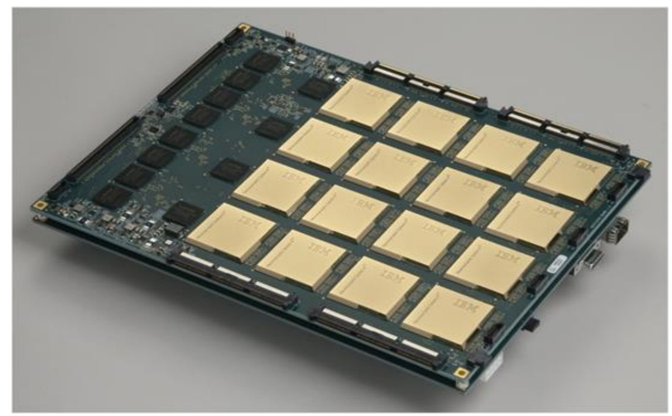
Neuromorphic computing systems: spiking neural networks, astrocyte-neuron networks

David Halliday
Department of Electronic Engineering, University of York.

→

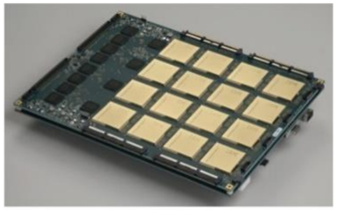


IBM True North.
From: J. Neural Eng. 13: 051001, 2016

UNIVERSITY of York

Overview of Talk

- Neuromorphic computing with Spiking Neural Networks (SNNs).
- Astrocyte – neuron networks:
  - Astrocyte regulation of neuronal activity.
  - Tripartite synapse model.
- Fault tolerant learning and self-repair in spiking astrocyte neural networks (SANNs):
  - Quad partite synapse model.
- Robotic demonstrators.



J. Neural Eng. 13: 051001, 2016

Neuromorphic Computing: Spiking Neural Networks

Pergamon

Neural Networks, Vol. 10, No. 9, pp. 1659–1671, 1997

Printed in Great Britain
0893–6080/97 $17.00+.00

PII: S0893-6080(97)00011-7

CONTRIBUTED ARTICLE

Networks of Spiking Neurons: The Third Generation of Neural Network Models

WOLFGANG MAASS

Institute for Theoretical Computer Science, Technische Universität Graz

(*Received* 27 *March* 1996; *accepted* 10 *November* 1996)

Abstract—*The computational power of formal models for networks of spiking neurons is compared with that of other neural network models based on McCulloch Pitts neurons (i.e., threshold gates), respectively, sigmoidal gates. In particular it is shown that networks of spiking neurons are, with regard to the number of neurons that are needed, computationally more powerful than these other neural network models. A concrete biologically relevant function is exhibited which can be computed by a single spiking neuron (for biologically reasonable values of its parameters), but which requires hundreds of hidden units on a sigmoidal neural net. On the other hand, it is known that any function that can be computed by a small sigmoidal neural net can also be computed by a small network of spiking neurons. This article does not assume prior knowledge about spiking neurons, and it contains an extensive list of references to the*

