SpiNNaker:
Technology and Project Leadership

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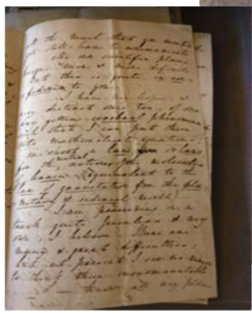
Professor Emeritus

The University of Manchester

200 years ago…

- Ada Lovelace, b. 10 Dec. 1815

"*I have my hopes, and very distinct ones too, of one day getting cerebral phenomena such that I can put them into mathematical equations--in short, a law or laws for the mutual actions of the molecules of brain. …. I hope to bequeath to the generations a calculus of the nervous system.*"



70 years ago…

Vol. LIX. No. 236.] [October, 1950

MIND

A QUARTERLY REVIEW

OF

PSYCHOLOGY AND PHILOSOPHY

I.—COMPUTING MACHINERY AND INTELLIGENCE

By A. M. Turing

1. *The Imitation Game.*

I propose to consider the question, 'Can machines think?' This should begin with definitions of the meaning of the terms 'machine' and 'think'. The definitions might be framed so as to reflect so far as possible the normal use of the words, but this attitude is dangerous. If the meaning of the words 'machine' and 'think' are to be found by examining how they are commonly used it is difficult to escape the conclusion that the meaning and the answer to the question, 'Can machines think?' is to be

Outline

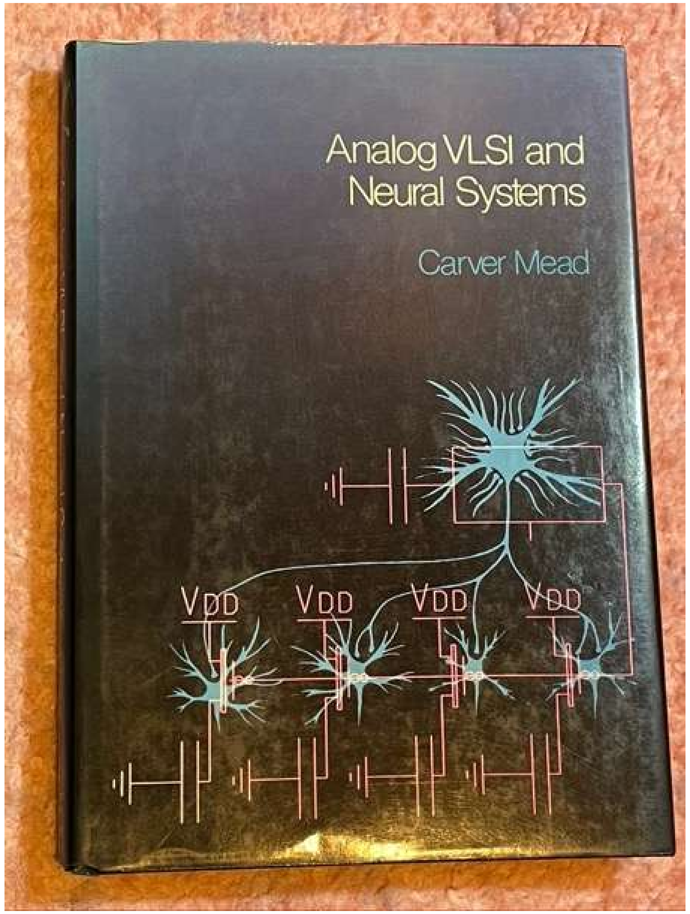
- Neuromorphic computing
- The SpiNNaker project
- SpiNNaker applications
- SpiNNaker2
- SpiNNaker2 applications
- Project leadership
- Conclusions

Neuromorphic Computing

Carver Mead

Caltech, 1980s

- observed analogy between ion channels in neurons and sub-threshold analogue transistor behaviour
- neuromorphic touch, hearing & vision sensors



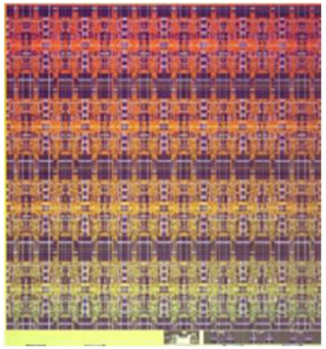
Neuromorphic systems worldwide

SpiNNaker
Biologically Inspired Massively Parallel Architectures

IBM TrueNorth

intel Loihi

BrainScaleS



Biological realism

Ease of use

Many-core (ARM) architecture
Optimized spike communication network
Programmable local learning
x0.01 real-time to x10 real-time

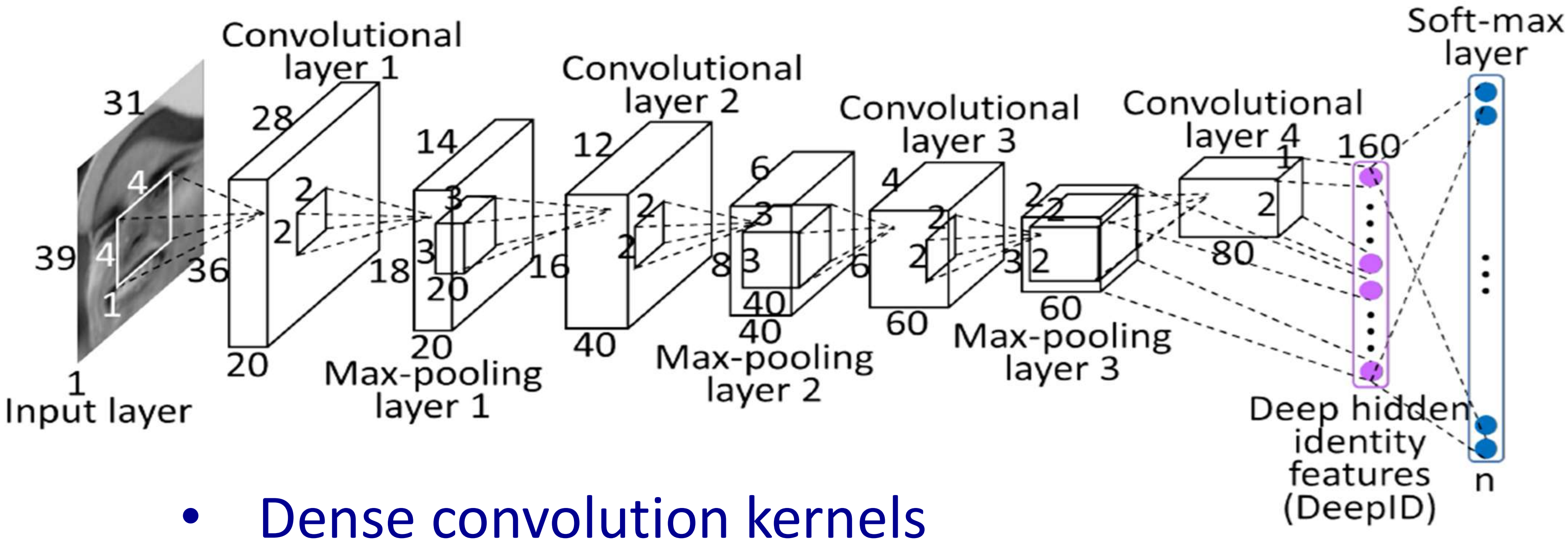
Full-custom-digital neural circuits
No local learning (TrueNorth)
Programmable local learning (Loihi)
Exploit economy of scale
x0.01 real-time to x100 real-time

