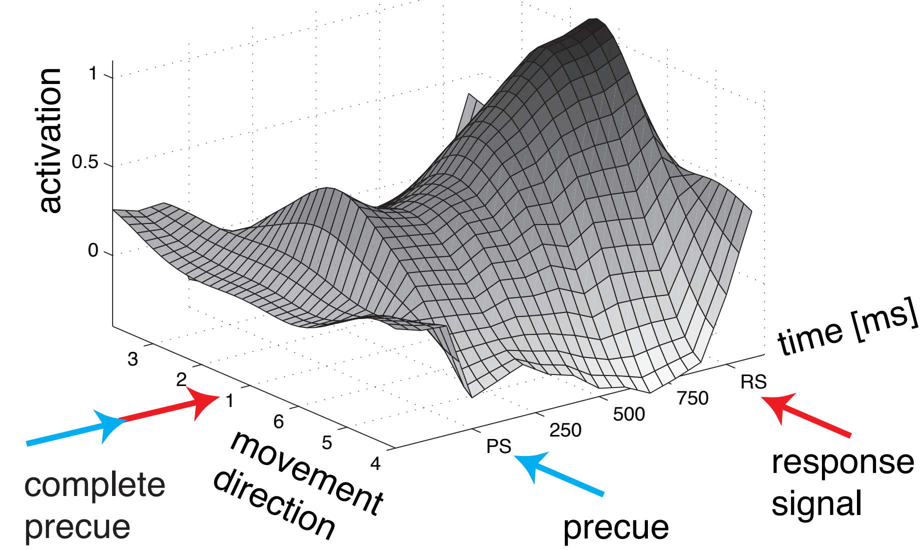
Neuronal correlate of behavior: population activity

"Reaching" task



Distribution of population activation = $\sum_{\text{neurons}}$ tuning curve * current firing rate





➡"Dynamic neural field" model

$$\tau\dot{u}(x,t) = -u(x,t) + h + \int f\big(u(x',t)\big)\omega(x-x')dx' + I(x,t)$$

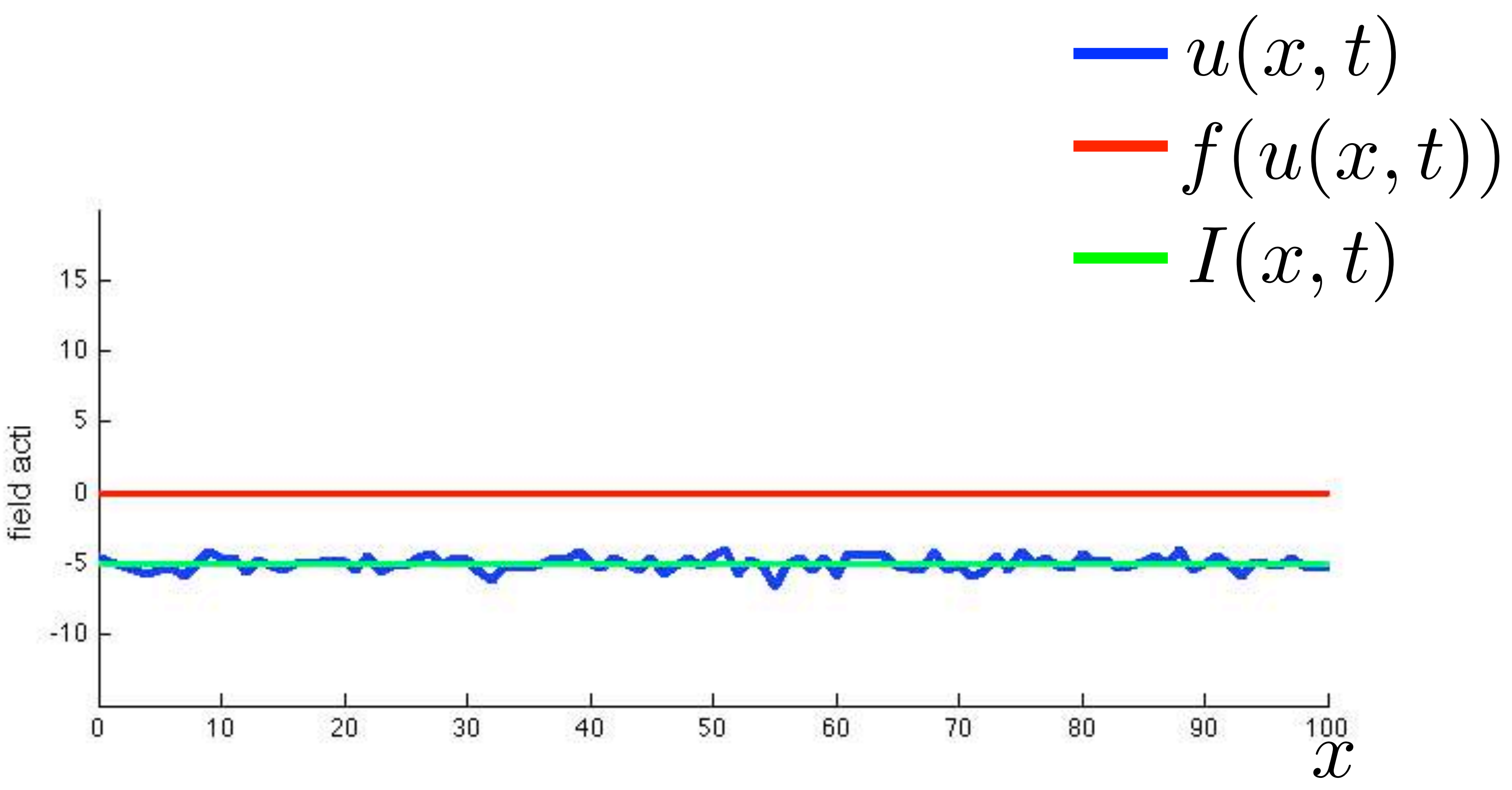
Amari, S. **Dynamics of pattern formation in lateral-inhibition type neural fields**. Biological Cybernetics, **1977**, 27, 77-87

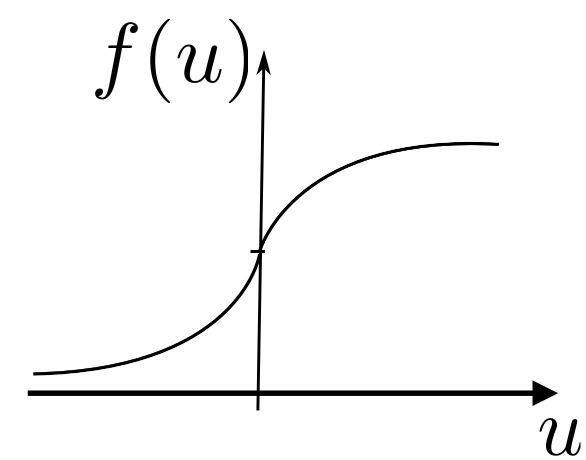
Wilson, H. R. & Cowan, J. D. **A mathematical theory of the functional dynamics of cortical and thalamic nervous tissue**. Kybernetik, **1973**, 13, 55-80

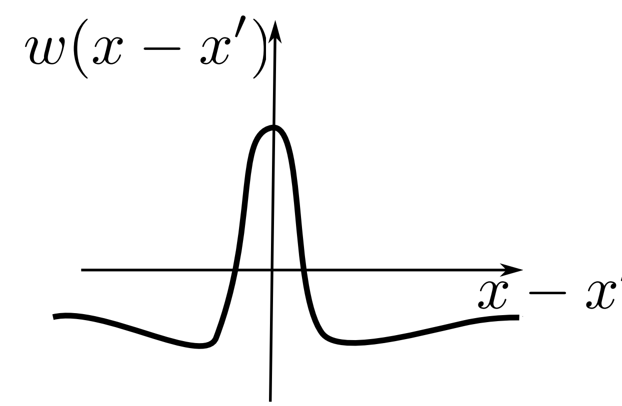
Gerstner, Grossberg, Ermentrout, Coombes, Schöner&Spencer, Erlhagen…

Neural dynamics

Dynamic Neural Field, WTA, bump-attractor networks





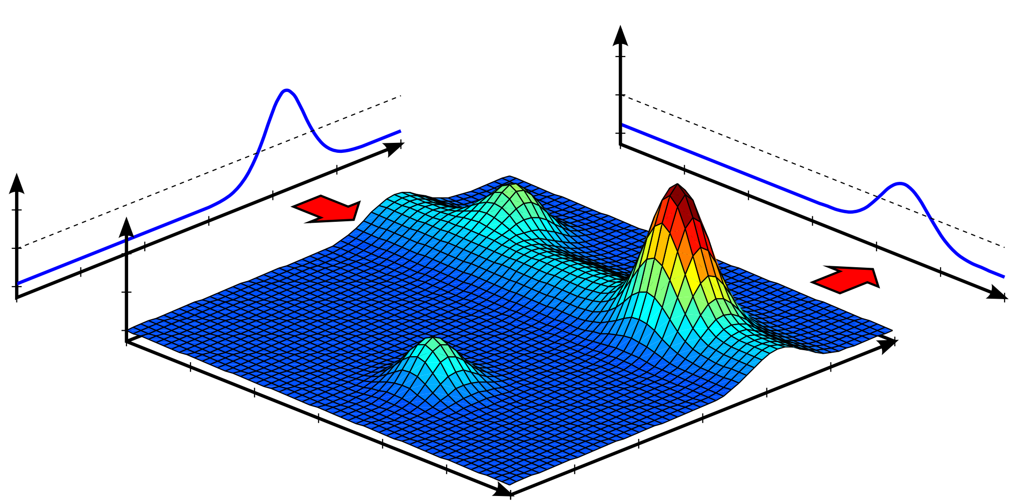


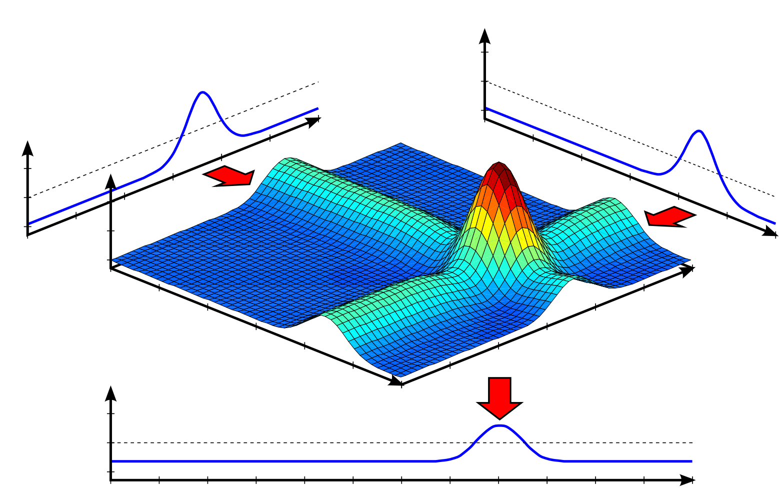
$$\tau\dot{u}(x,t) = -u(x,t) + h + \boxed{\int f(u(x',t))\omega(x-x')dx'} + I(x,t)$$

“Cognitive” properties of Neural Fields

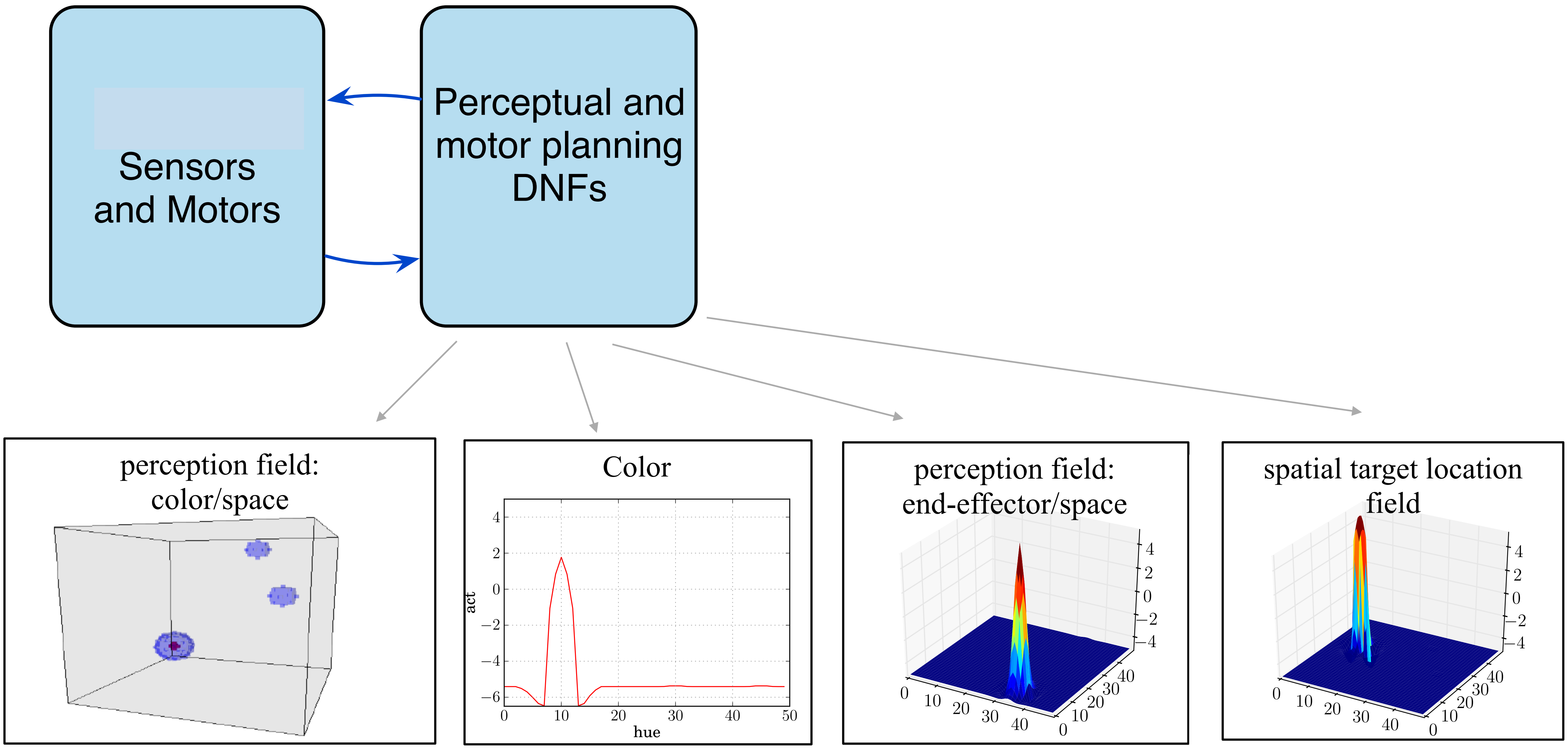
- “Detection” and “forgetting” instabilities
  - continuous time ⟶ discrete “events”
- Localised “bumps”
  - continuous space ⟶ discrete “categories”
- “Selection” instability
  - stabilisation of selection decisions
- Sustained activation
  - modelling working memory

➡ DNF “Architectures”