Neuromorphic Computing: Computing with spike timings

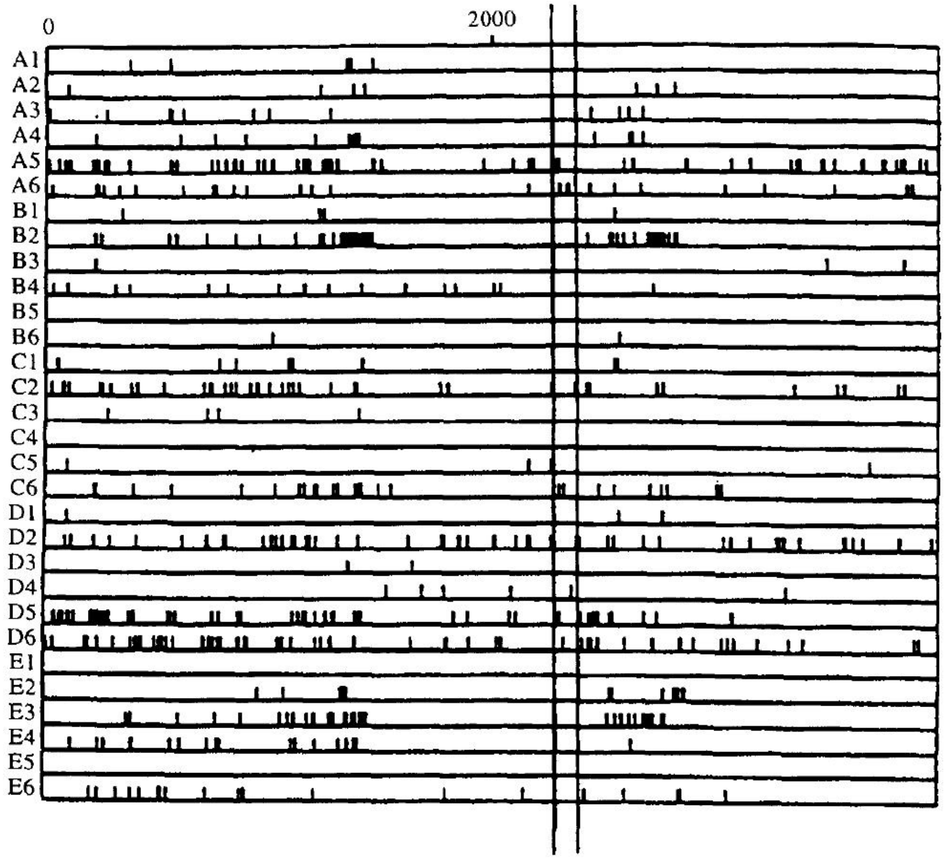


FIGURE 1. Simultaneous recordings (over 4 sec) of the firing times of 30 neurons from monkey striate cortex by Krüger & Aiple (1988). Each firing is denoted by a short vertical bar, with a separate row for each neuron. For comparison we have marked the length of an interval of 100 msec by two vertical lines. This time span is known to suffice for the completion of some complex multilayer cortical computations.

Maass, *Neural Networks,* **10**, 1659-1671 (1997).

Astrocyte - neuron networks: The tripartite synapse

Regulation of synaptic transmission through two pathways which regulate probability of release (PR).

1. Direct: reduces PR.
2. Indirect: via astrocyte increases PR.

Following synaptic failure:

- Indirect signalling via astrocyte increases PR, and repairs fault.