Analog neural cores
Digital spike communication
Biological local learning
Programmable local learning
x10.000 to x1000 real-time

Bio-inspiration

- Can massively-parallel computing resources accelerate our understanding of brain function?
- Can our growing understanding of brain function point the way to more efficient parallel, fault-tolerant computation?

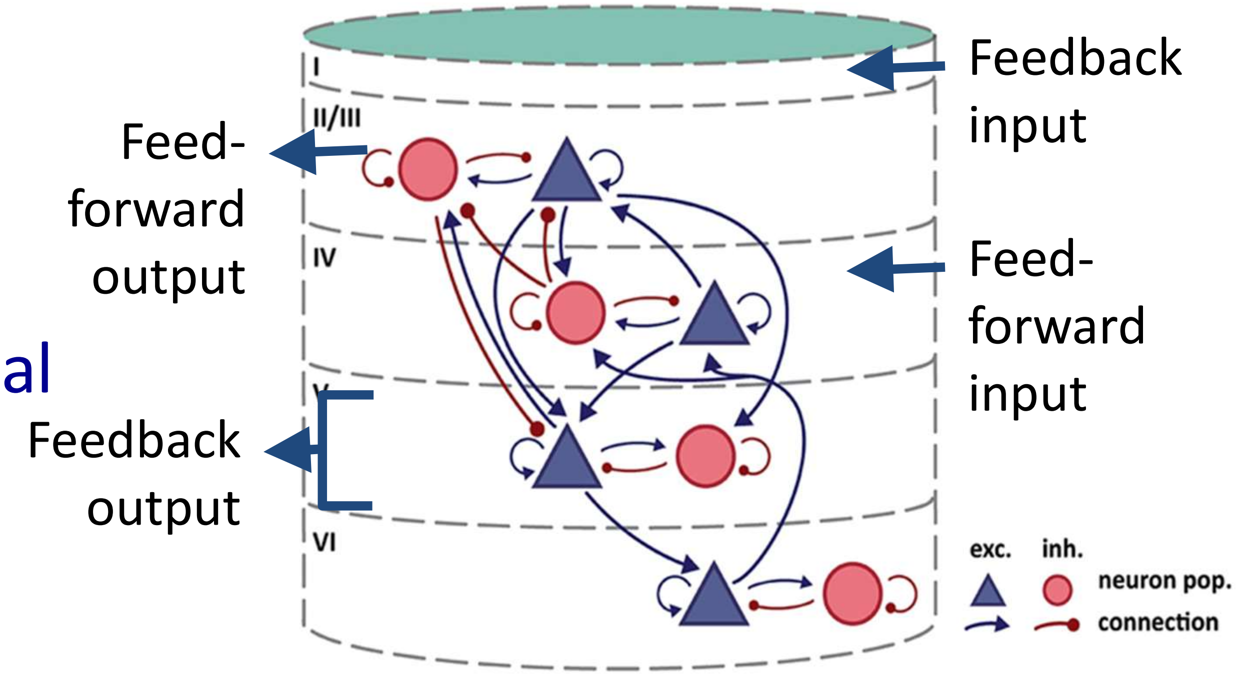
ConvNets - structure



- Dense convolution kernels
- Abstract neurons (no spikes)
- Feed-forward connections (mainly)
- Trained through backpropagation

The cortex - structure

- Spiking neurons
- Complex information flow
- Two-dimensional cortical structure
- Sparse connectivity
  - < 10%