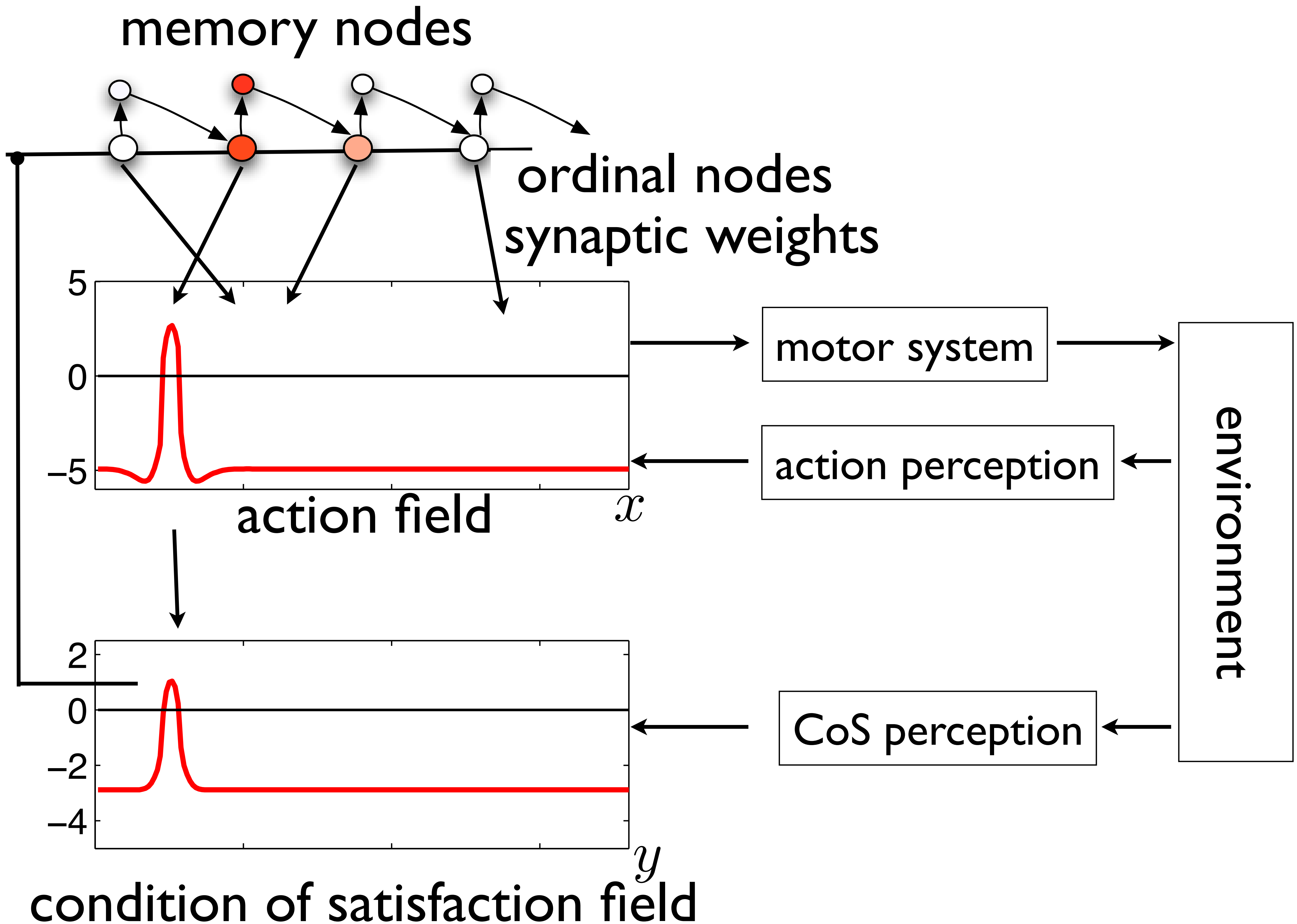


A problem with attractors



- ➡ not the ability to move
- ➡ movement corresponds to an attractor

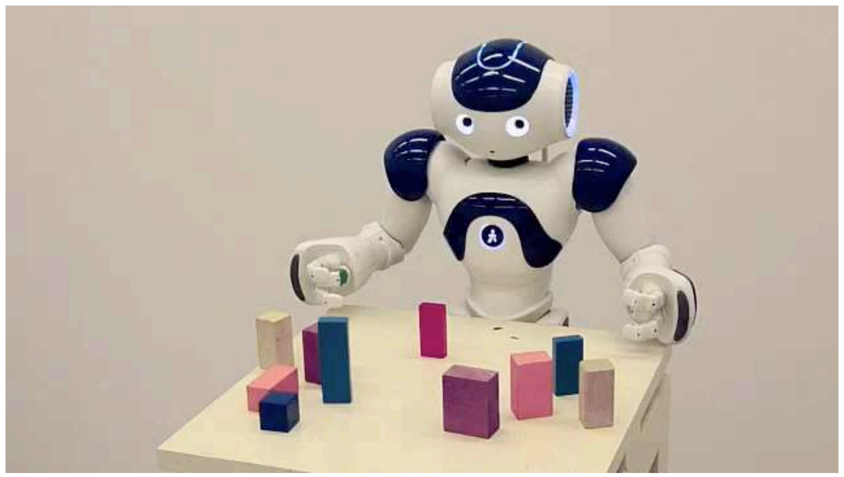
Representing sequences of attractors

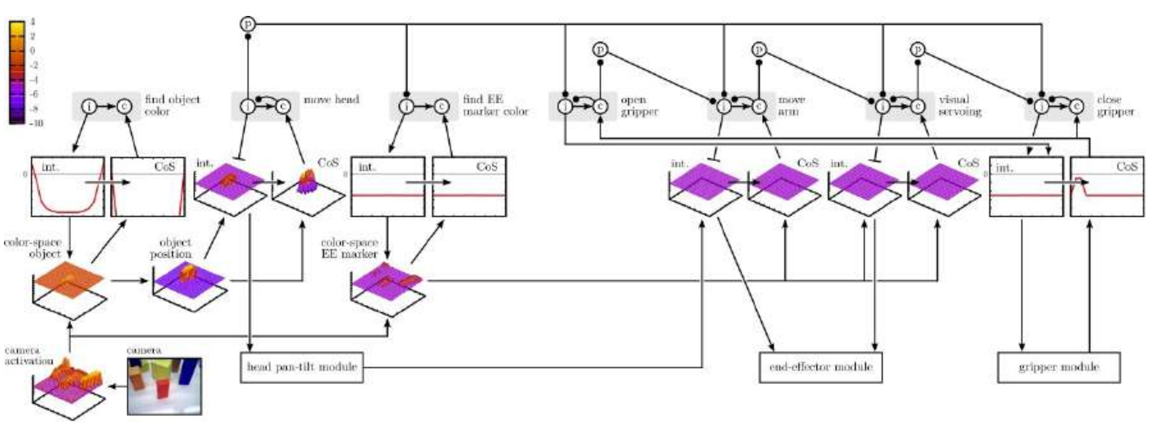


Sandamirskaya, Y. & Schöner, G. An Embodied Account of Serial Order: How Instabilities Drive Sequence Generation. Neural Networks, **2010**, 23, 1164-1179

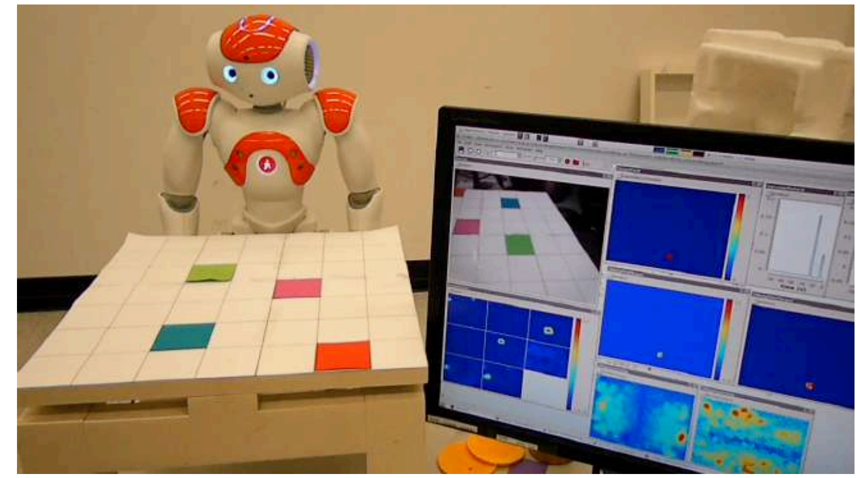
Embodied DNF architectures

Action selection

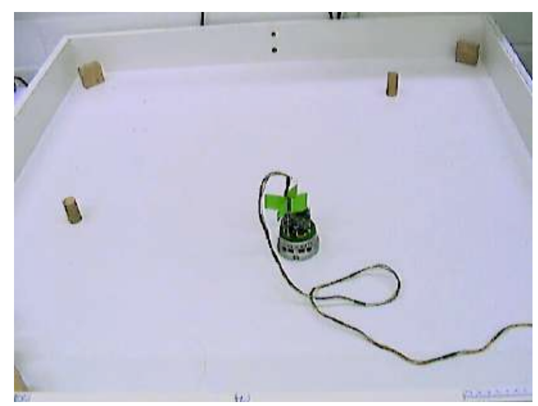


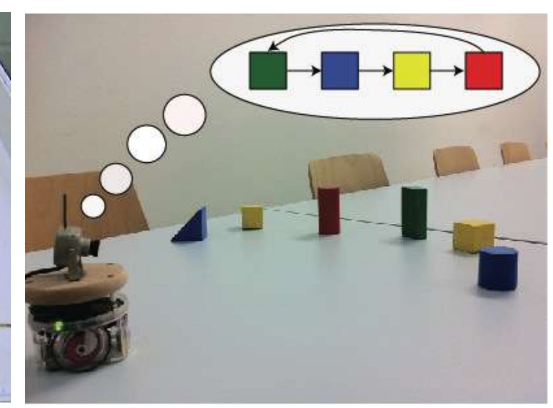


Learning to look

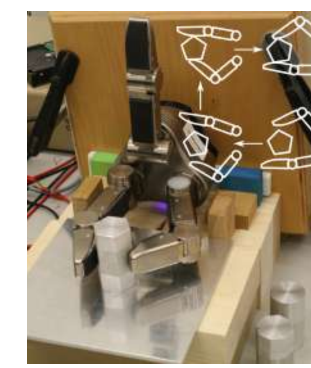


Sequence learning

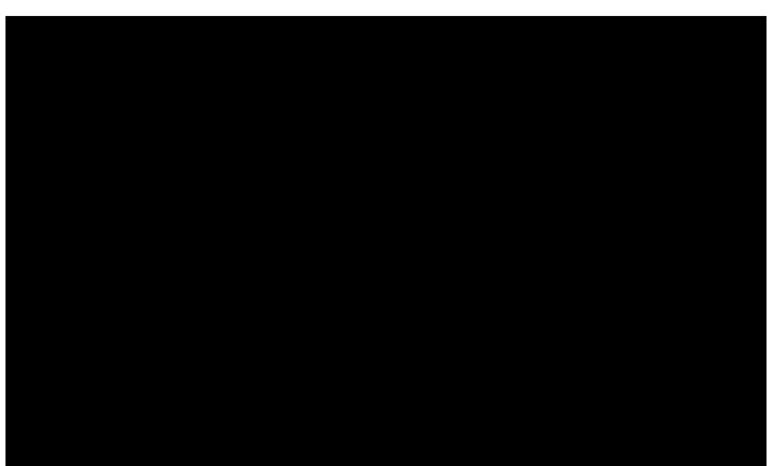


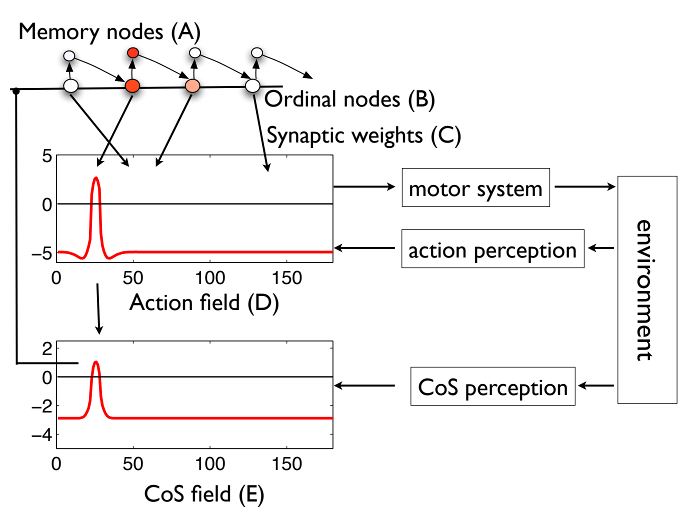


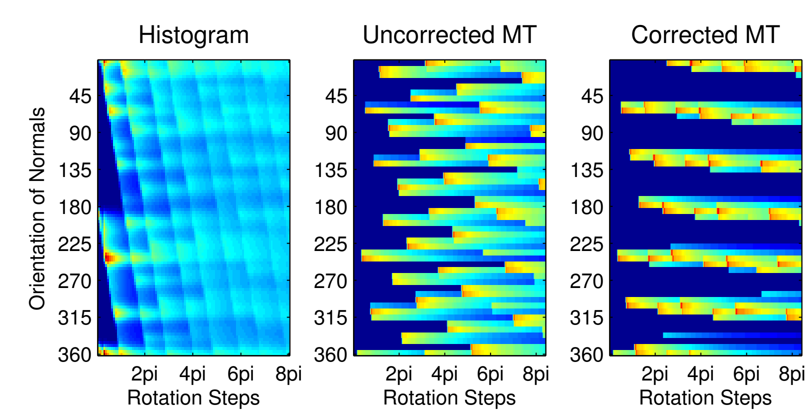
Haptic learning



Planning & acting



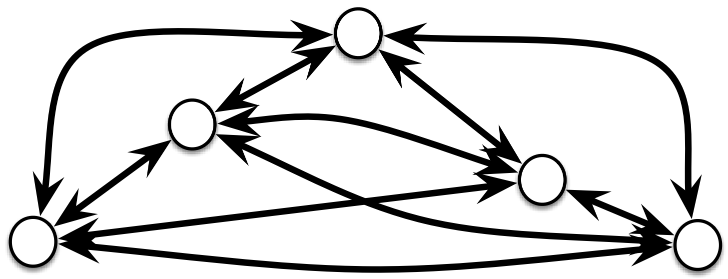




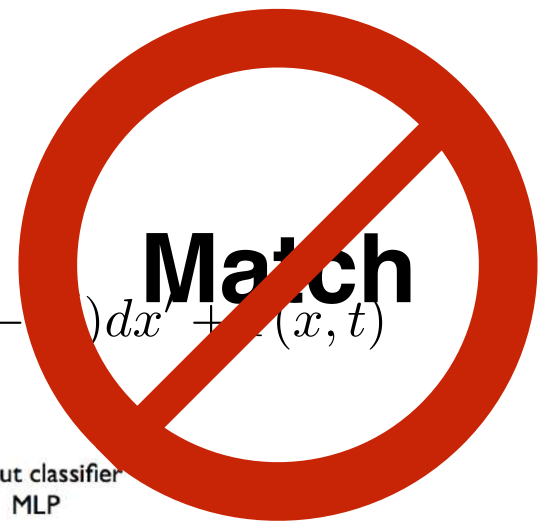
Sandamirskaya, 2010-2015

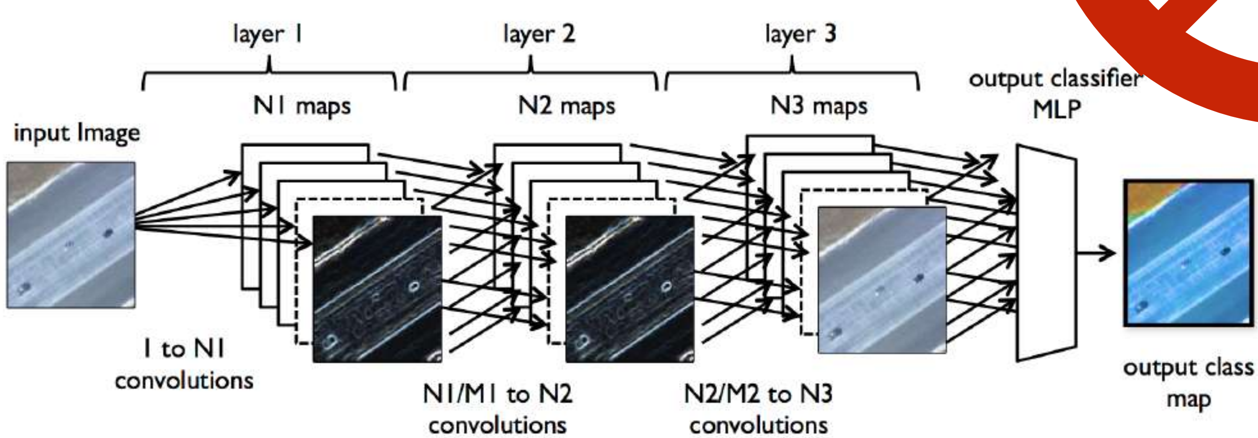
“Implementation issue”

Neuronal dynamics



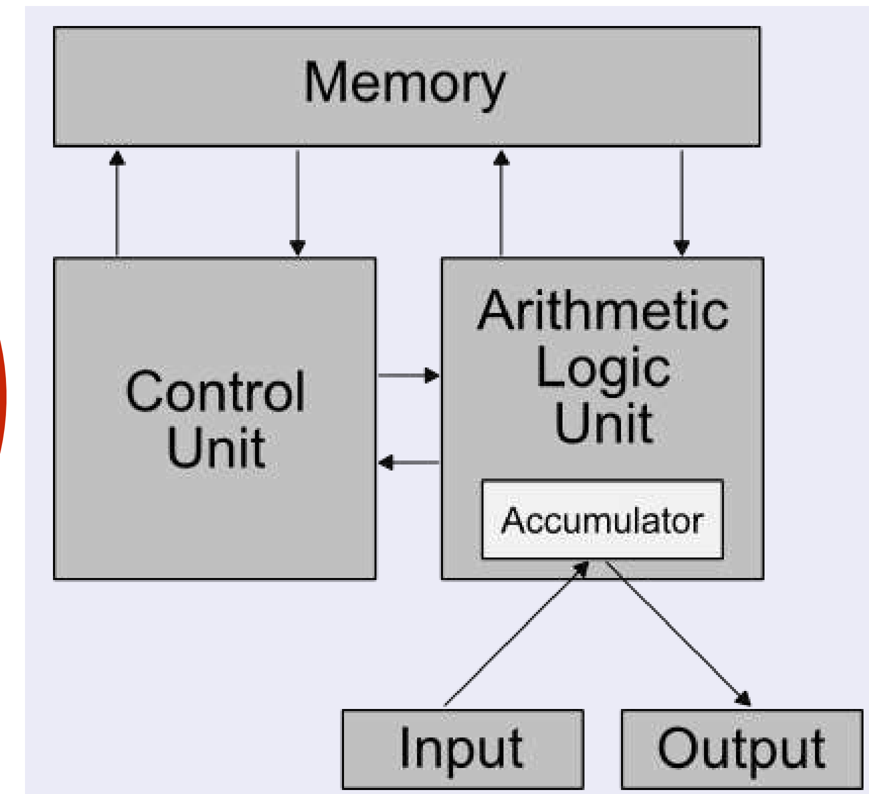
$$\tau \dot{u}(x,t) = -u(x,t) + h + \int f(u(x',t))\omega(x-x')dx' + I(x,t)$$