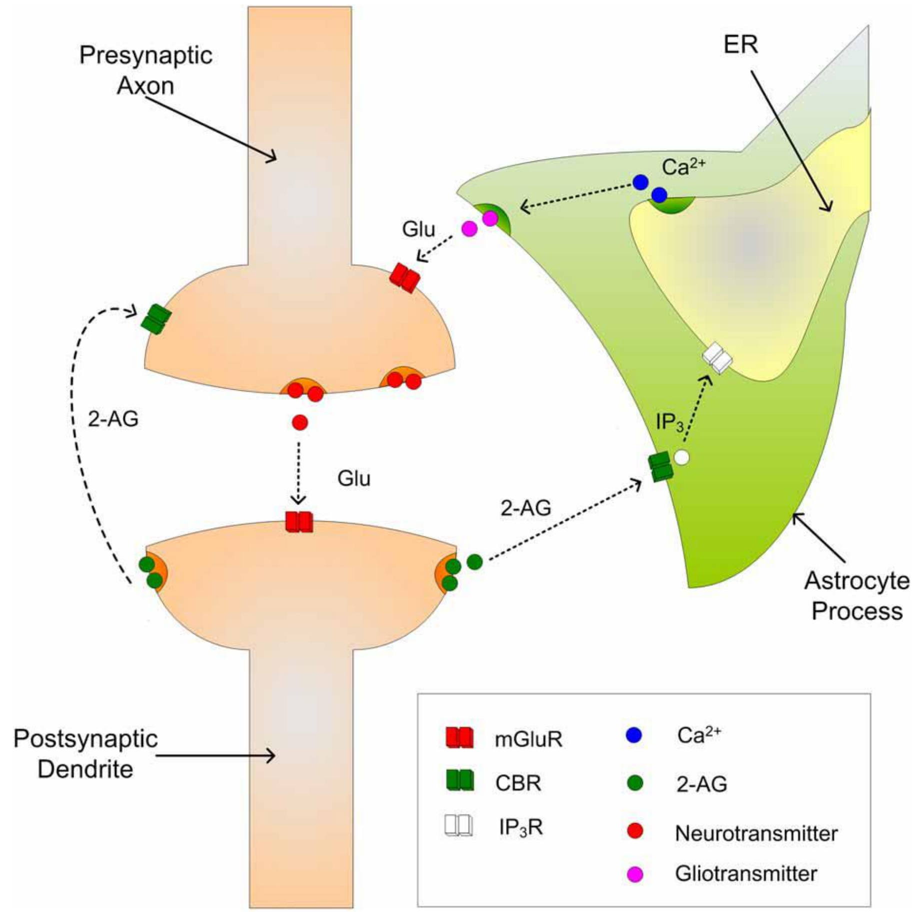


Figure: Wade et al. Front. Comput. Neurosci. 6: 76, 2012

Self repairing Spiking Astrocyte Neural Network (SANN).

Model:

- Two Leaky integrate and fire (LIF) spiking neurons.
- Ten synaptic inputs each.
- One Astrocyte.

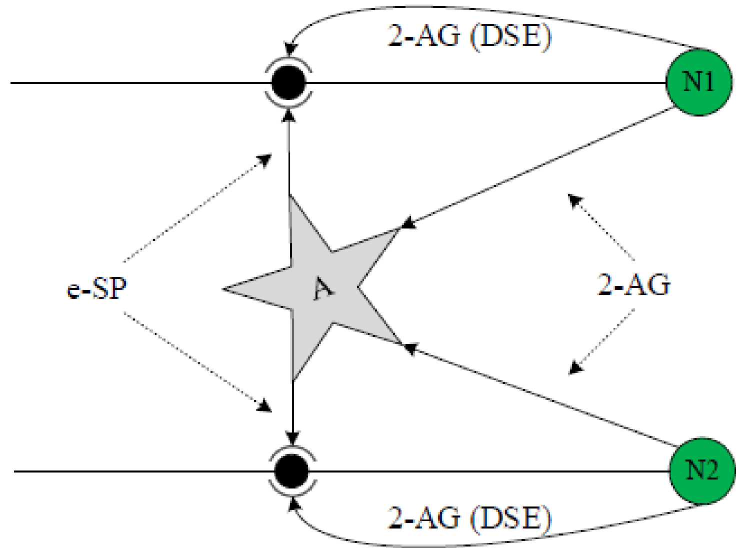


Figure: Wade et al. Front. Comput. Neurosci. 6: 76, 2012

Results:

- FPGA implementation.
- Re-establishes firing after 80% synaptic failure in inputs to neuron 1.

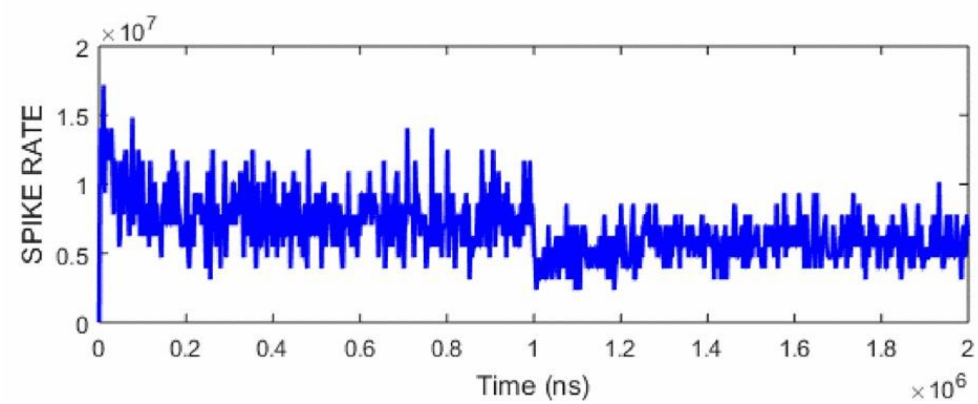
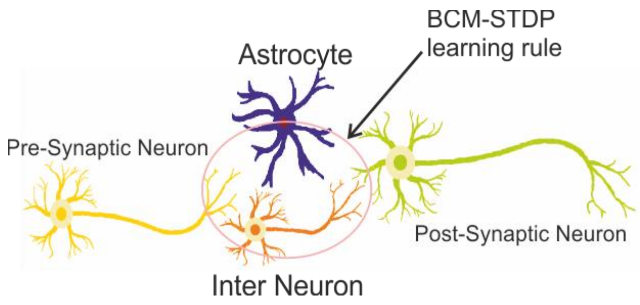


Figure: Johnson et al. Proc IEEE SSCI, 2016

Fault tolerant learning and self-repair.