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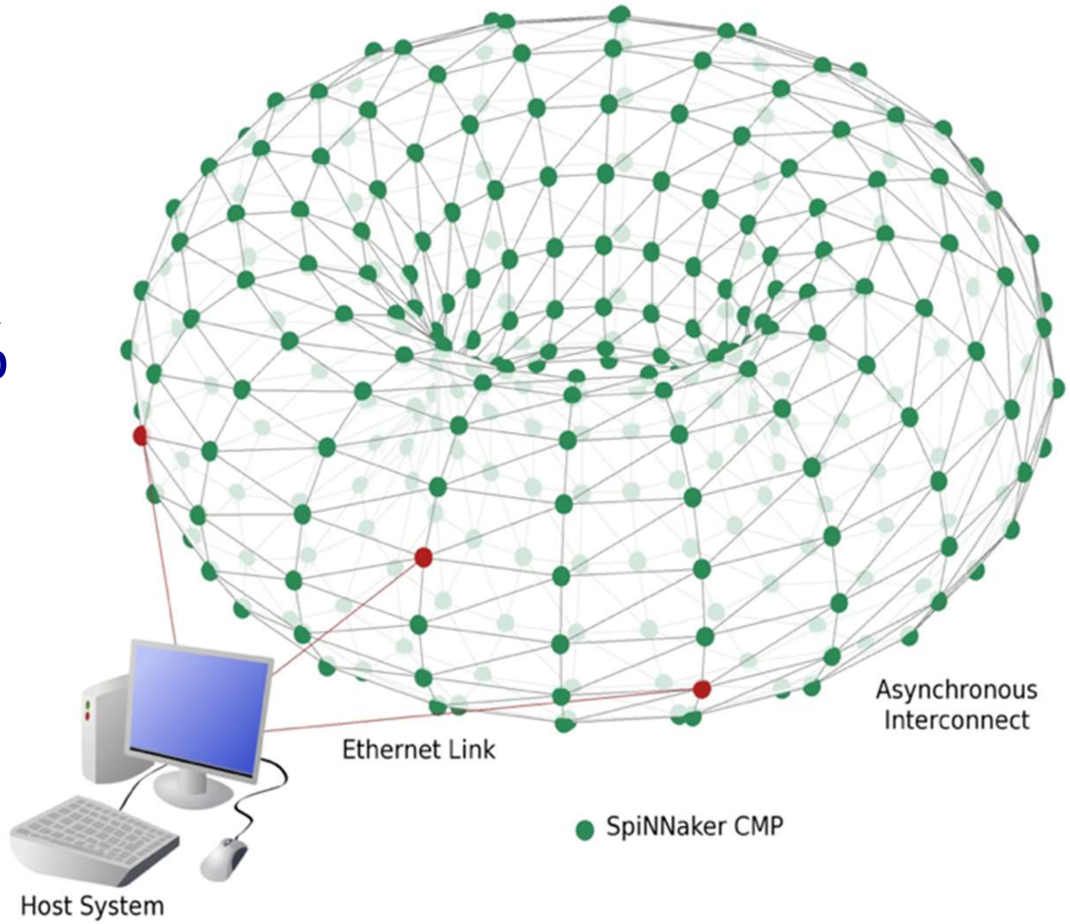
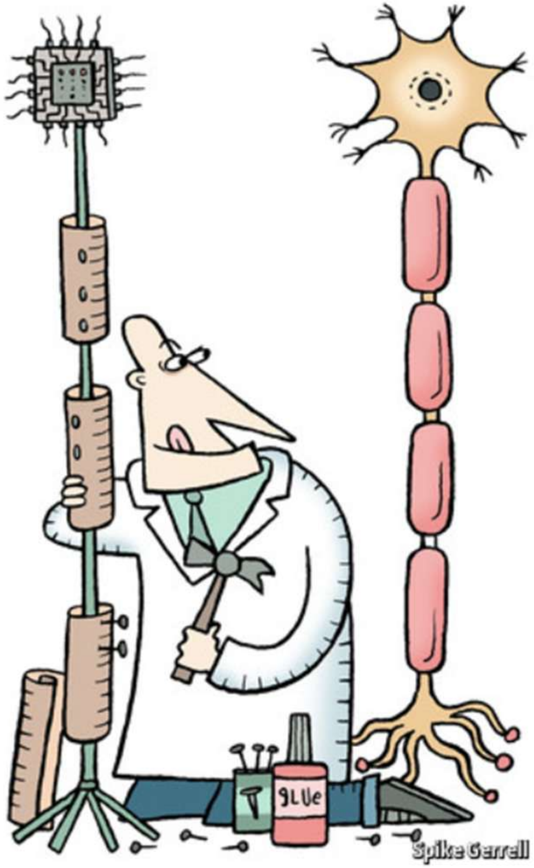
SpiNNaker project

- A million mobile phone processors in one computer
- Able to model about 1% of the human brain…
- …or 10 mice!

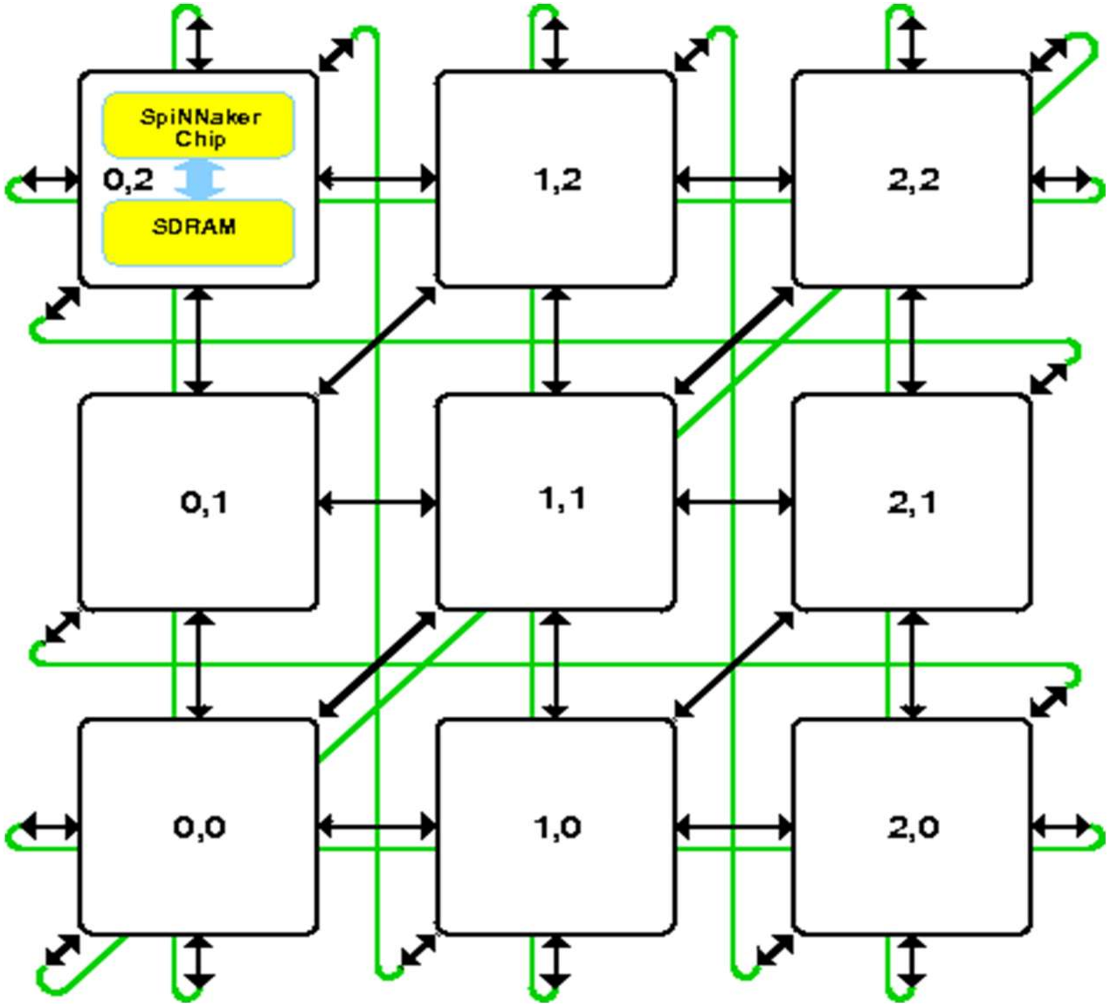


Design principles

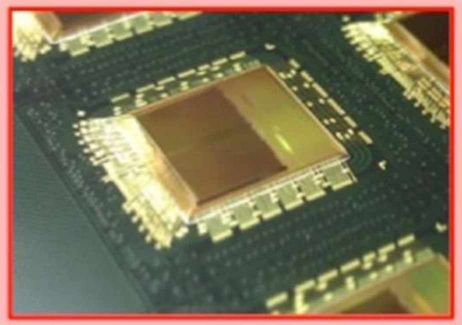


- *Virtualised topology*
  - physical and logical connectivity are decoupled
- *Bounded asynchrony*
  - time models itself
- *Energy frugality*
  - processors are free
  - the real cost of computation is energy