- analogue values
- parallel processing
- memory and computation interlinked

“Von Neumann” computer



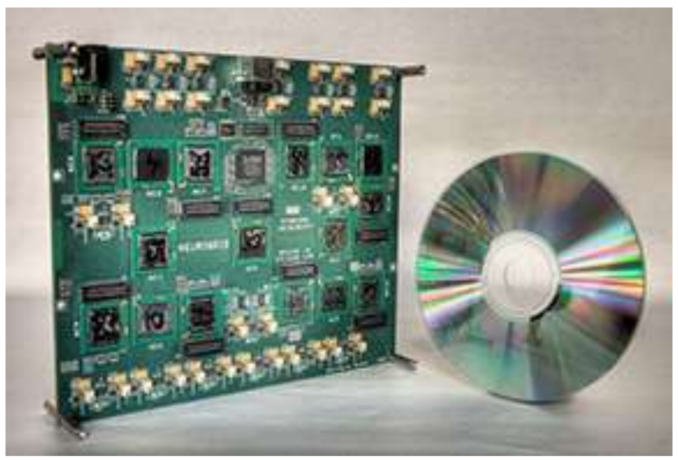
- digital representations
- sequential processing
- separate memory unit

Neuromorphic Hardware

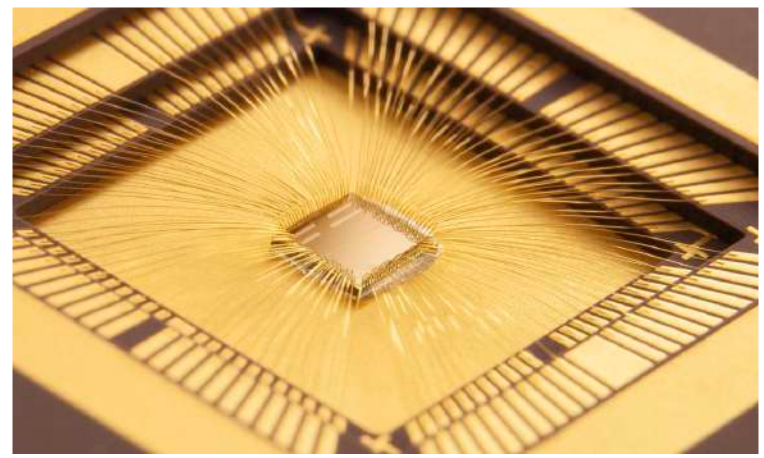
➡ Brain-inspired computing or sensing devices that emulate activity of biological neurons and synapses

Analog

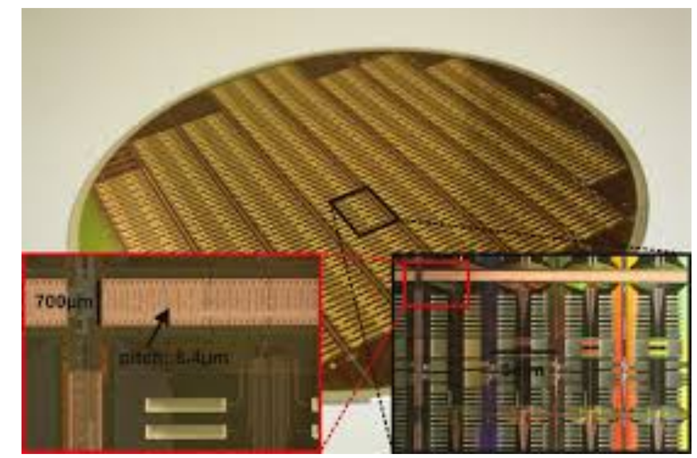
“BrainDrop” (Stanford)



DYNAP (Zurich)

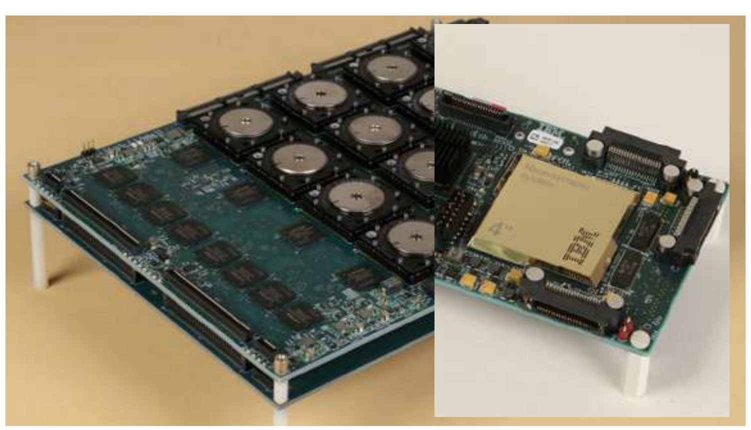


BrainScaleS (Heidelberg)



Digital

“TrueNorth” (IBM)



Loihi (Intel)

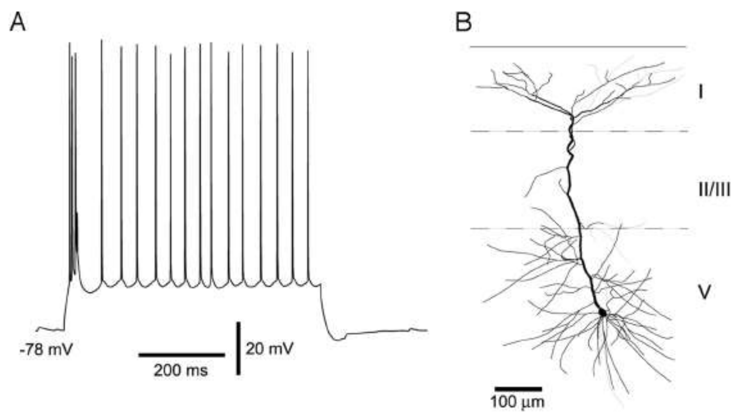
SpiNNaker (Manchester)

NEUROTECH

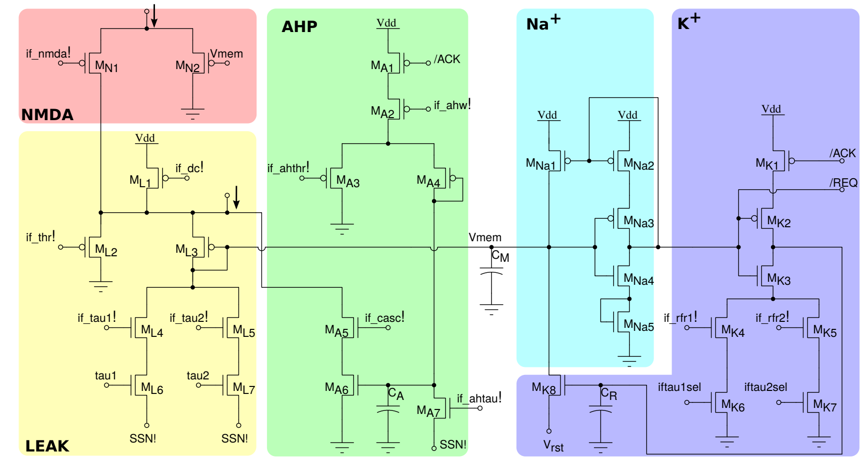
NEUROMORPHIC COMPUTING TECHNOLOGY LEADING TO AI REVOLUTION

Create and promote neuromorphic community in Europe: www.neurotechai.eu

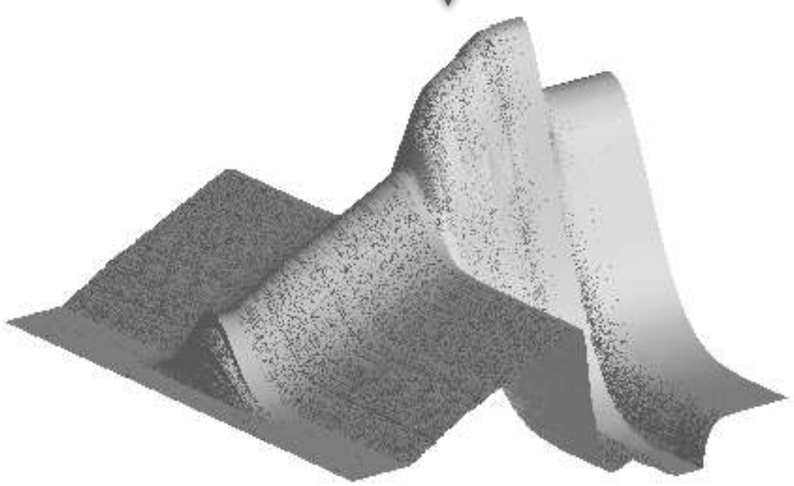
Neuromorphic Hardware



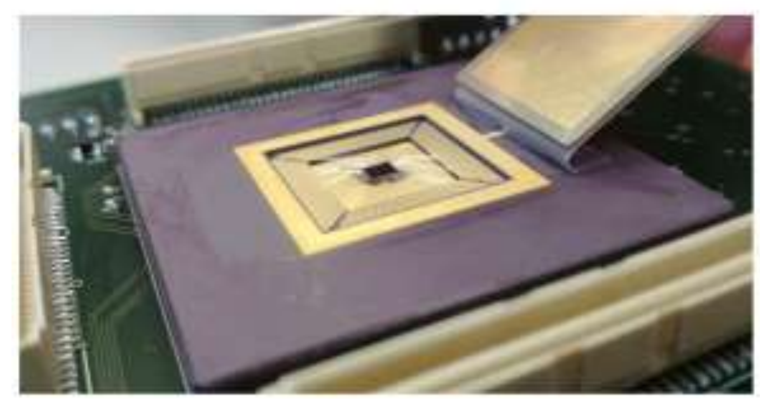
neuron



circuit of a neuron

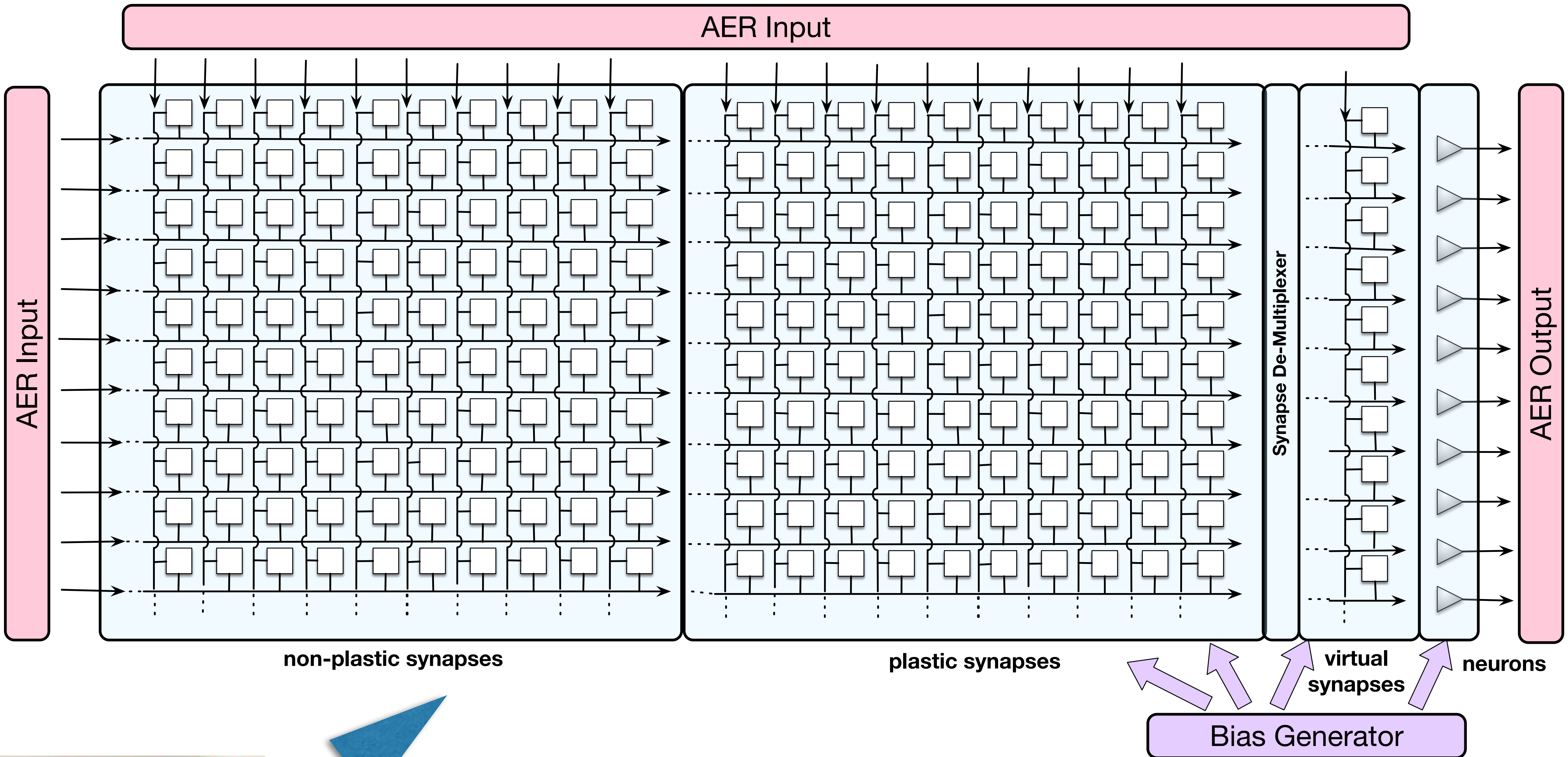


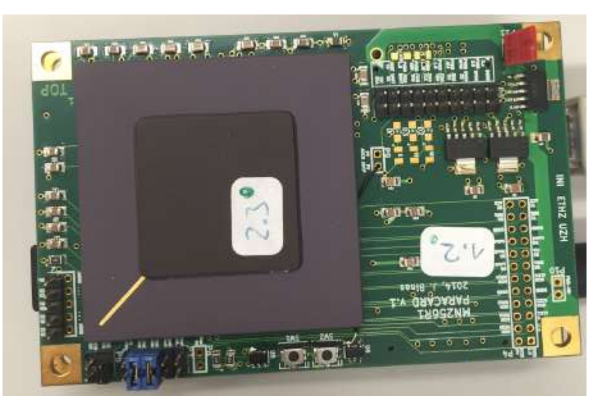
population dynamics



VLSI device (ROLLS, CXQUAD)

Reconfigurable OnLine Learning Spiking (ROLLS)



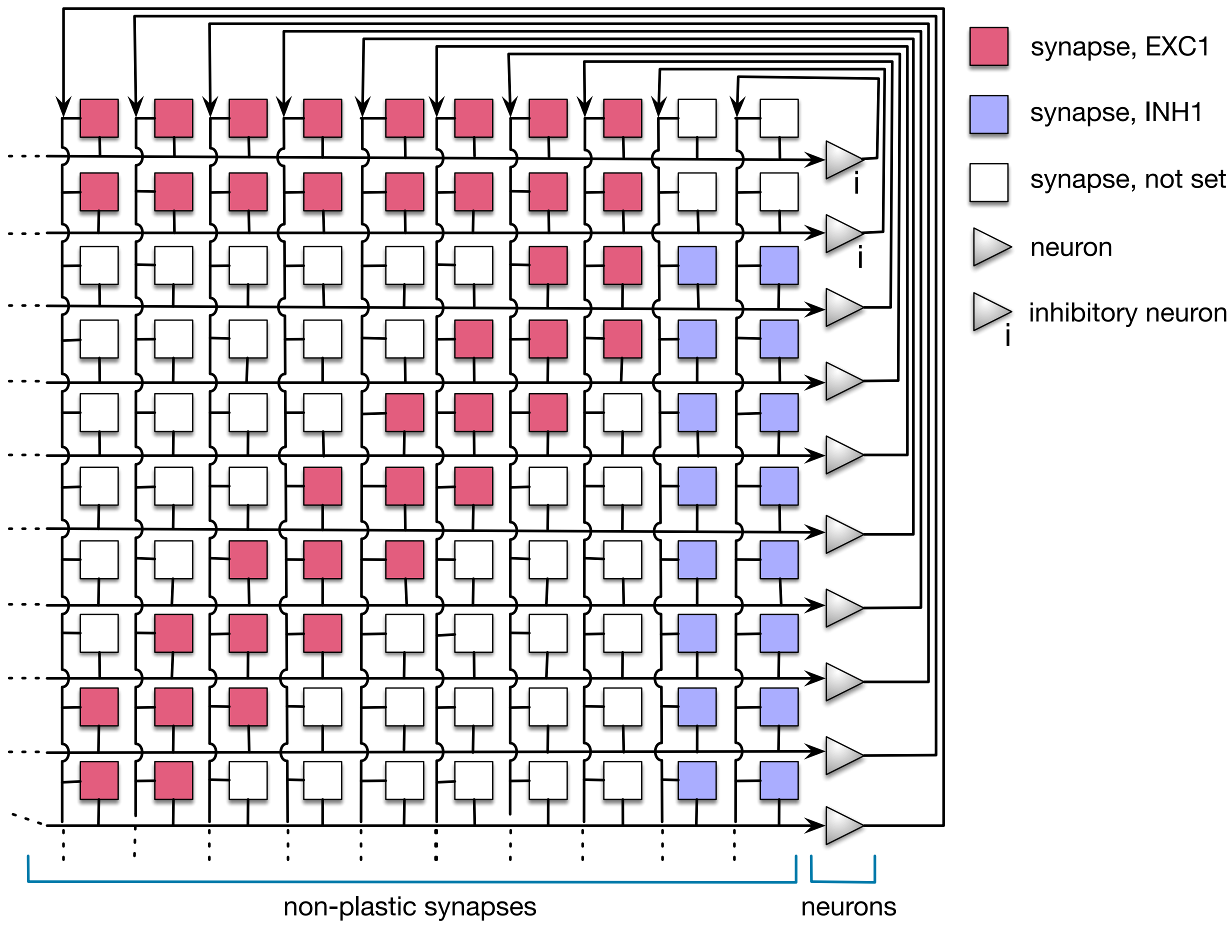


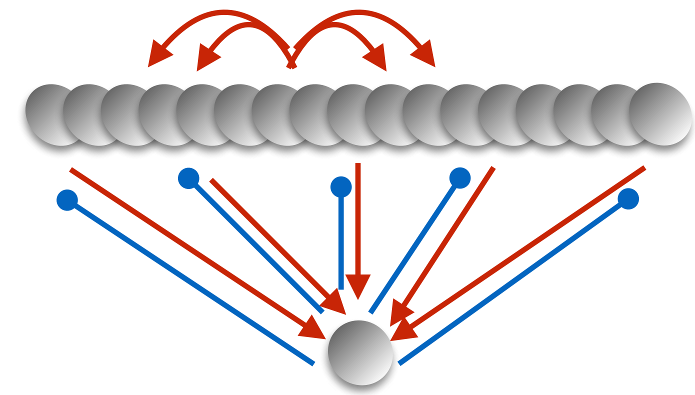
- analog circuits for neurons and synapses
- digital communication of spikes