Overview:

- Combine SANN with learning.
- Based on coupling between tripartite synapses and GABA interneuron.
- GABA interneuron acts to band-pass filter and route spike trains according to pre-synaptic firing frequencies.
- Novel learning rule combines Bienenstock, Cooper Munro (BCM) rule with Spike Time Dependent Plasticity (STDP).

Activity dependent band pass filtering in quadpartite synapse.

(A) At low firing rates – inhibition dominates. PR is low (red).

(B) With increased firing – Calcium induced glutamate release from astrocyte overcomes inhibition. PR increases (green).

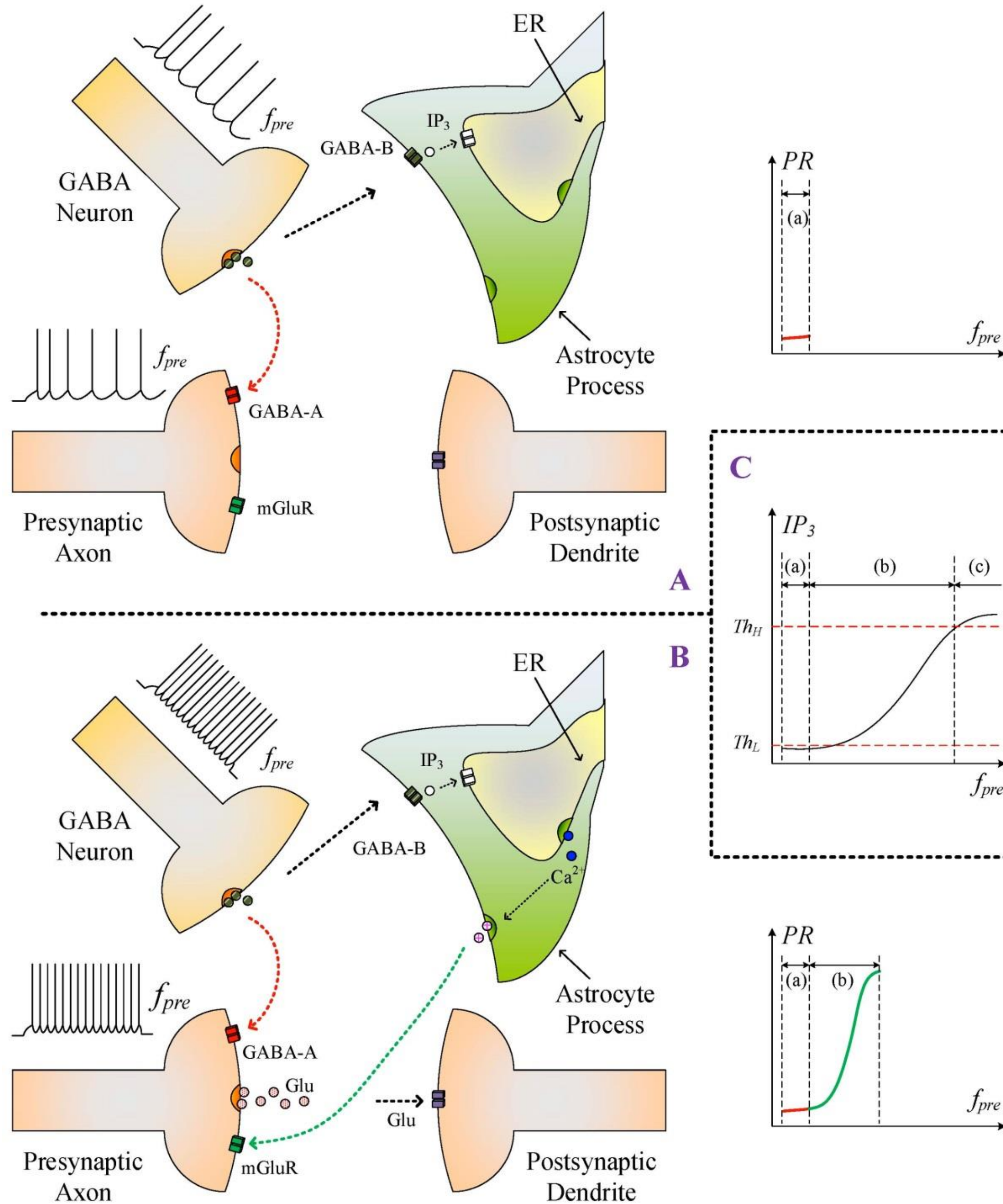


Figure: Liu et al. IEEE TNNLS 30: 865-875, 2019

Quadpartite synapse: Band pass filtering of inputs firing rate

(A) At low firing rates – inhibition dominates. PR is low (red).