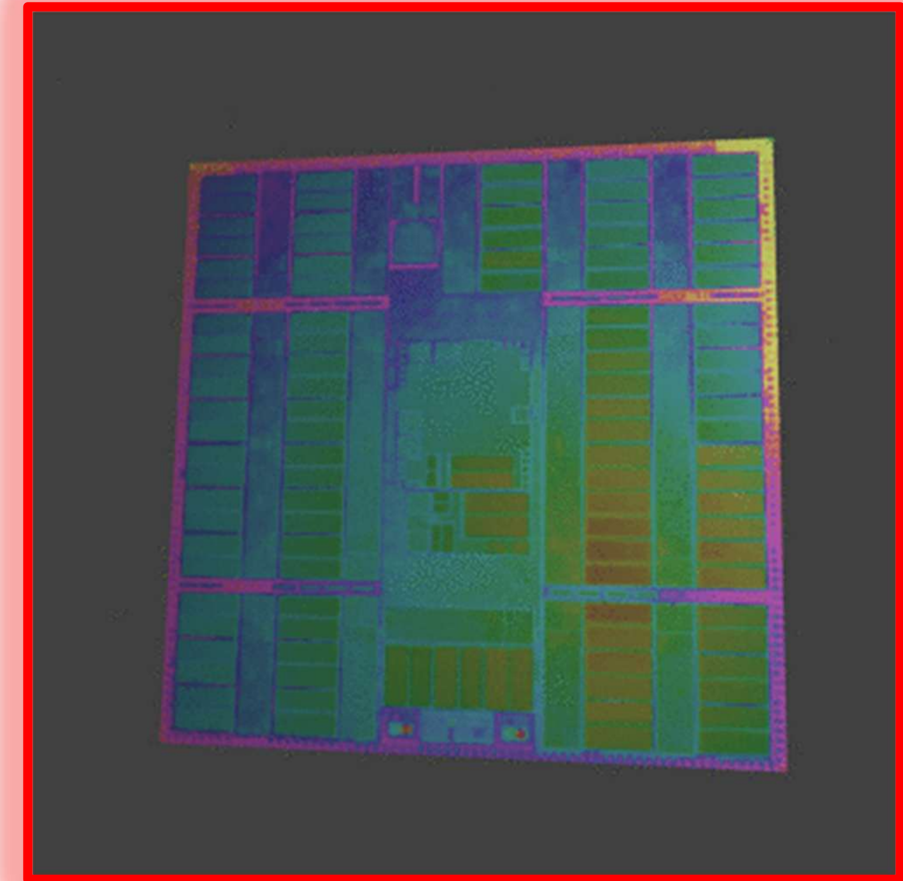
SpiNNaker system



SpiNNaker chip



Multi-chip packaging by UNISEM



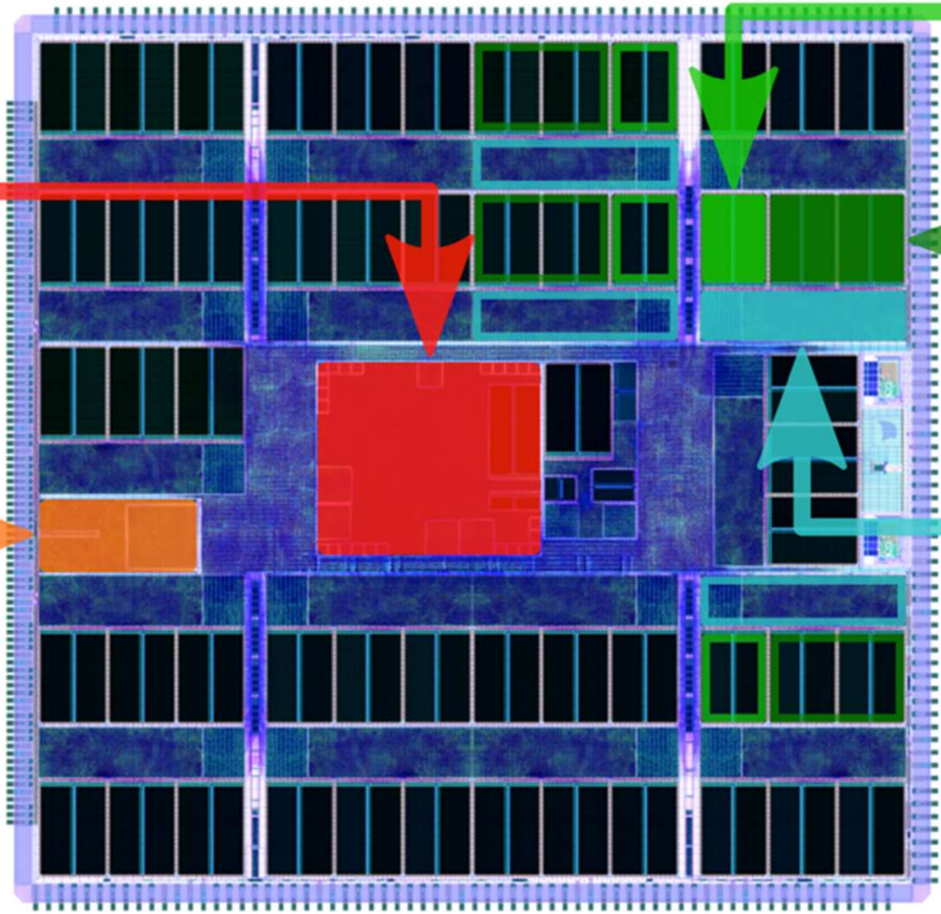
Chip resources

Router

routing tables
spike packet routing
system comms.