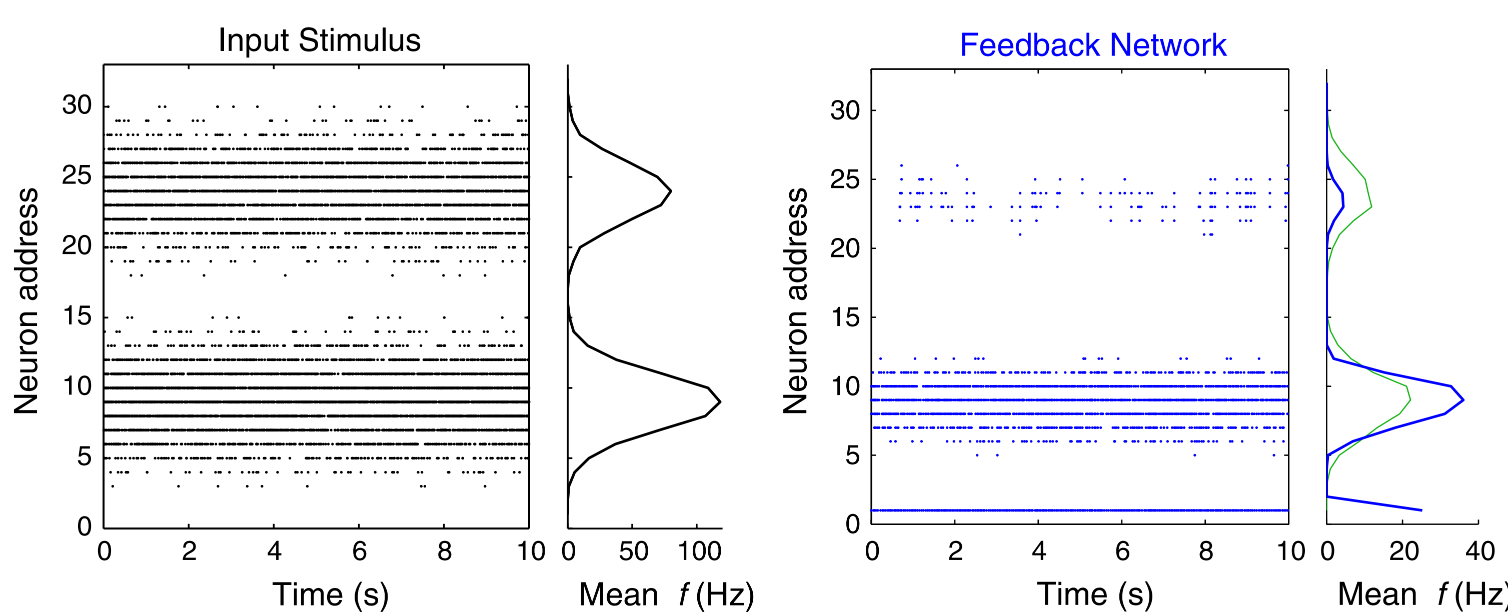
➡“programming” = wiring-up and setting parameters

Qiao et al, 2015

A Dynamic Neural Field on a neuromorphic chip

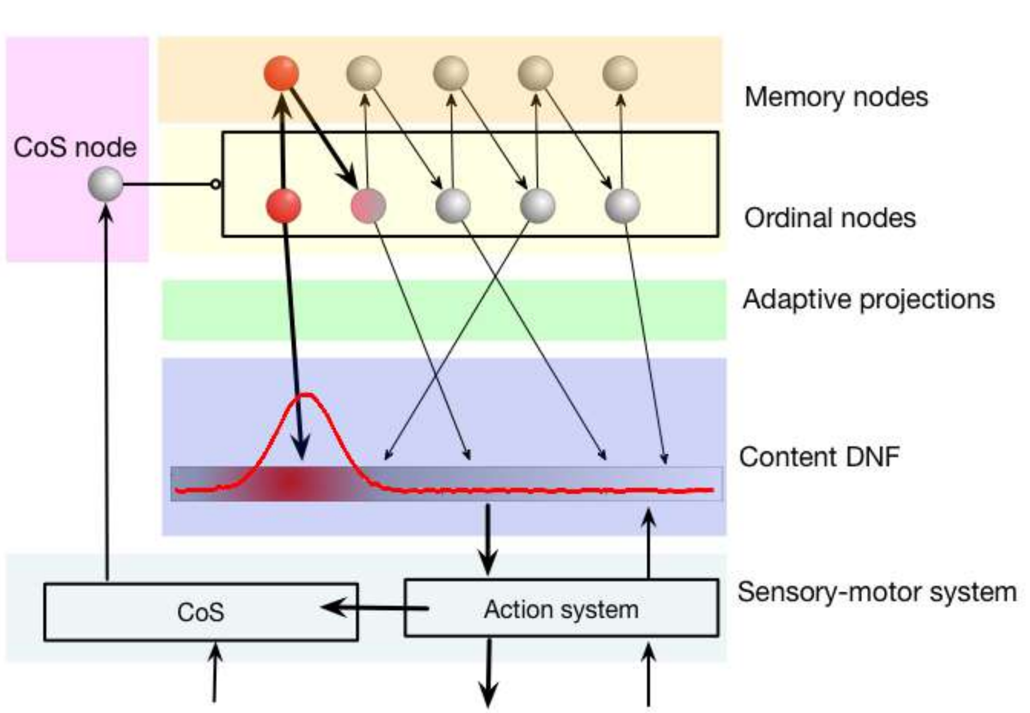


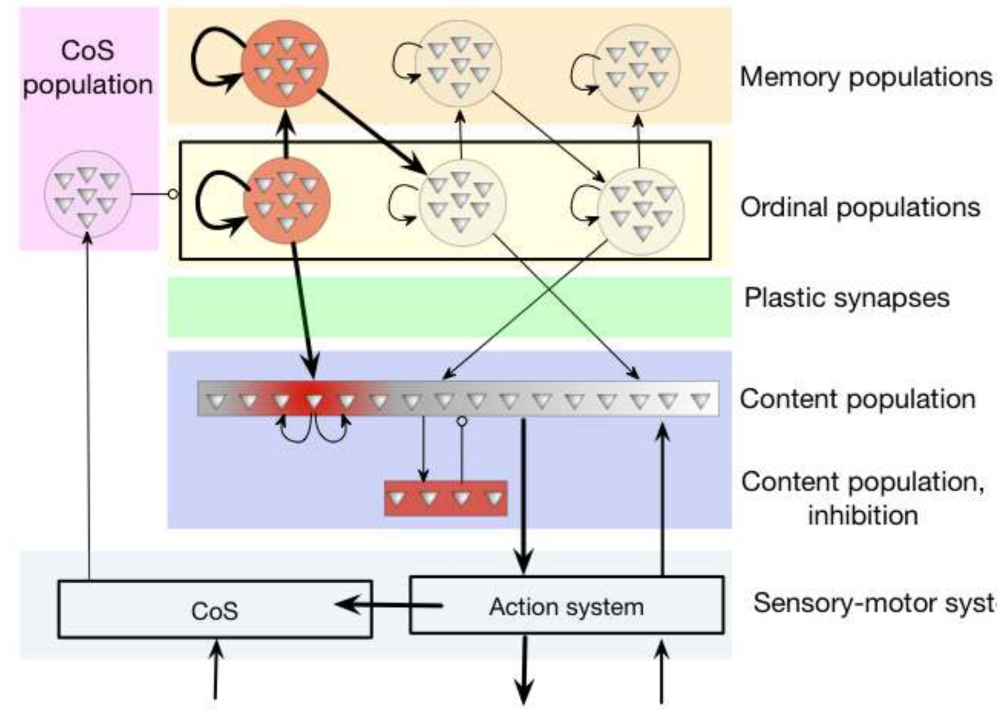




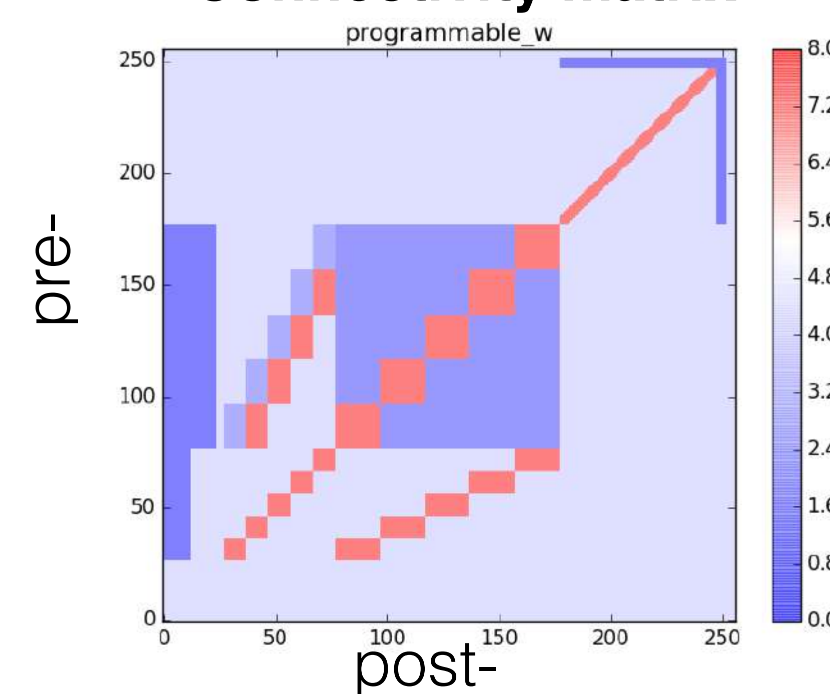
Indiveri et al, 2009

Sequence learning “program”

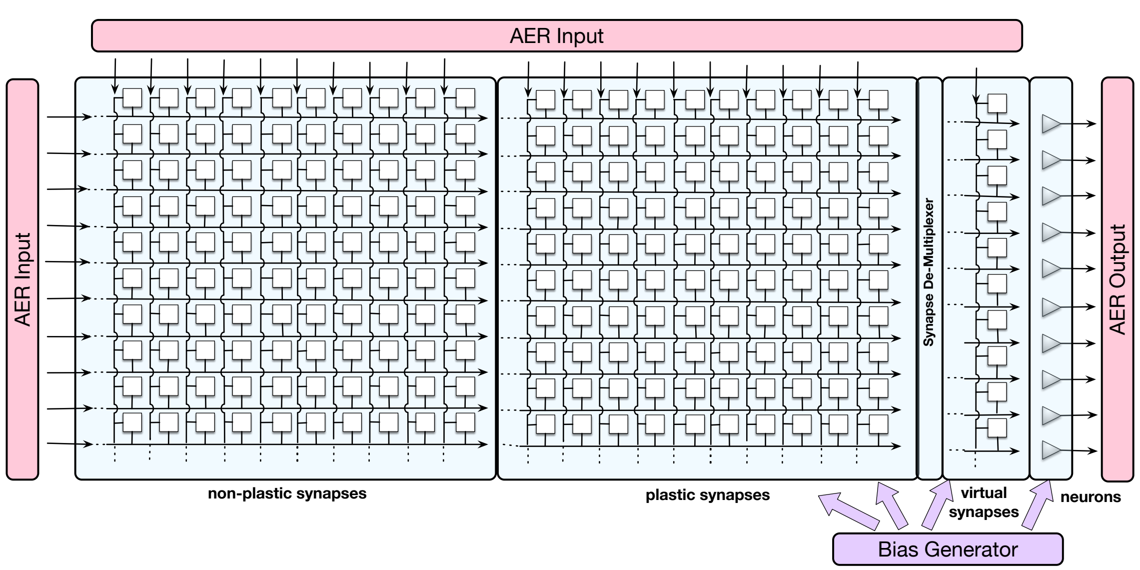




Connectivity matrix

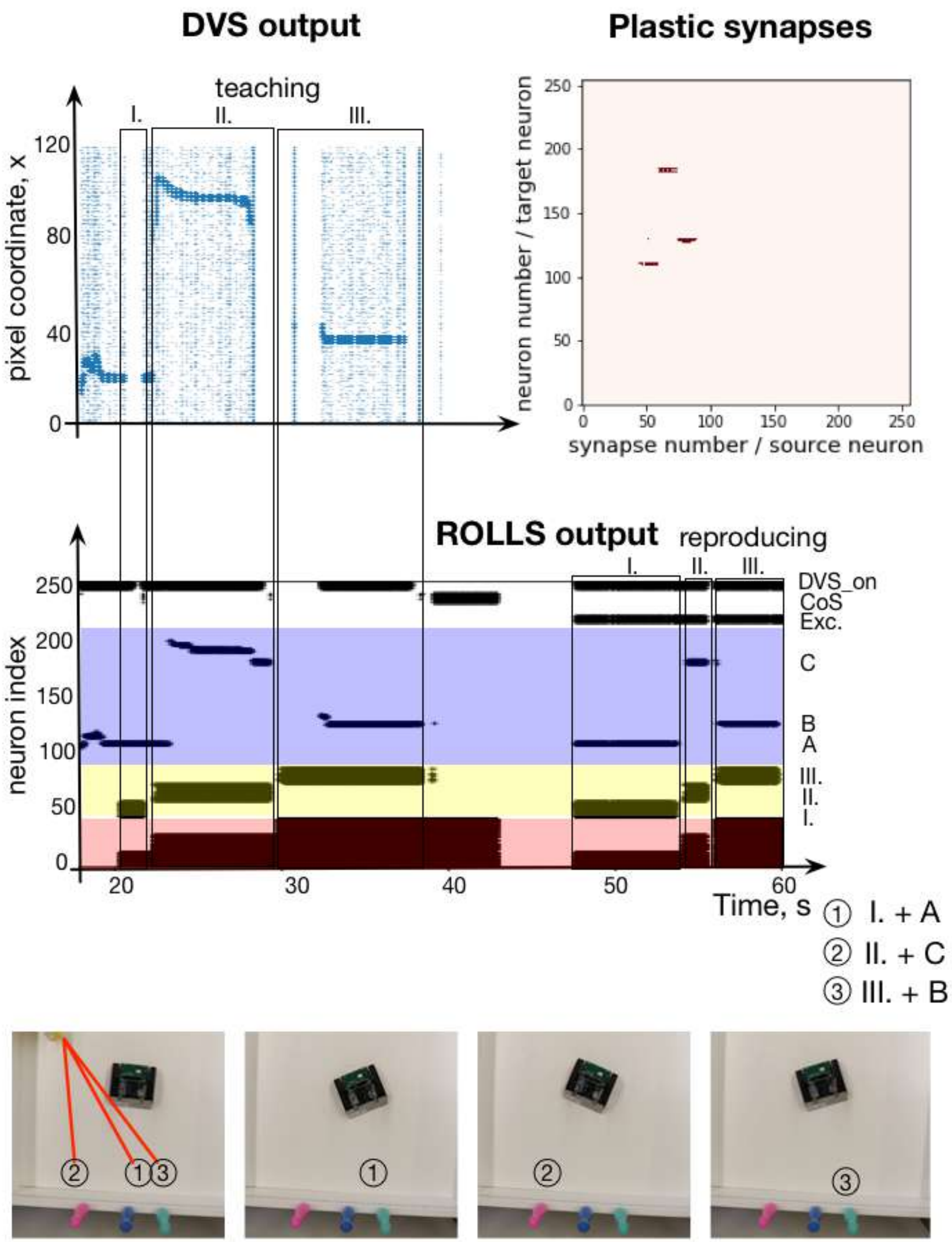


“Programm”