(B) With increased firing – Calcium induced glutamate release from astrocyte overcomes inhibition. PR increases (green).
(C) Further increase in firing – Calcium transient stops. PR reduces (yellow).

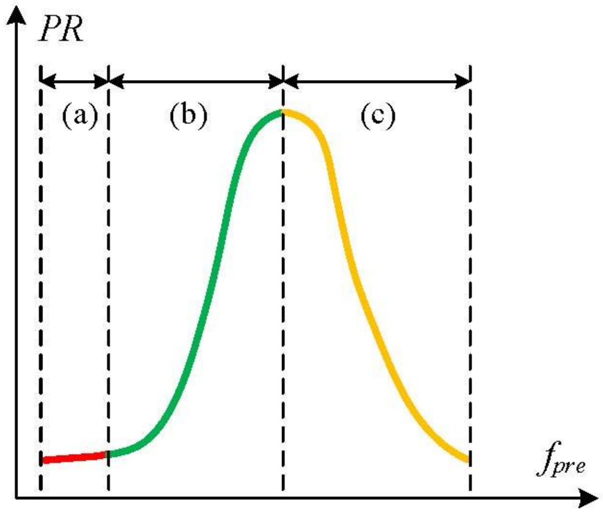


Figure: Liu et al. IEEE TNNLS 30: 865-875, 2019

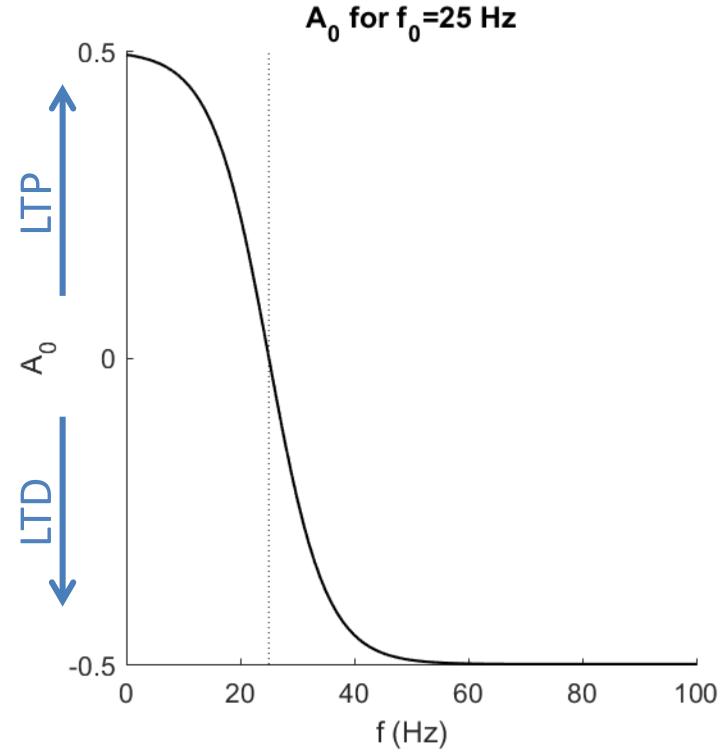
- Creates frequency selective PR as a function of pre-synaptic firing rate.
- Model using Gaussian bandpass filter: $\boldsymbol{PR} = \mathbf{exp}\left(\frac{-(f_{pre} - f_s)^2}{2\sigma^2}\right)$

Fault tolerant learning: BCM-STDP (BSTDP) rule

- Role of post-synaptic firing rates: Modulates height of STDP learning window.
- As post synaptic firing increases: retrograde signalling reduces PR, shuts off learning.