RAM port

synapse states
activity logs



Instruction memory

run-time kernel
application callbacks

Data memory

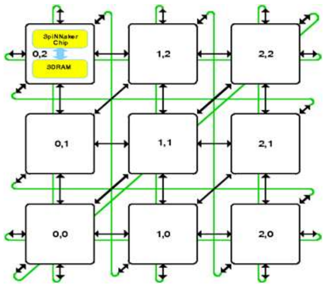
kernel state
neuron states
stack and heap

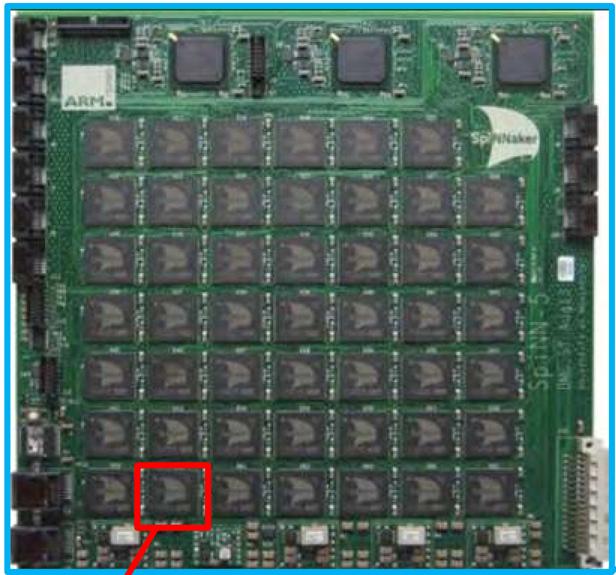
Processor

neuron and synapse
state computations

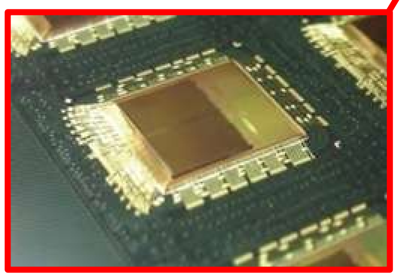
SpiNNaker machines

SpiNNaker board
(864 ARM cores)



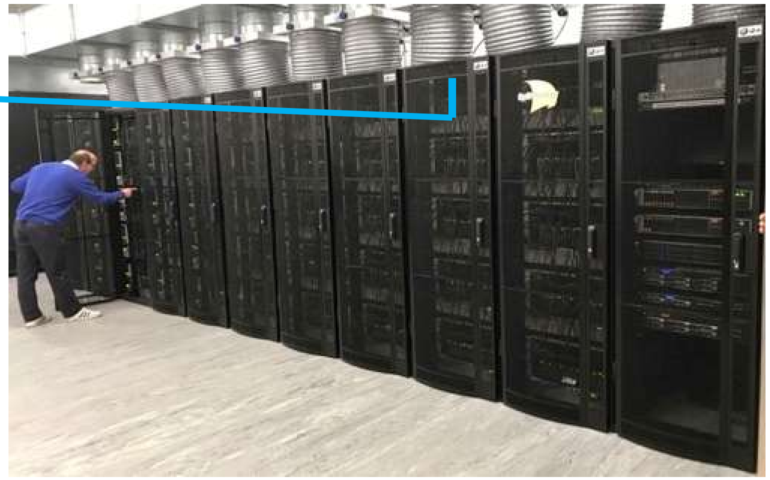


SpiNNaker chip
(18 ARM cores)



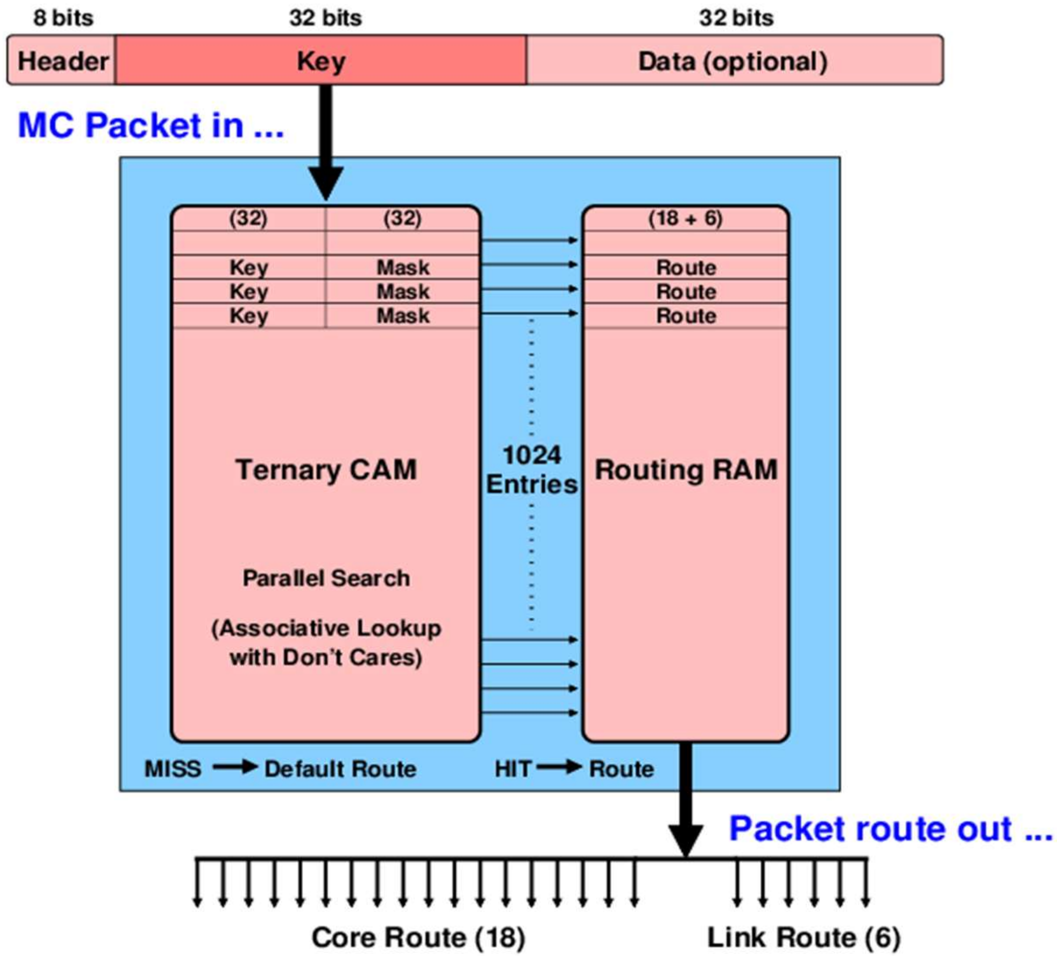
- HBP platform
  - 1M cores
  - 11 cabinets (including server)
- Launch 30 March 2016
  - then 500k cores
  - ~450 remote users
  - 5M SpiNNaker jobs run