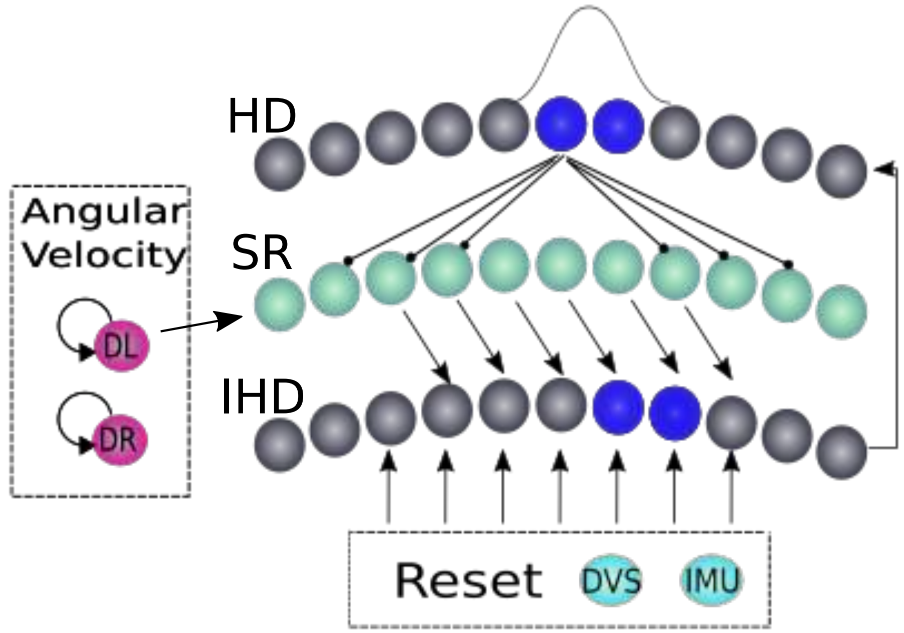
Kreiser, R.; Aathmani, D.; Qiao, N.; Indiveri, G. & Sandamirskaya, Y. Organising Sequential Memory in a Neuromorphic Device Using Dynamic Neural Fields. Frontiers in Neuromorphic Engineering, **2018**

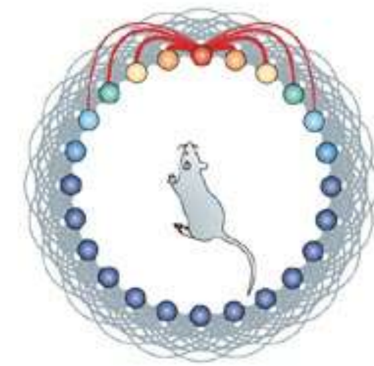
Embodied experiment

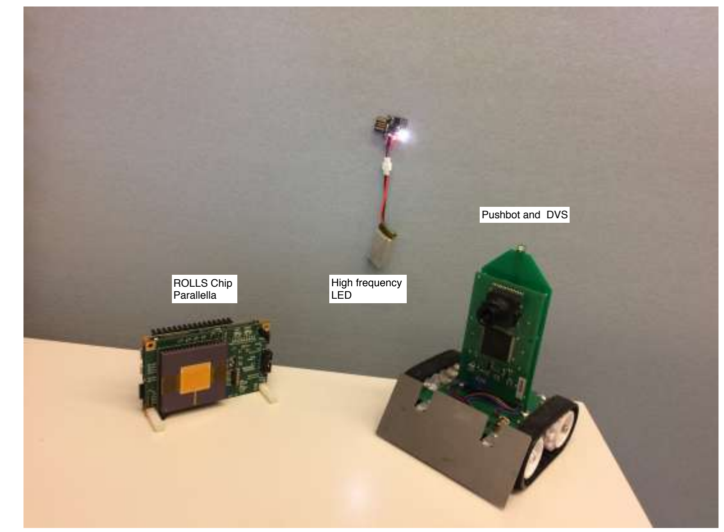


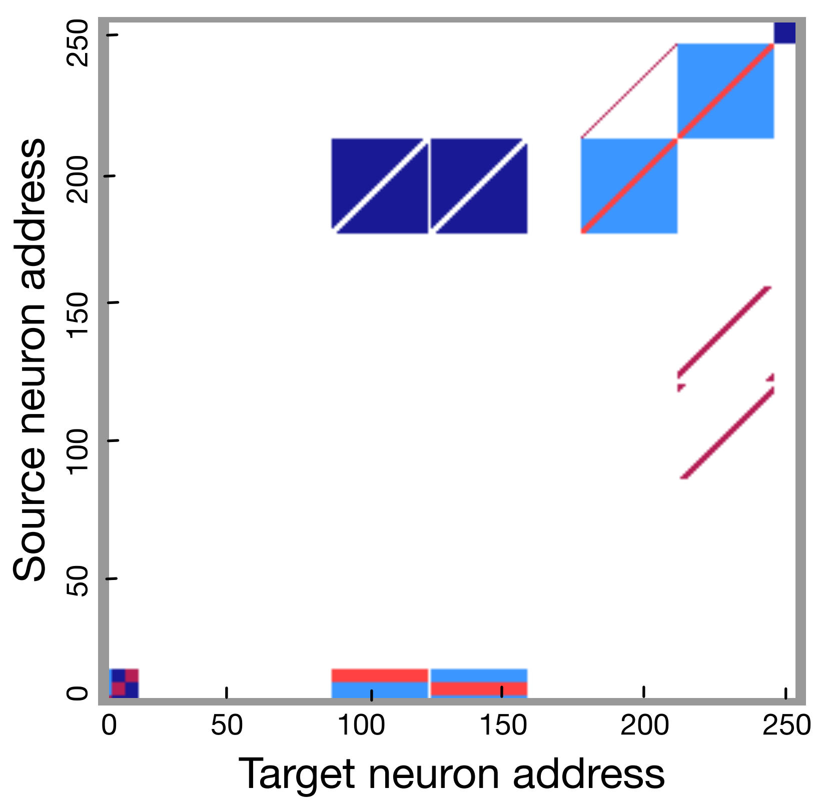
Kreiser, R.; Aathmani, D.; Qiao, N.; Indiveri, G. & Sandamirskaya, Y. Organising Sequential Memory in a Neuromorphic Device Using Dynamic Neural Fields. Frontiers in Neuromorphic Engineering, **2018**

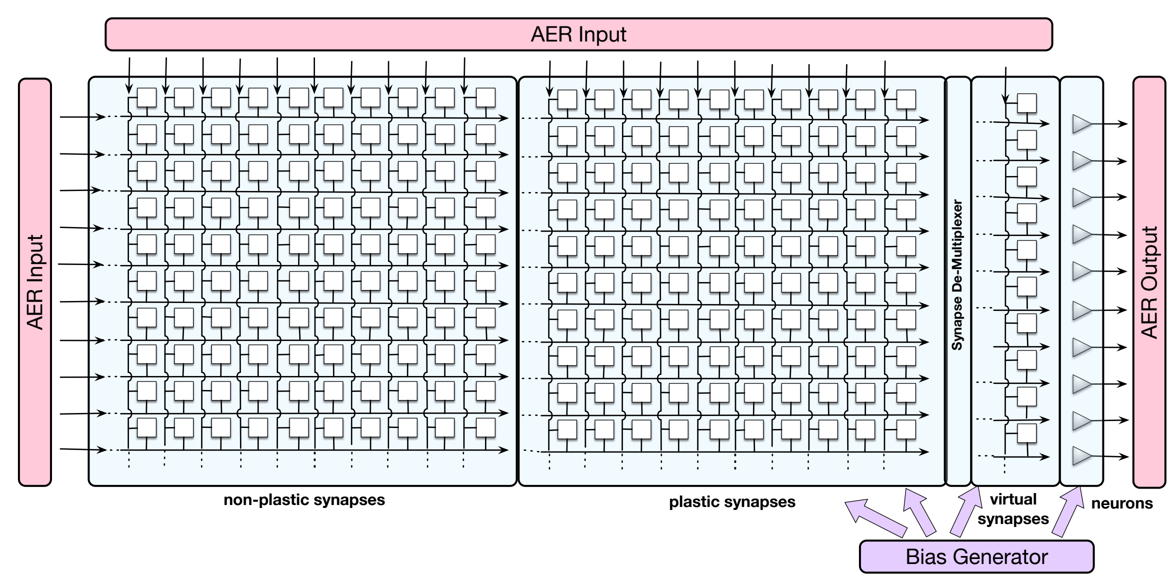
Navigation: Head-direction network







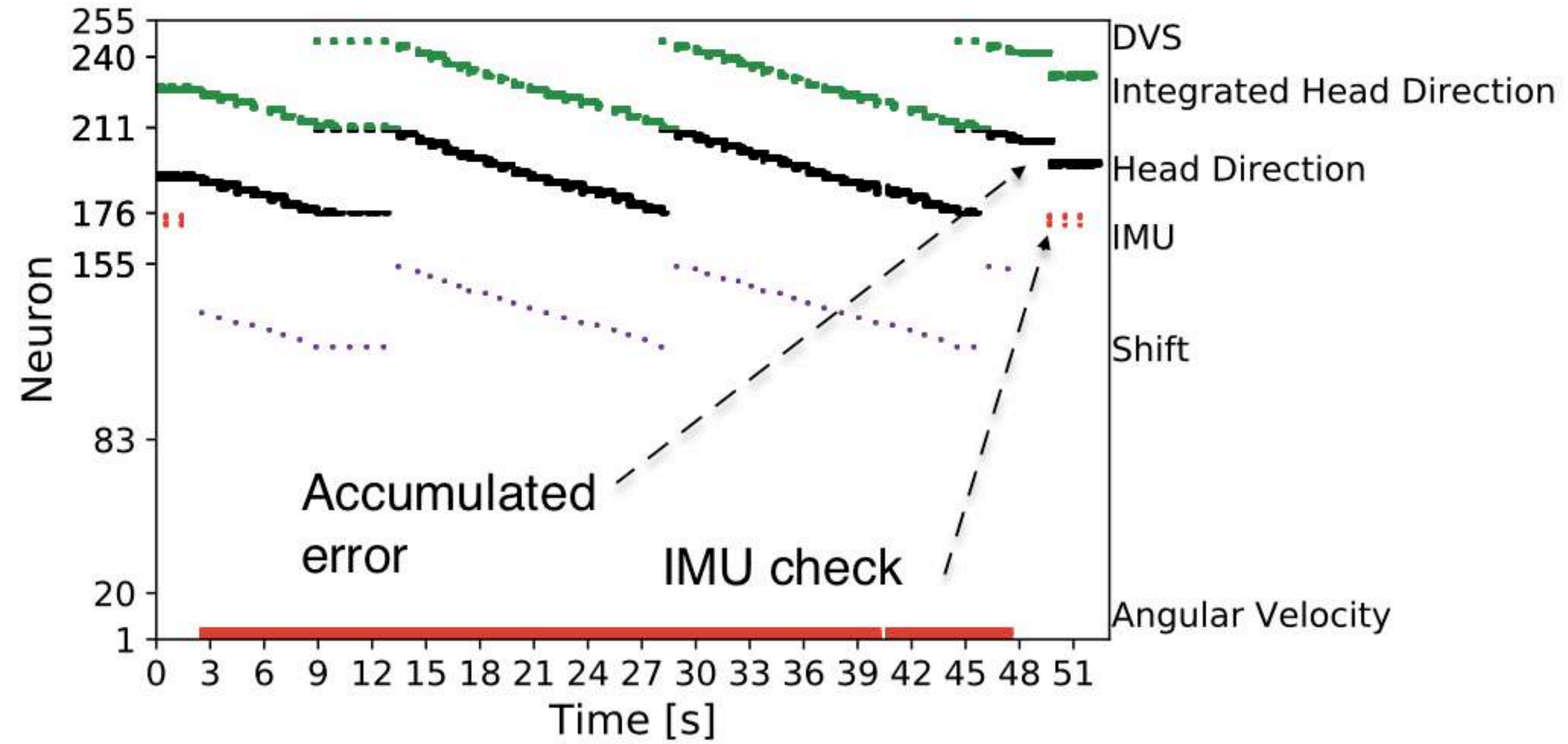




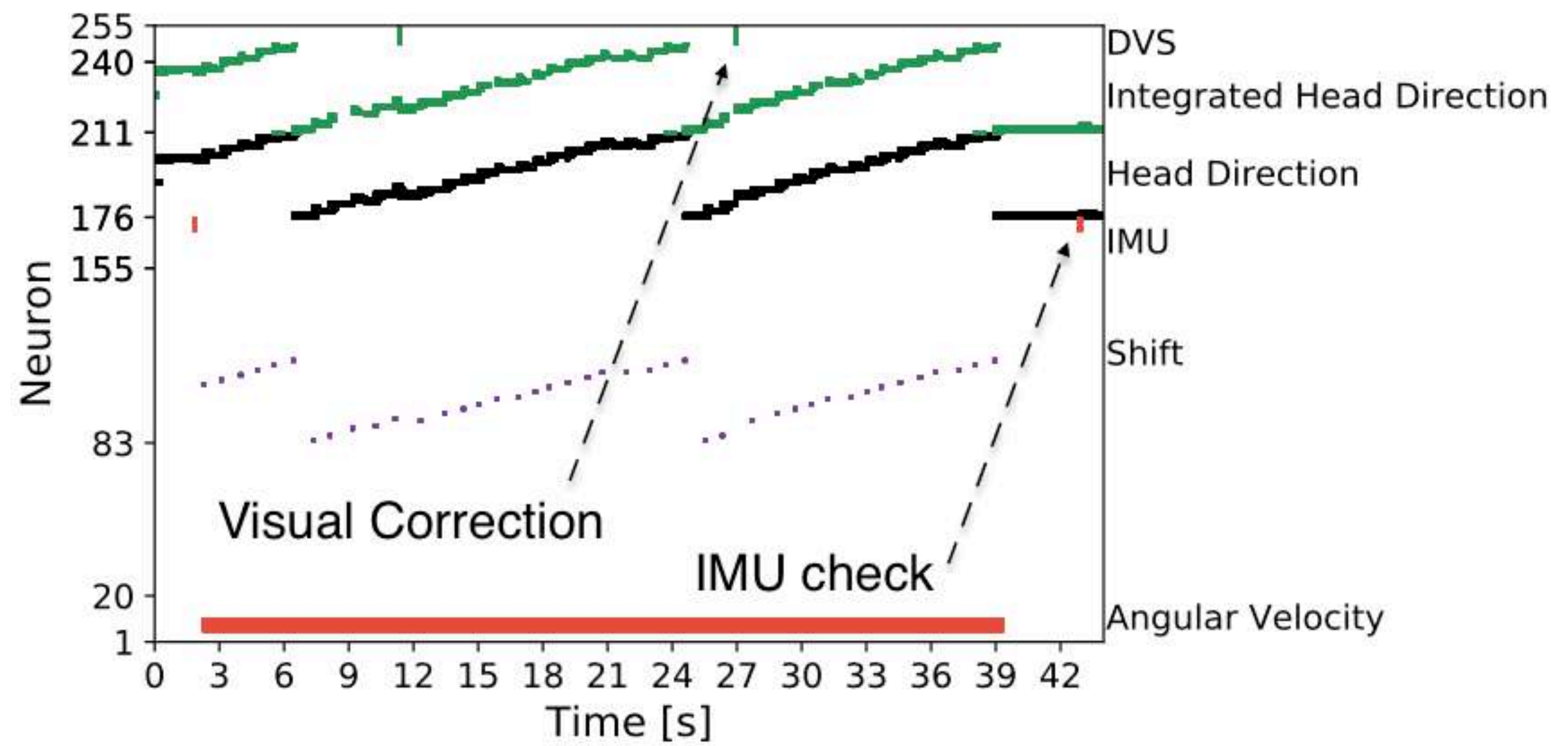
Kreiser, R.; Cartiglia, M. & Sandamirskaya, Y. A Neuromorphic approach to path integration: a head direction spiking neural network with visually-driven reset. IEEE Symposium for Circuits and Systems, ISCAS, **2018**