- Want rule that modulates learning window as function of post-synaptic firing rate.
- Process similar to BCM rule (Bienenstock, Cooper Munro rule)

- BCM rule: $\boldsymbol{A_0 = \frac{A}{1+\exp(a(f-f_0))}}$ - $\boldsymbol{A_-}$
- Switches between LTP and LTD according to post-synaptic firing rate.



SANN network with fault tolerant learning

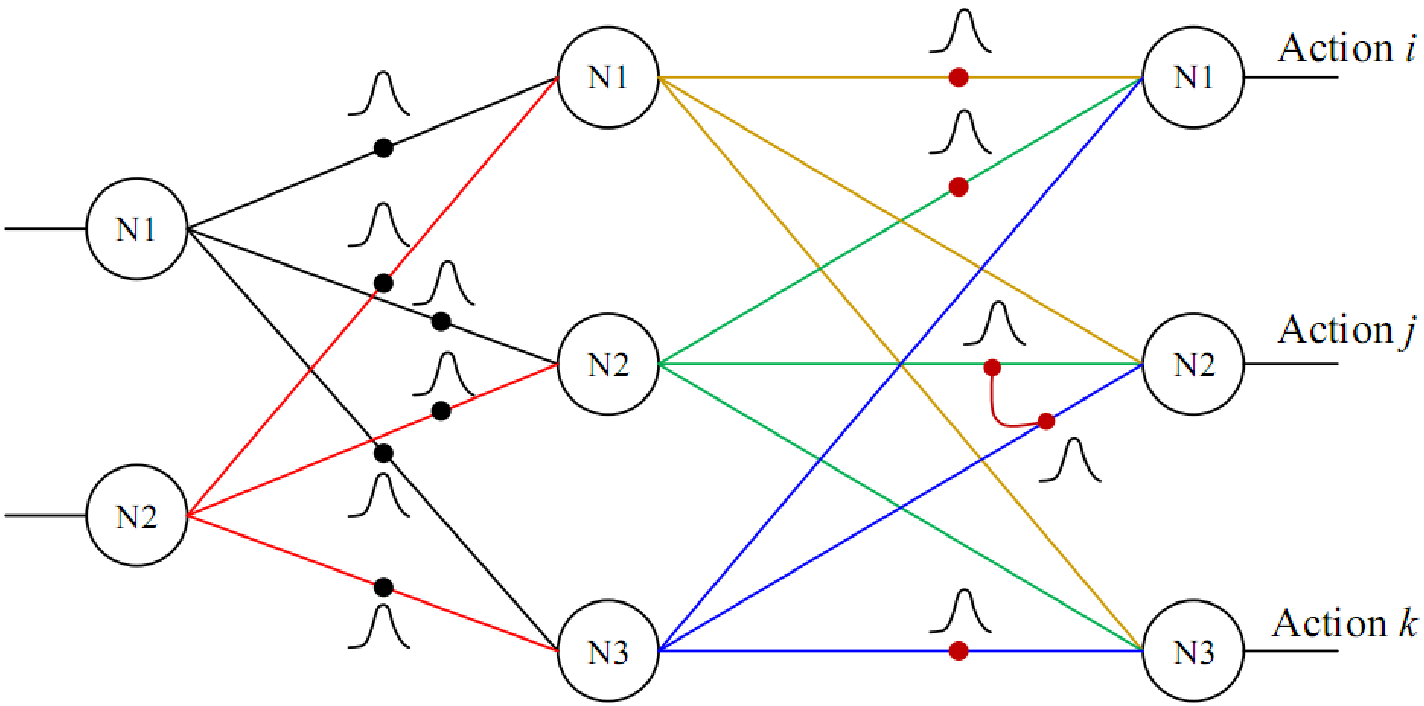


Figure: Liu et al. IEEE TNNLS 30: 865-875, 2019

- Mapping of inputs to outputs using frequency selective PR.
- Creates set of "receptive fields" for difference actions *i*, *j*, *k*, …
- Using binary mappings for different conditions.