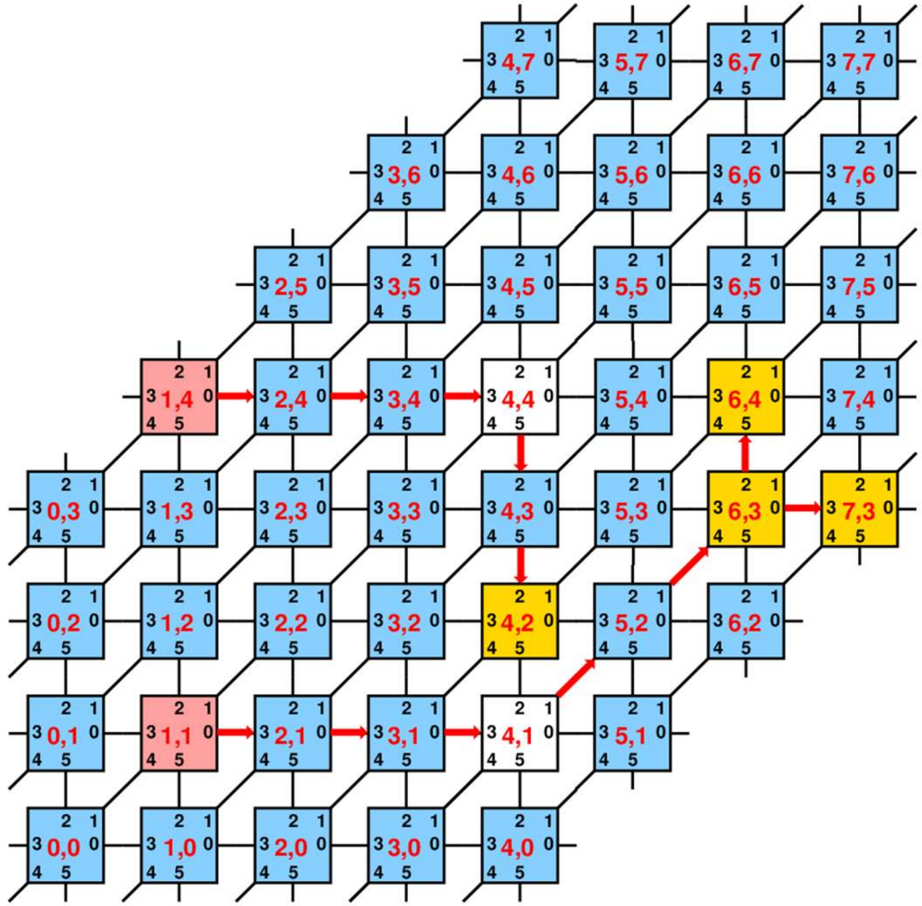
Human Brain Project



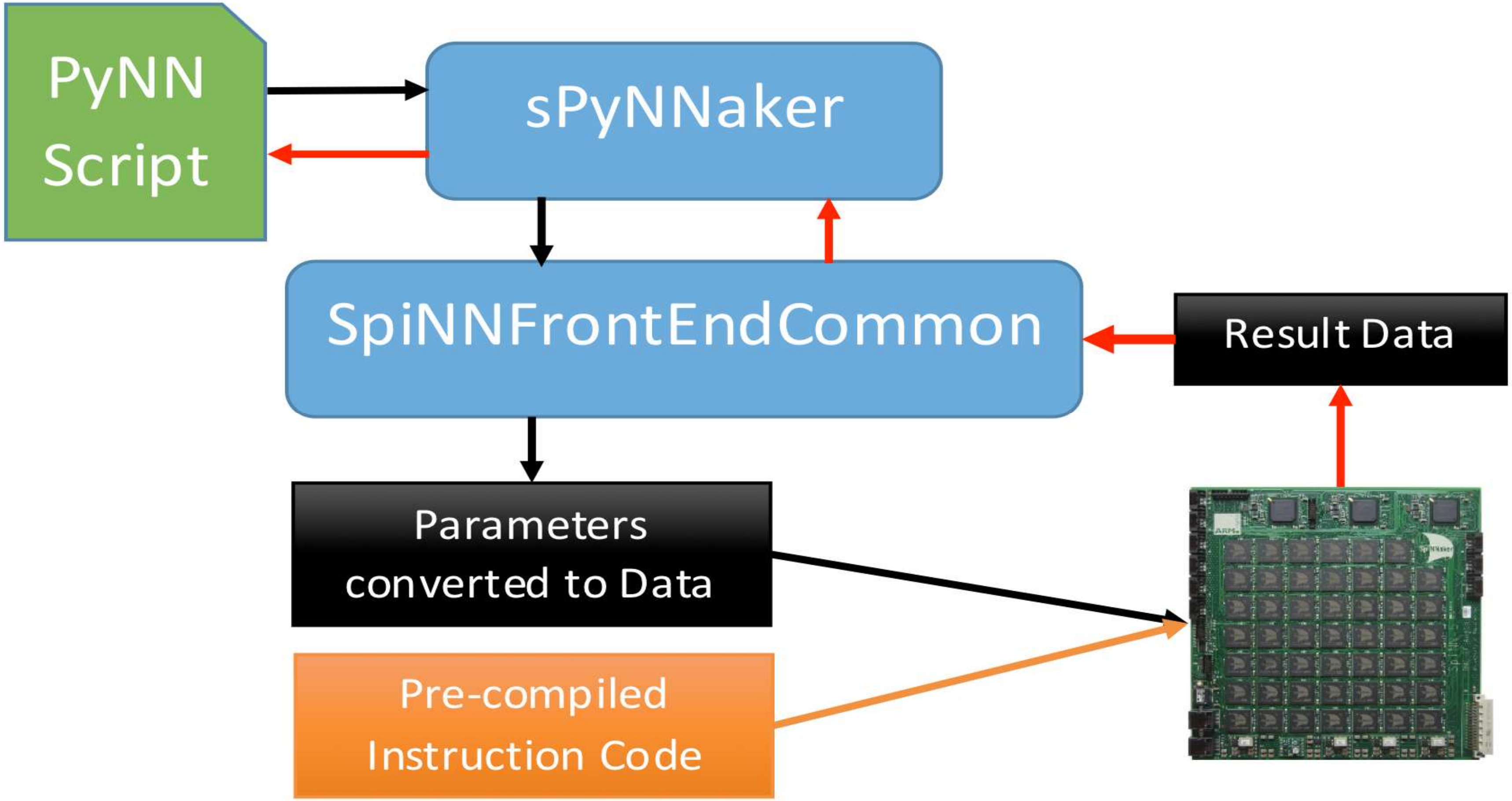
SpiNNaker racks
(1M ARM cores)