Navigation: Head-direction network

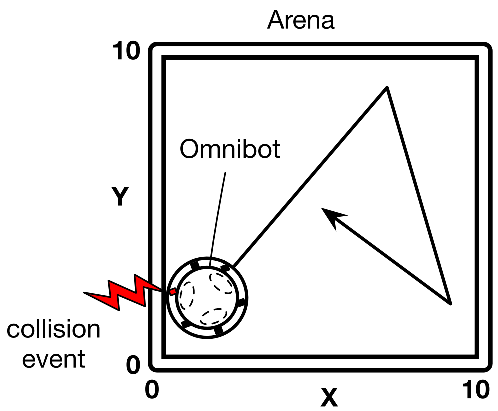
"Proprioception" only

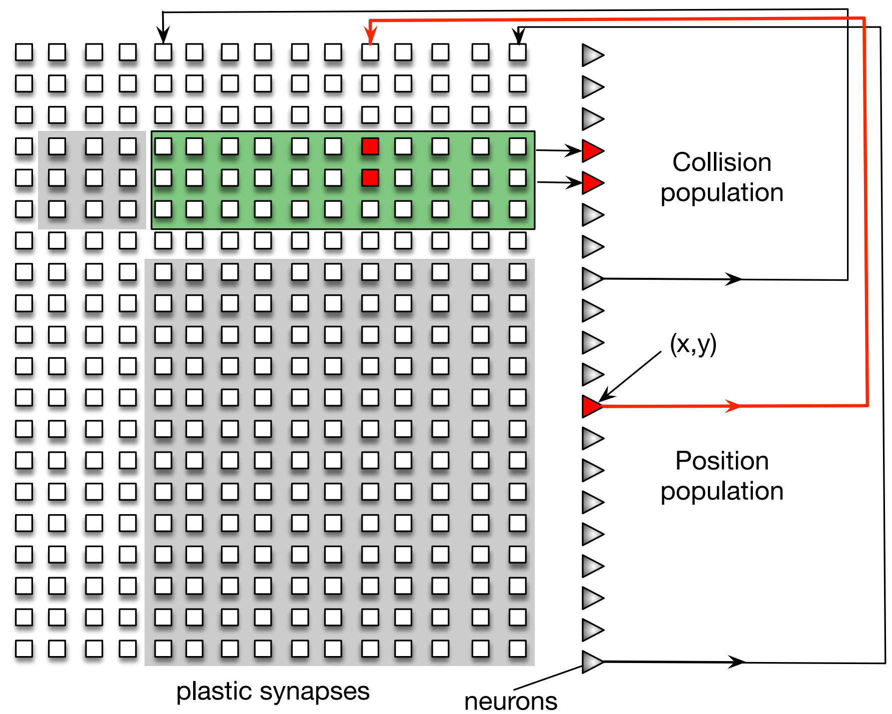


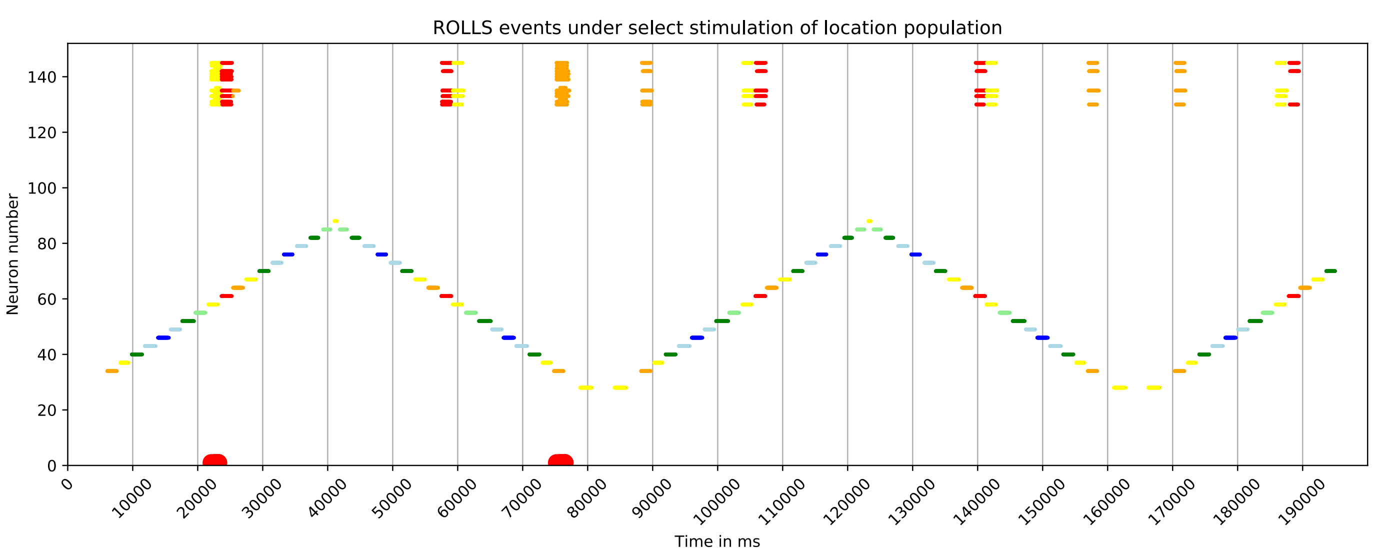
Correction using vision

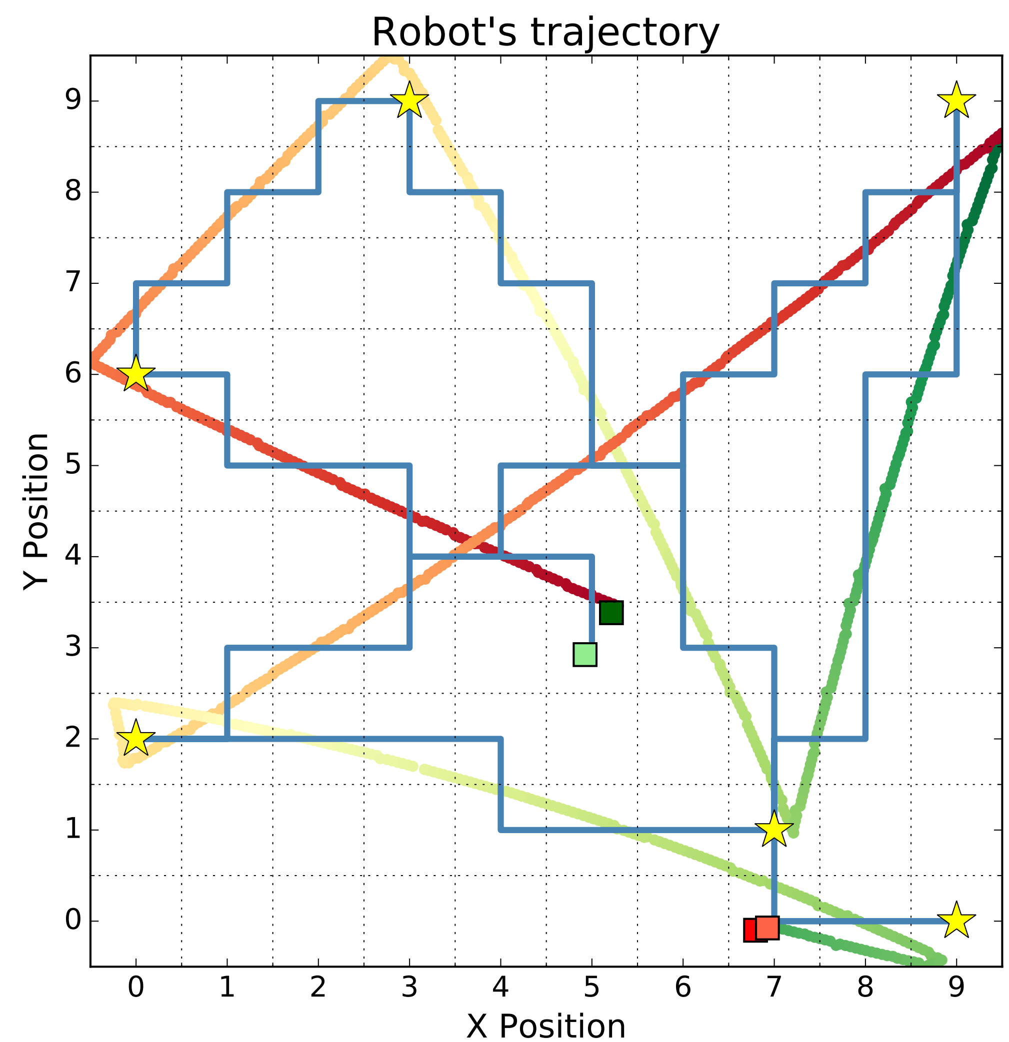


Map formation on the ROLLS chip



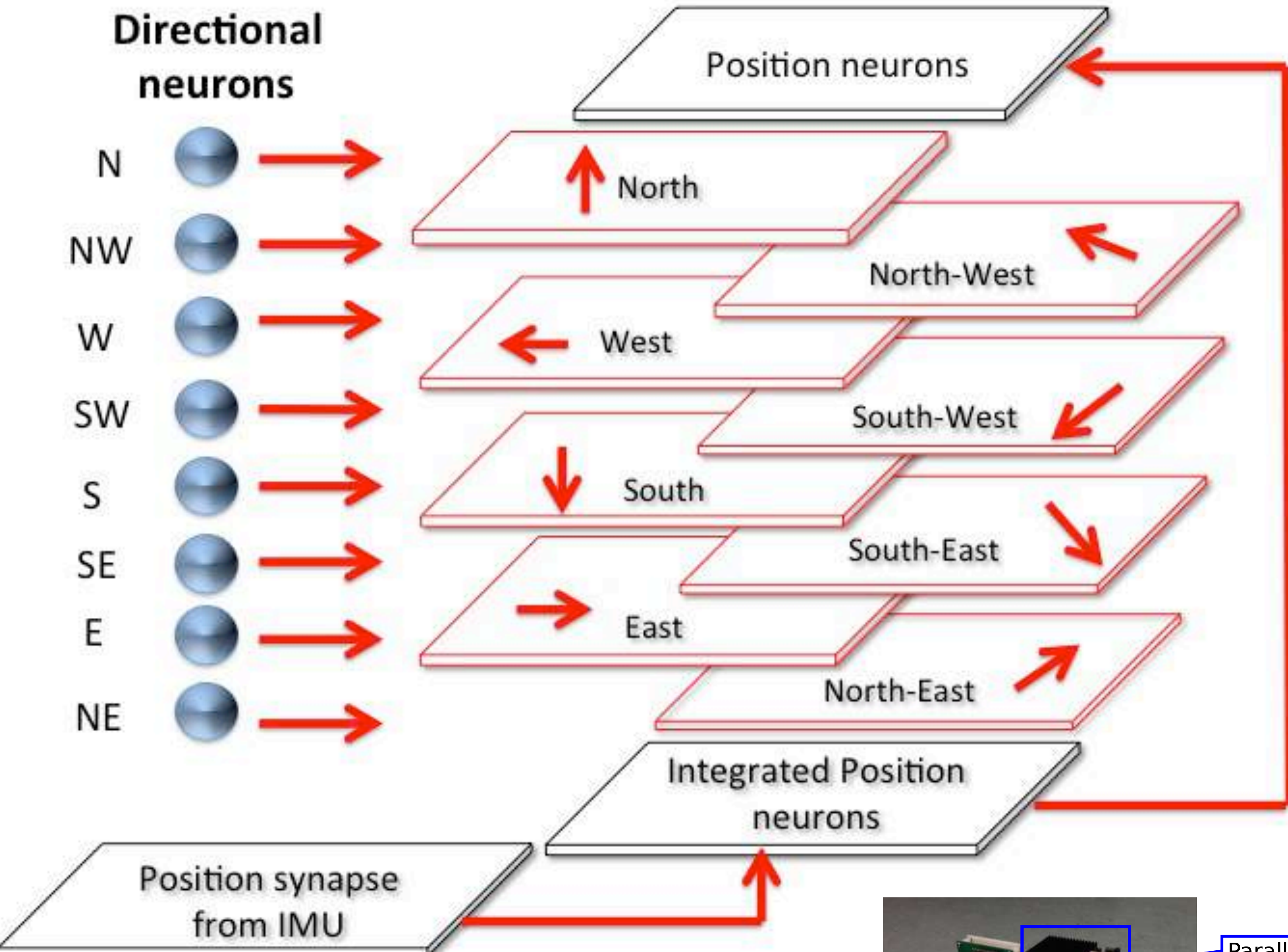


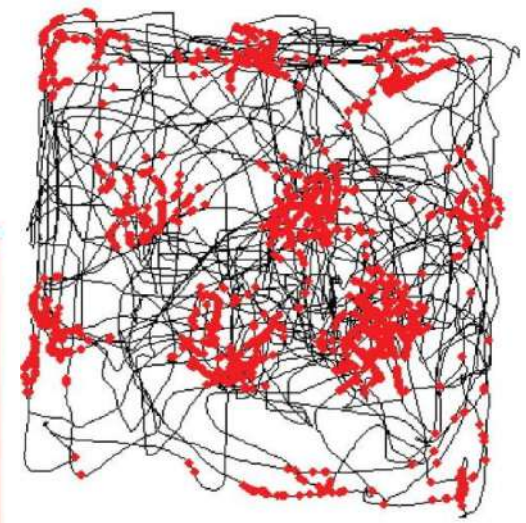




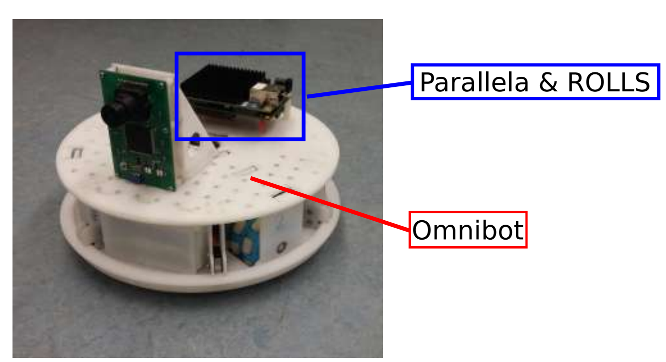
Map formation: Path integration in 2D

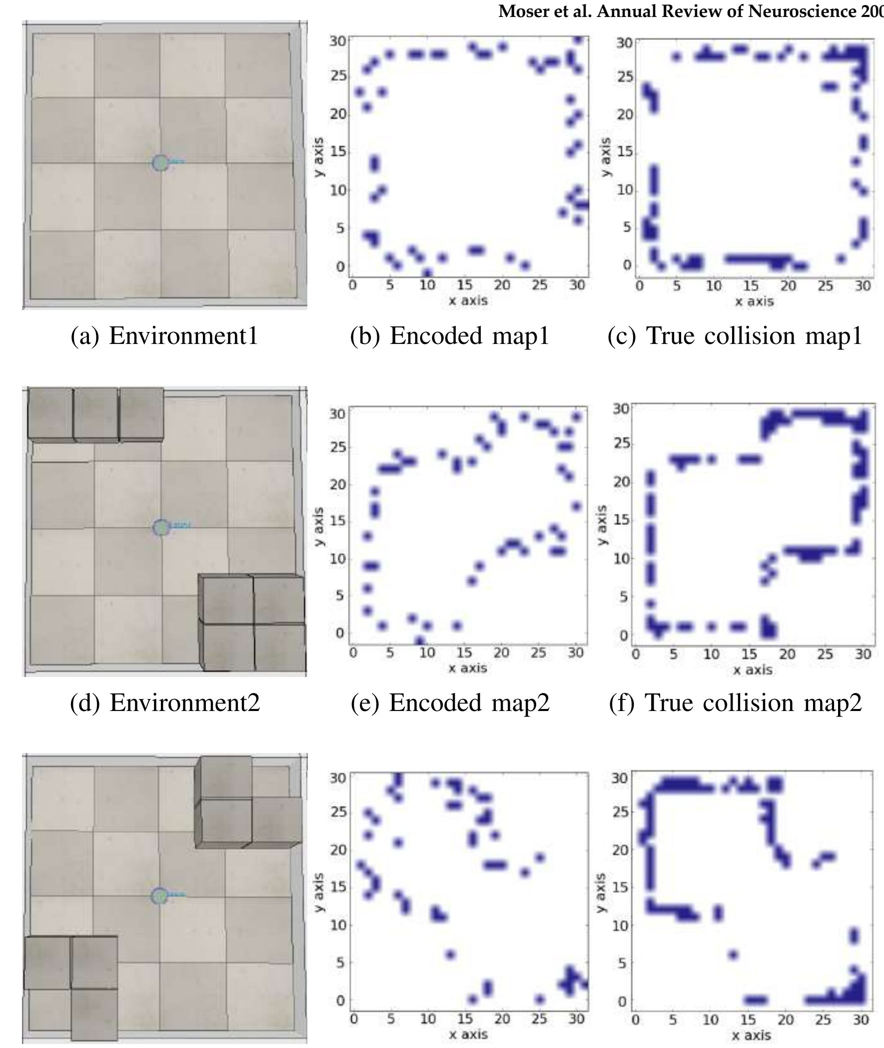
“Grid cells”