Hardware results: Fault recovery

- Three inputs: N1 – N3
- One output: N4
- Systematic failure of 7 of 8 synapses from each input

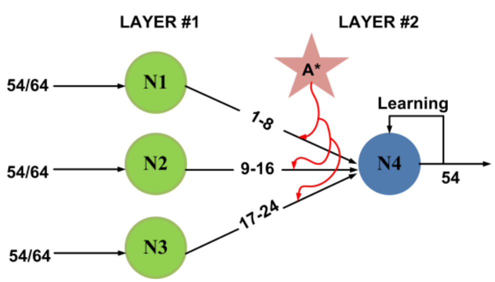


Figure: Johnson et al. 2018

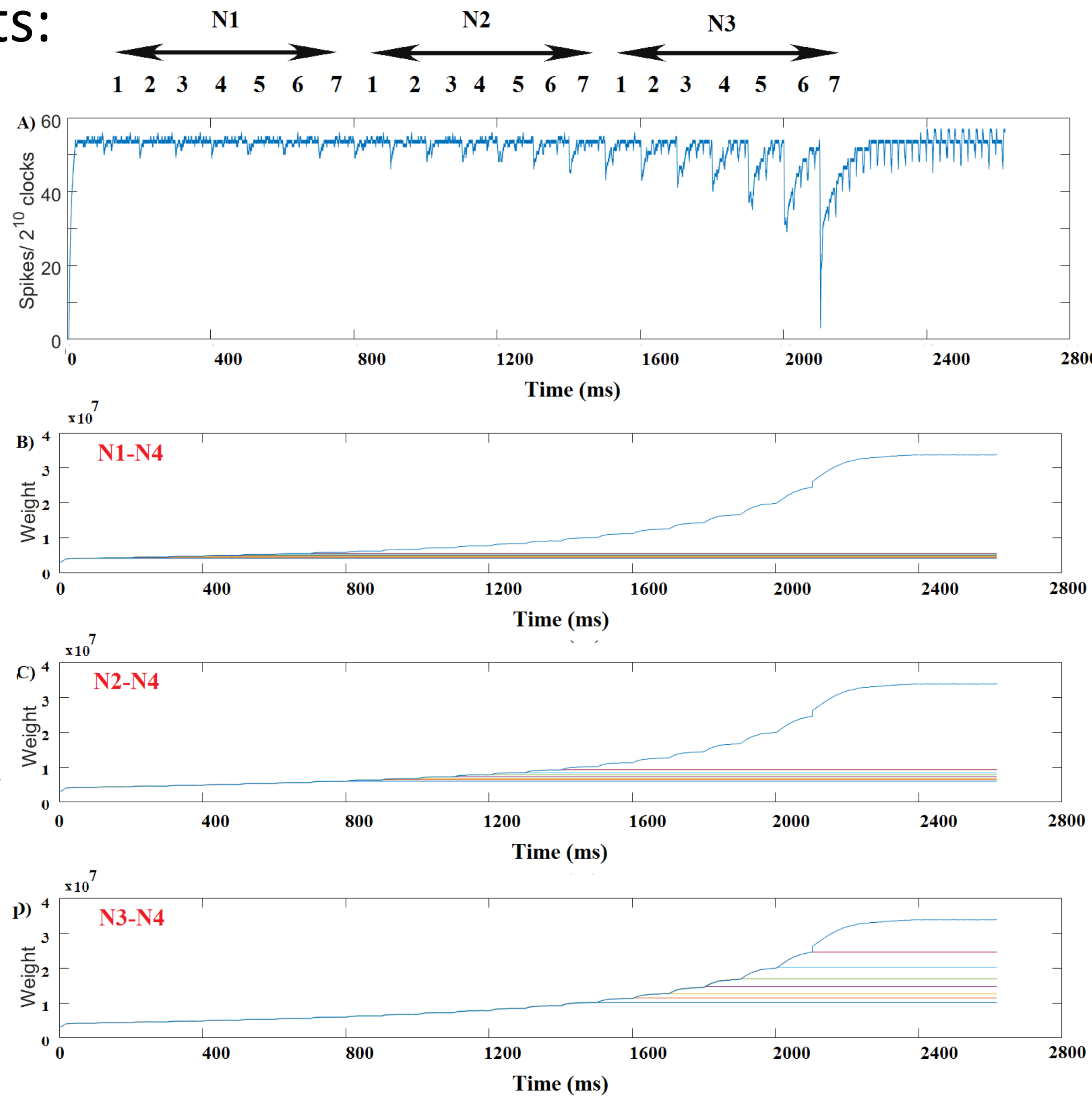
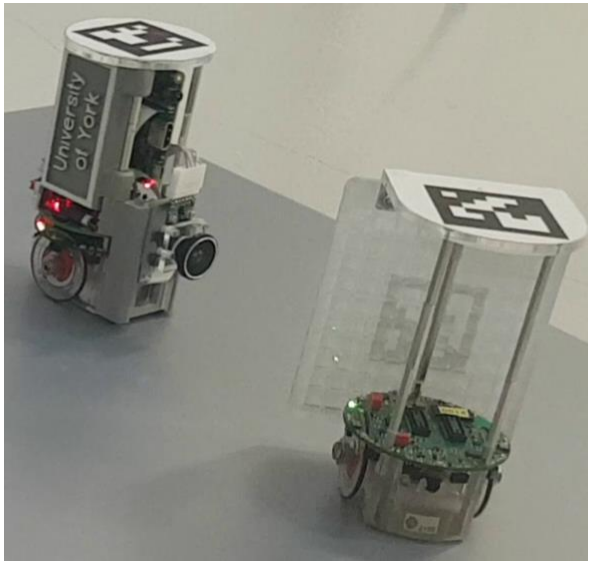