Multicast routing

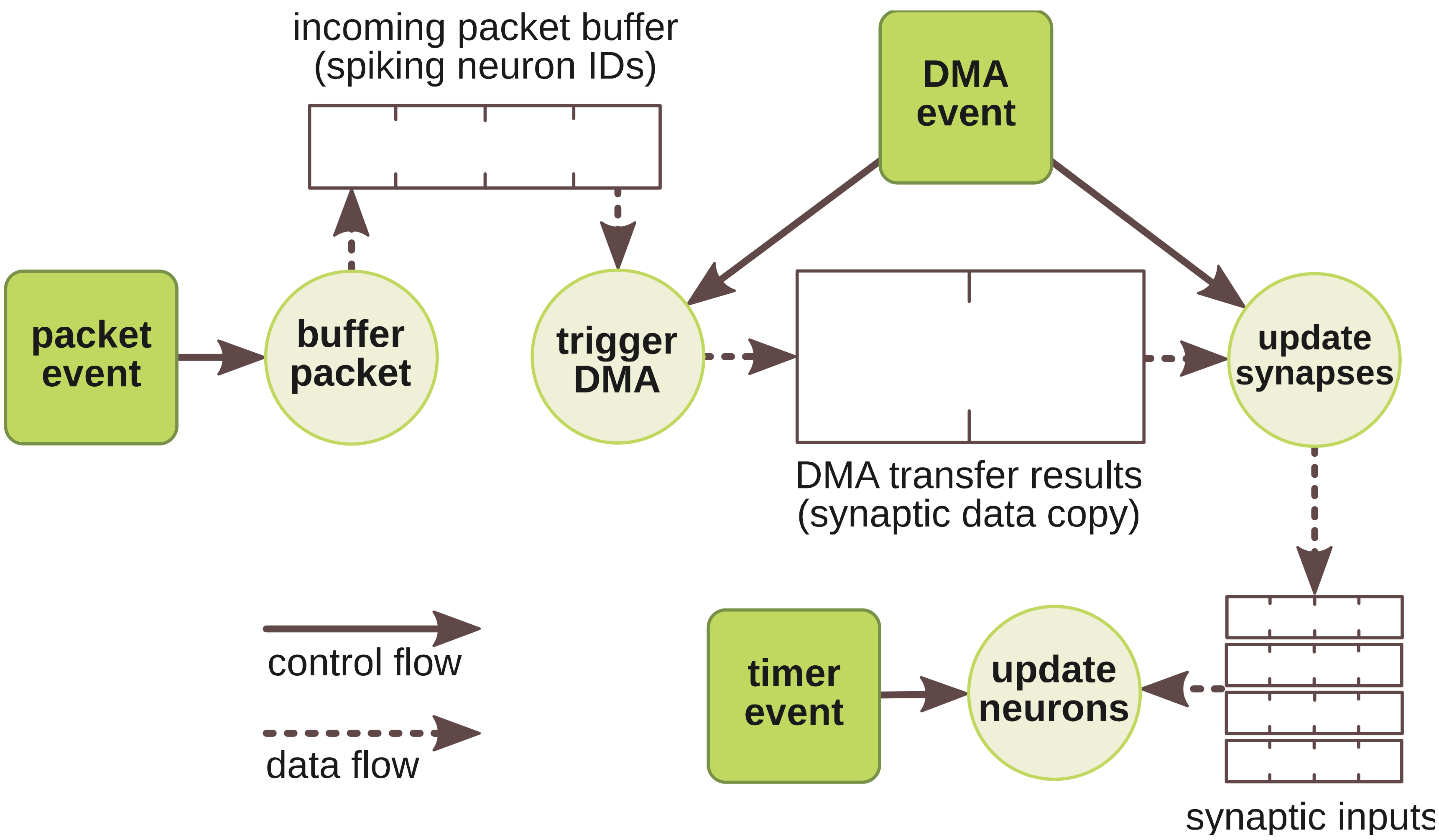




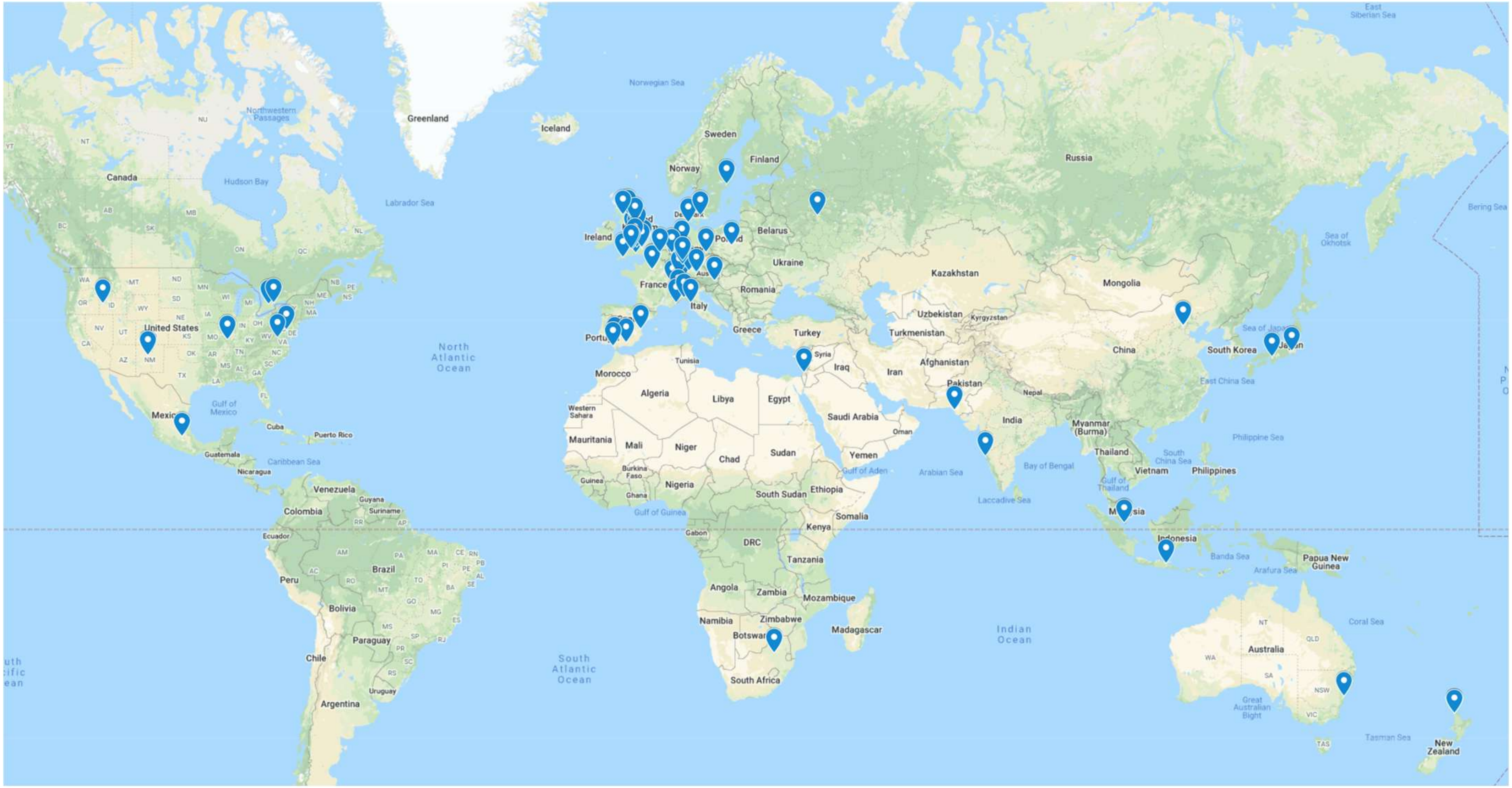
High-level software flow



Event-driven software model



SpiNNaker machines



Publications mentioning neuromorphic chips

SpiNNaker GS citations:

- 1,033: *The SpiNNaker Project*, Proc. IEEE, 2014.
- 664: *Overview of the SpiNNaker system architecture*, IEEE Trans. Computers, 2012.