Moser et al. Annual Review of Neuroscience 2008

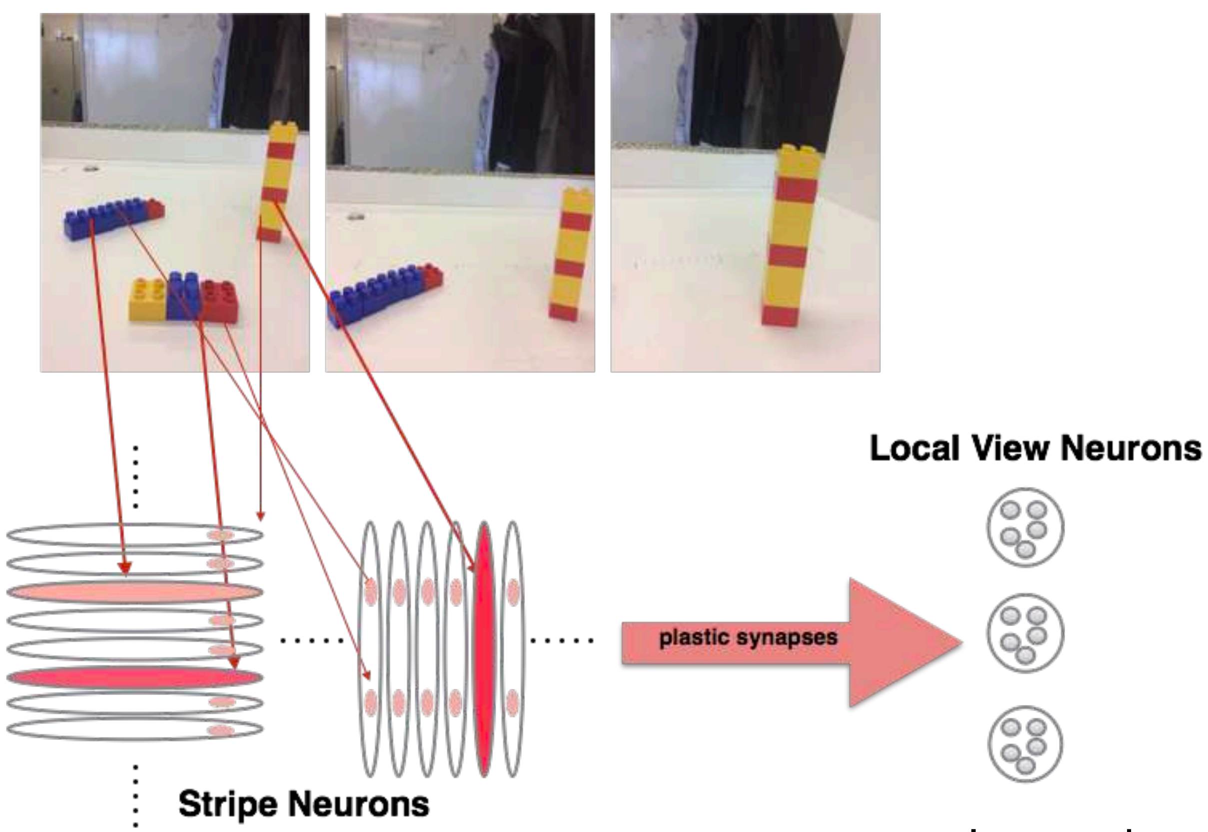




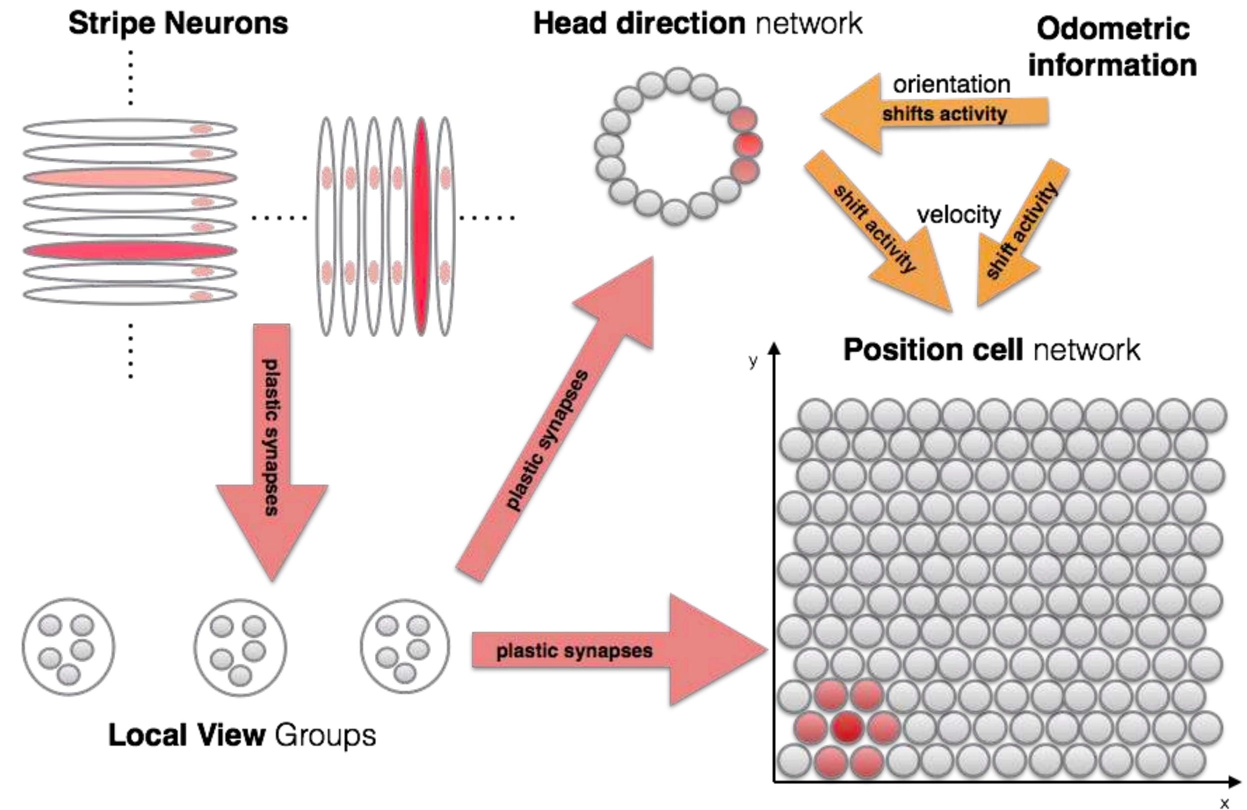
Kreiser, R.; Pienroj, P.; Renner, A. & Sandamirskaya, Y. Pose Estimation and Map Formation with Spiking Neural Networks: towards Neuromorphic SLAM. 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, **2018**

Neuromorphic SLAM

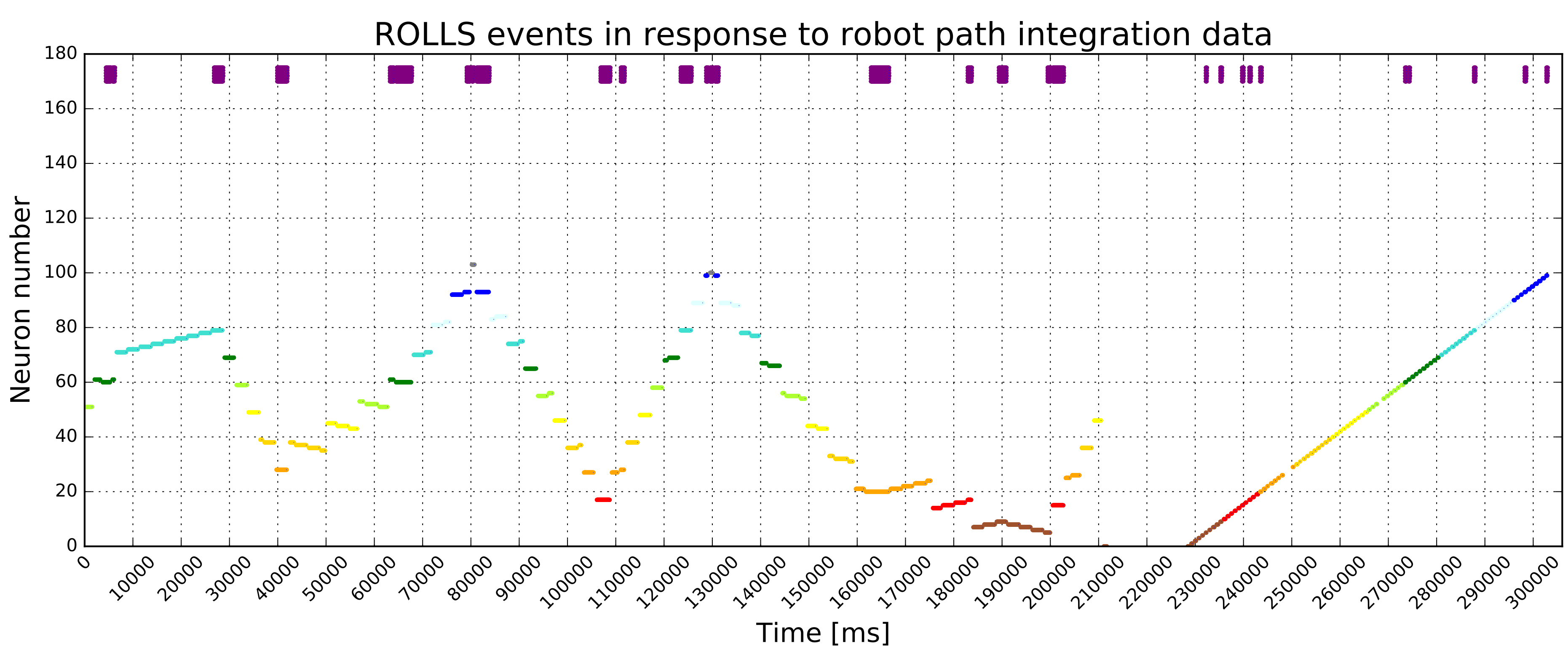
Local view cells



Position representation



Learning a map on chip



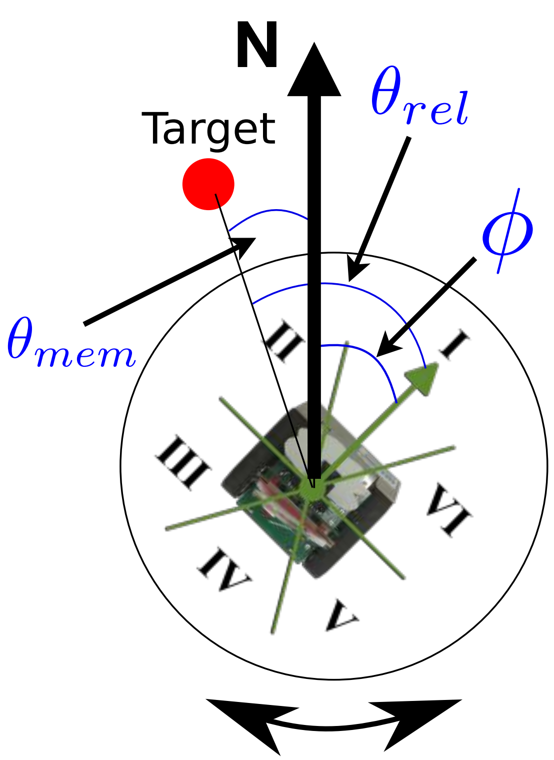
Reference frames transformation on chip

View-based target representation:

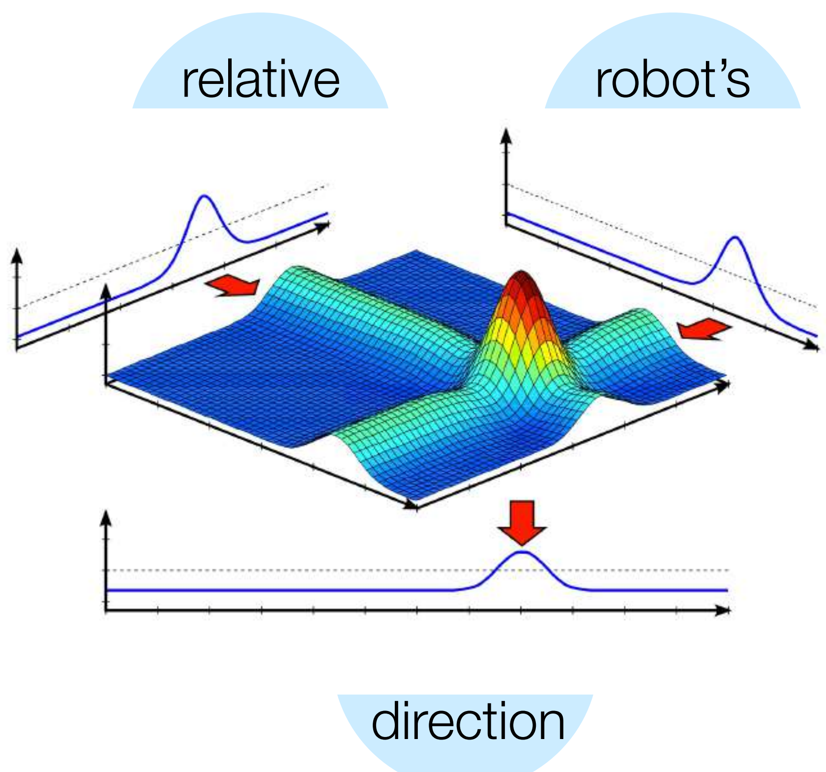
- target in view

- target lost from view

Allocentric target representation:



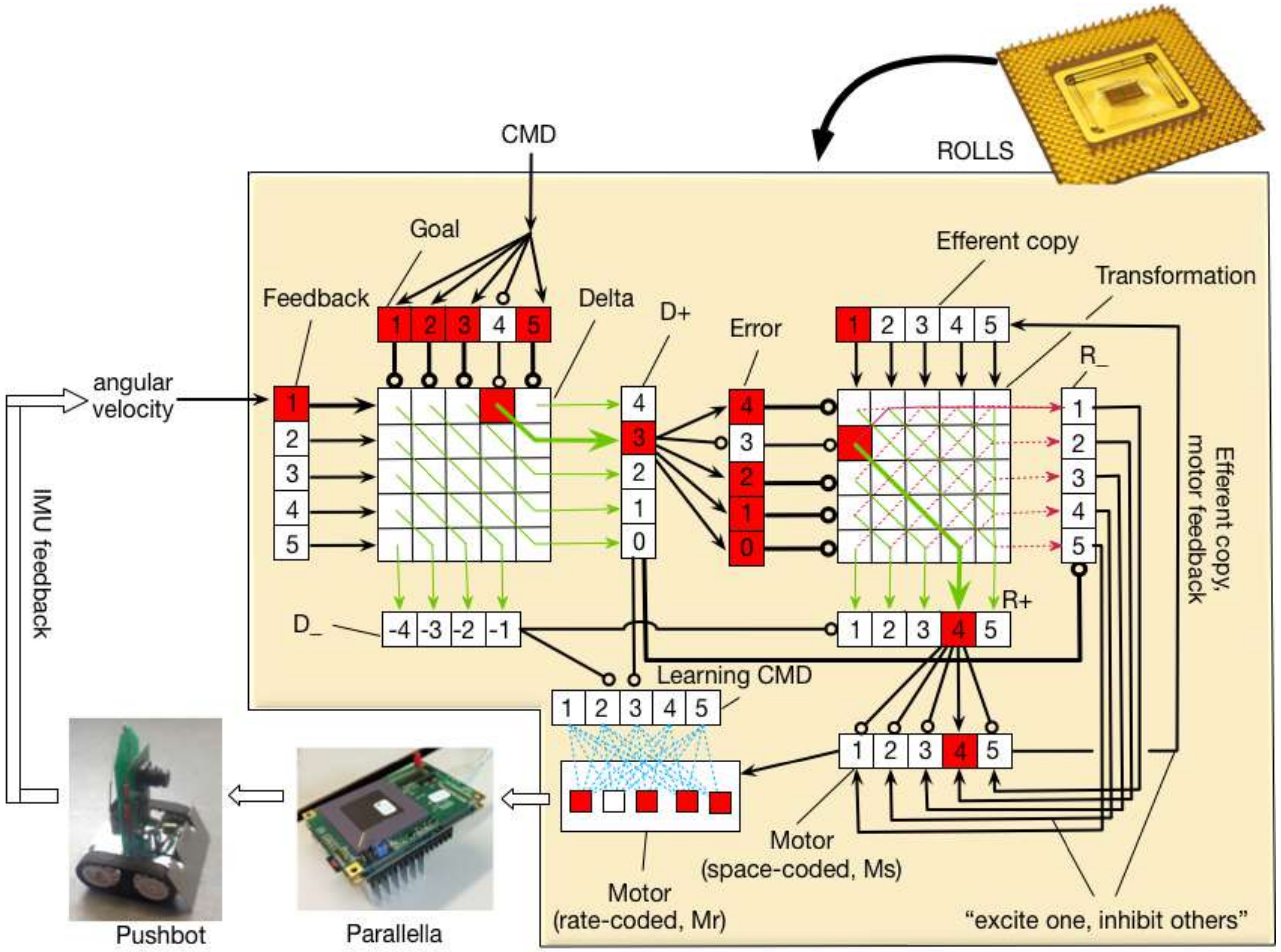
Neural ref. frame transformation:



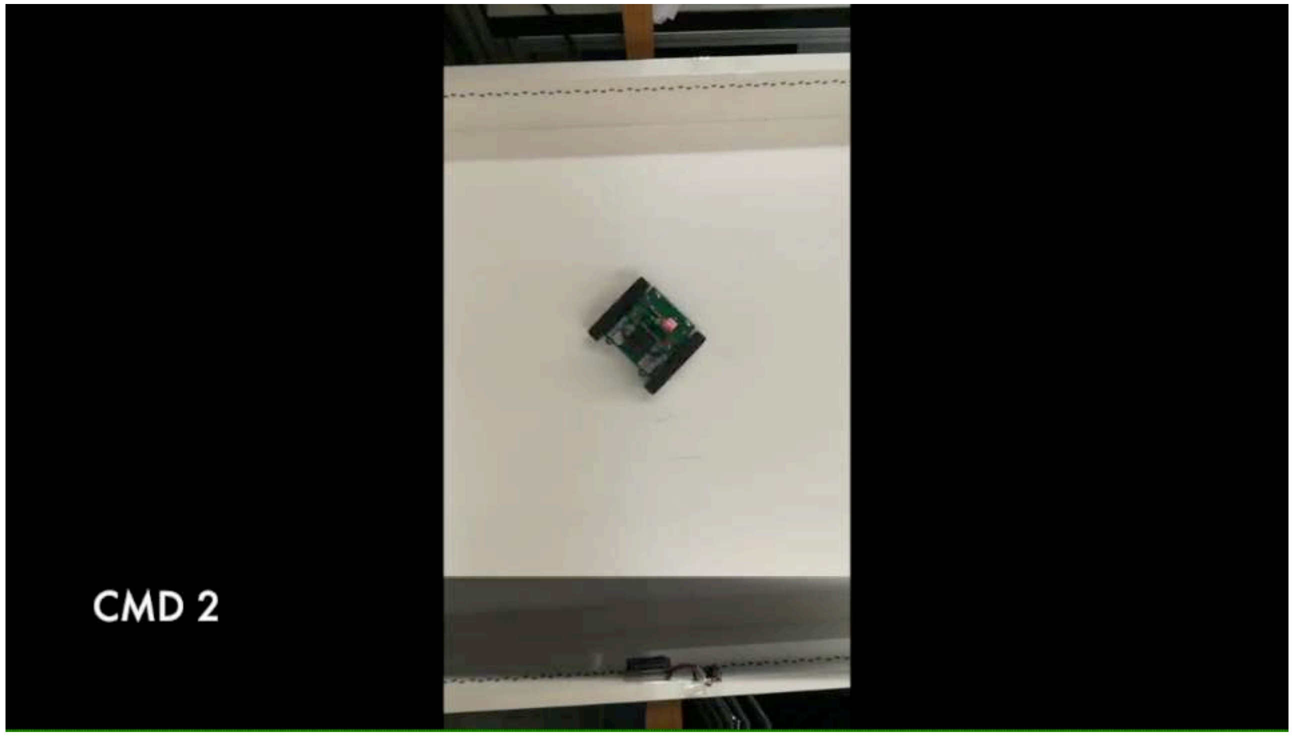
ROLLS device

Blum, H.; Dietmüller, A.; Milde, M.; Conradt, J.; Indiveri, G. & Sandamirskaya, Y. A neuromorphic controller for a robotic vehicle equipped with a dynamic vision sensor. Robotics: Science and Systems (RSS), **2017**

Motor control, learning



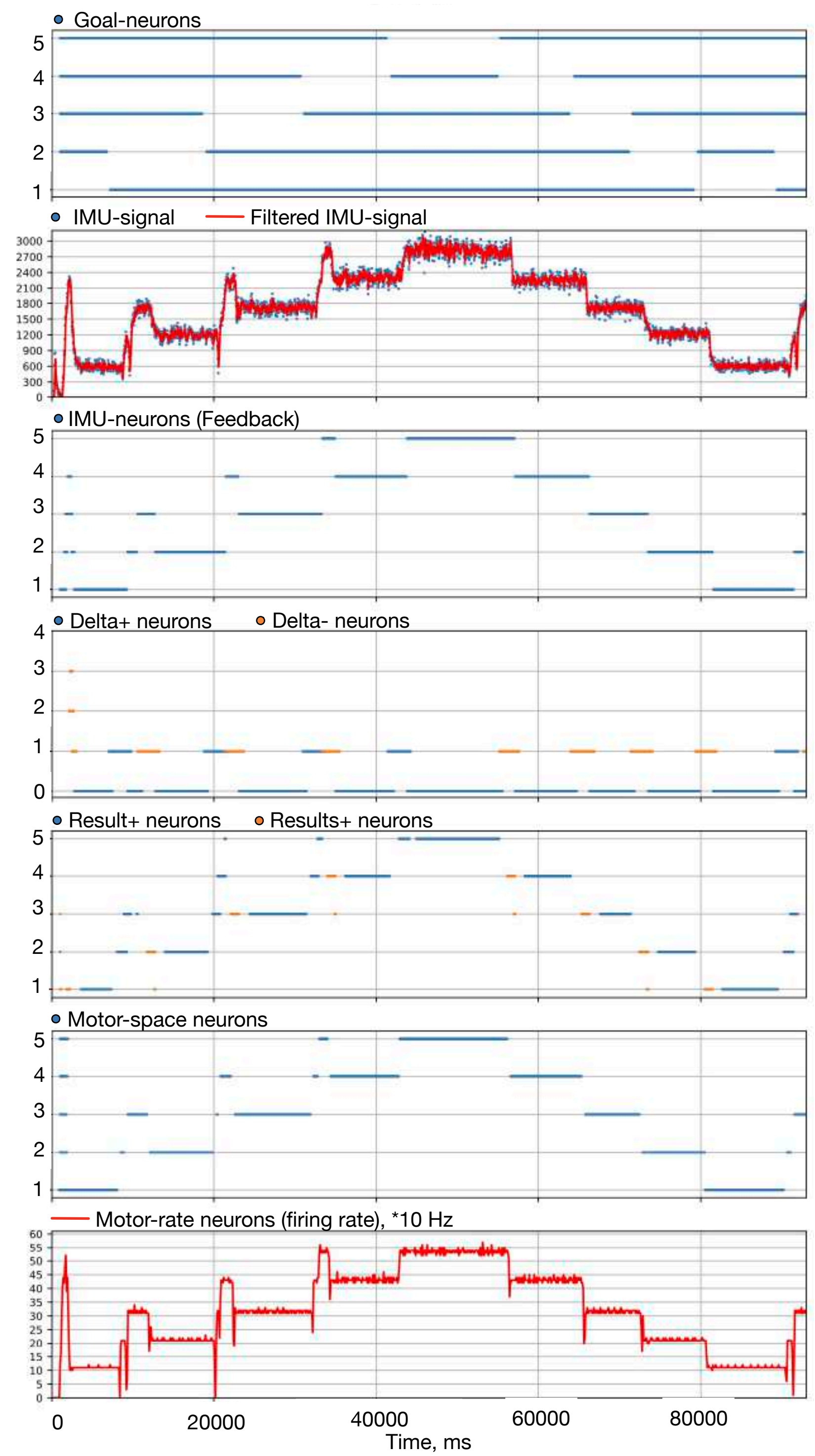
- PI-controller with spiking silicon neurons
- On-chip learning of feedforward control
- Easy to integrate with other SNN models



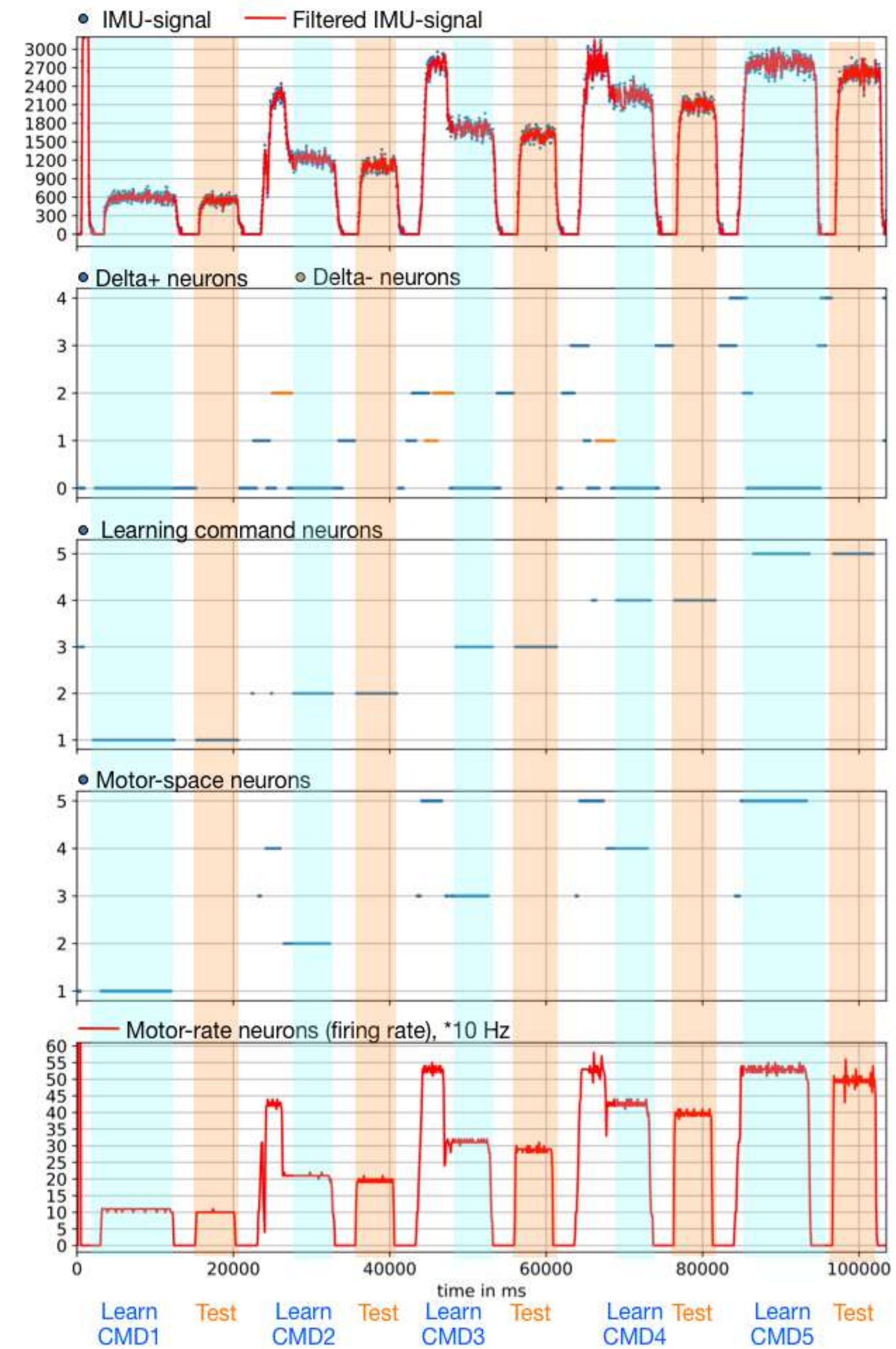
Glatz, S.; Kreiser, R.; Martel, J. N. P.; Qiao, N. & Sandamirskaya, Y. Adaptive motor control and learning in a spiking neural network, fully realised on a mixed-signal analog/digital neuromorphic processor. ICRA, arxiv, **2019**

Motor control: results

Controller



Learning the inverse mapping

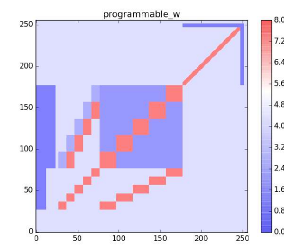


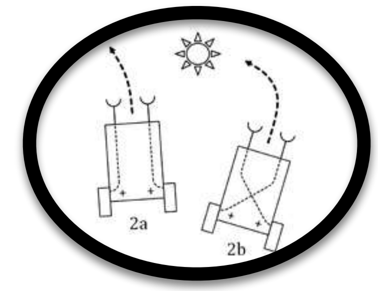
Glatz, S.; Kreiser, R.; Martel, J. N. P.; Qiao, N. & Sandamirskaya, Y. Adaptive motor control and learning in a spiking neural network, fully realised on a mixed-signal analog/digital neuromorphic processor. ICRA, arxiv, **2019**

Why are these architectures fundamental?

➡ **Braintenberg vehicle, sequences**

- attractors in a sensory-motor loop

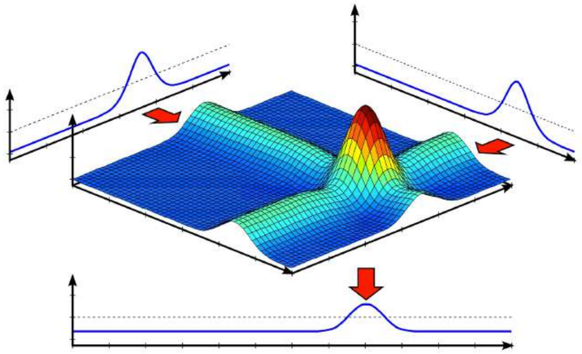




Milde et al 2017a,b; Kreiser et al 2018

➡ **Reference frame** transformations

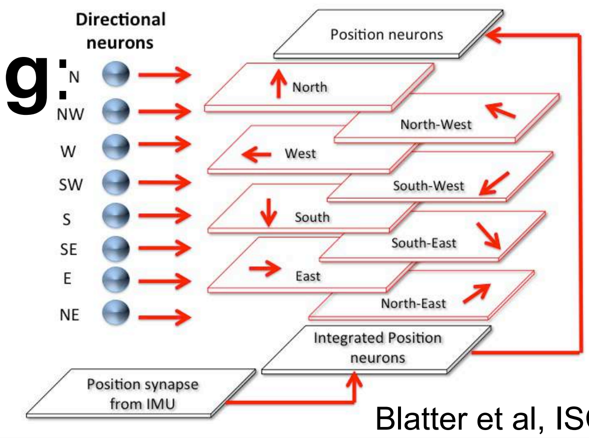
- key for linking modalities

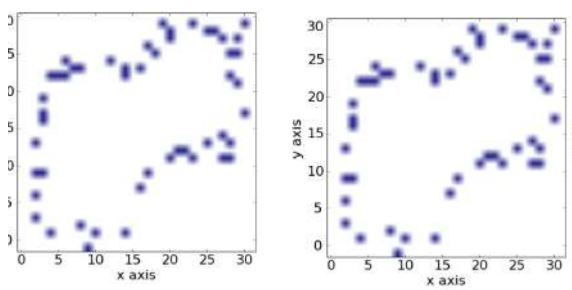


Blum et al 2017

➡ Simultaneous **localisation and mapping**: path integration, learning a map

- state estimation, building representations

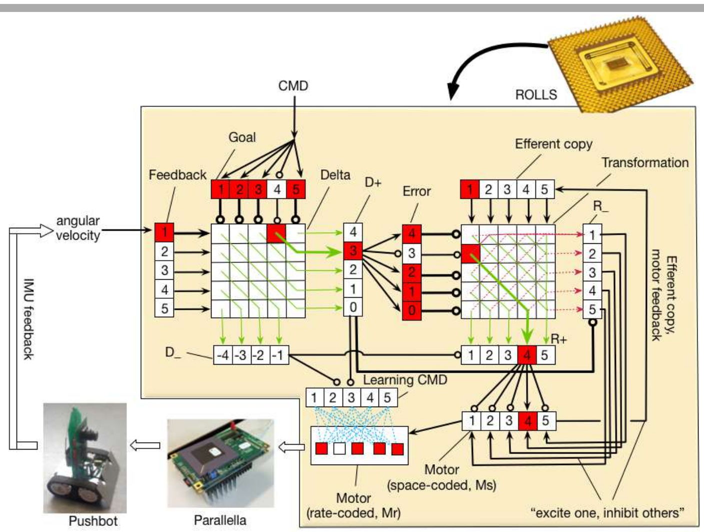


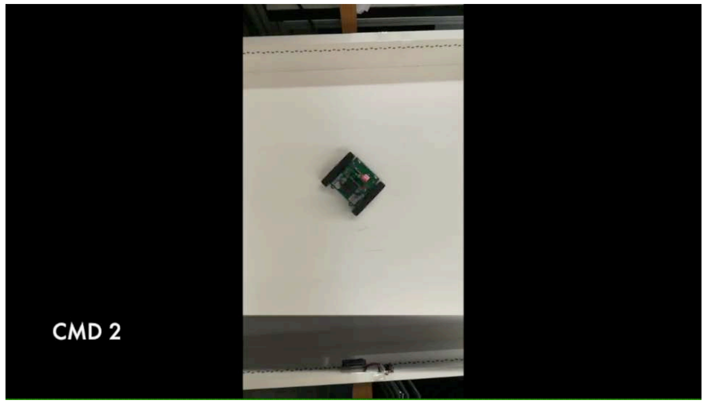


Blatter et al, ISCAS, under rev; Kreiser et al 2018a, b

➡ **Adaptive motor control**

- key element for adaptive behavior





Glatz et al, arxiv, 2018

Take-home message

- embodied cognitive computing requires:
    - decision making
    - memory

- these can be realised in neuronal dynamics (i.e. networks with recurrence)

- neural-dynamic architectures can be realised with spiking and continuous dynamics

- and can be interfaced to sensors and motors

➡ to create embodied neuromorphic cognitive systems

Funding

- Marie Curie IF
- FET PROACT

- Ambizione
- Project coordination

- Forschungskredit
- GRC Grant

- Junior Group fellowship

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Thank you!