Figure: Johnson et al. Proc VLSID 49-54, 2018

Application: Robot obstacle avoidance with target detection.



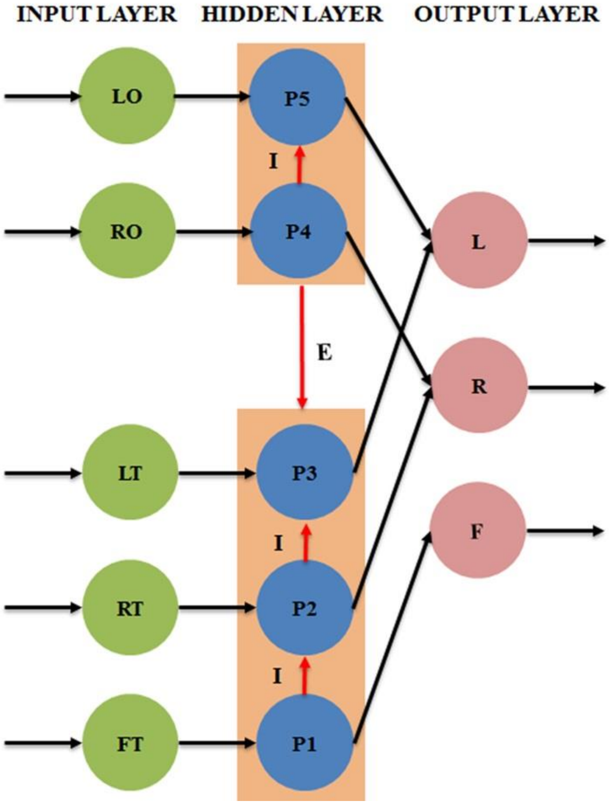


Figure: Millard et al. Proc DATE, 2018

- Proximity sensors: Forward, Left, Right.
- Target detection: Forward, Left, Right.
- Prioritised activity: Obstacle avoidance, then target detection.

Two networks:

1. Obstacle avoidance.
2. Target detection.

Actions: Forward, Left, Right.

Neuromorphic computing systems: spiking neural networks, astrocyte-neuron networks

Acknowledgements

Anju Johnson
Alan Millard
Evren Cesur
Maciej Napora
James Hilder
Andy Tyrrell
Jon Timmis

Junxiu Liu
Shvan Karim
Liam McDaid
Jim Harkin

Funding

EPSRC
Pioneering research and skills

EP/N007050/1
EP/N00714X/1

Self-rePAiring spiking Neural NEtwoRk (SPANNER)