- 367: *SpiNNaker: A 1w 18-core SoC for…*, IEEE JSSC, 2013.
- 356: *SpiNNaker: mapping neural networks…*, IJCNN 2008.
- *342: Large-scale neuromorphic computing systems*, J. Neural Engineering, 2016.

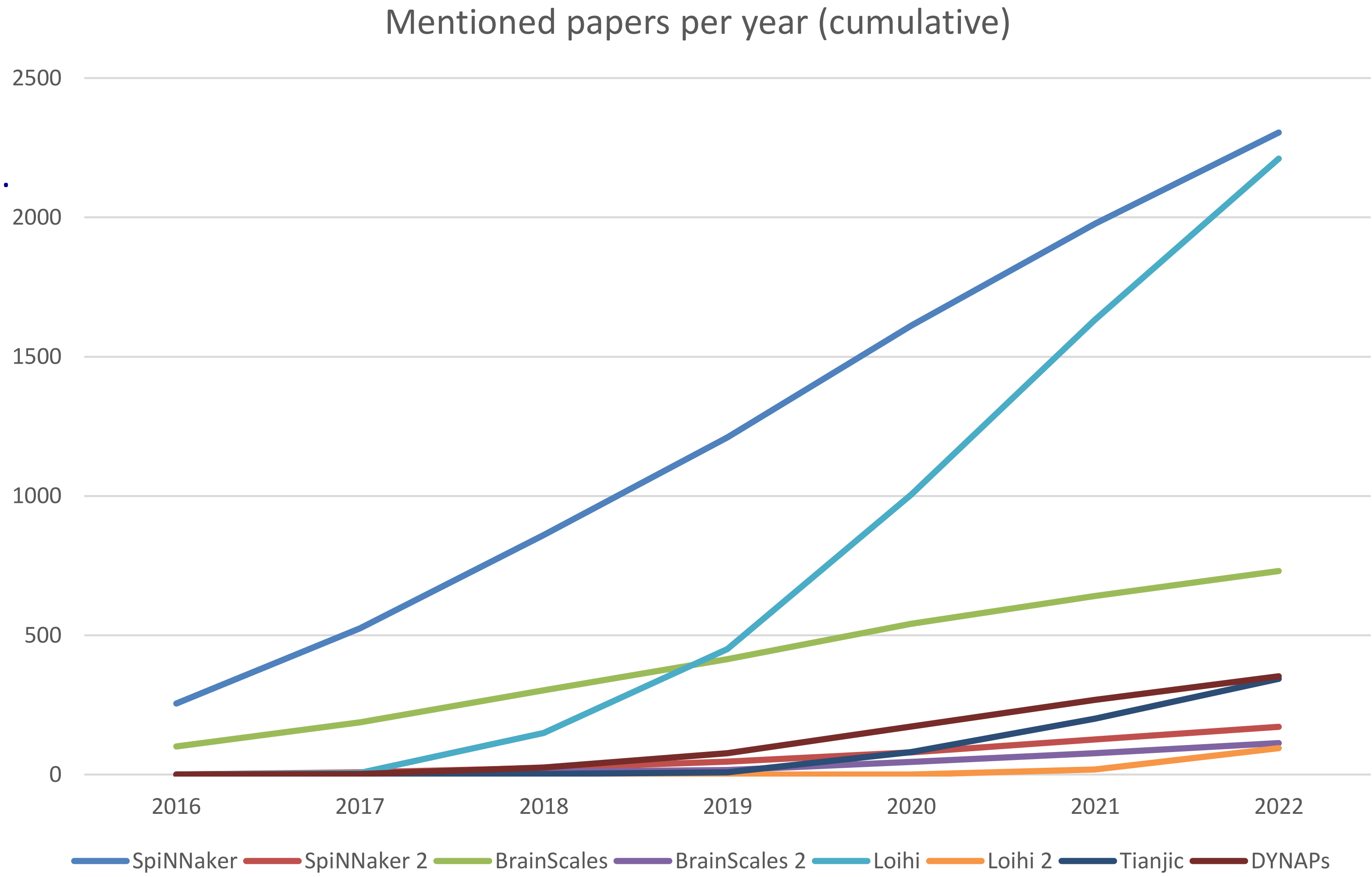


Figure courtesy of Taygun Bulut Durmaz, UP Madrid.

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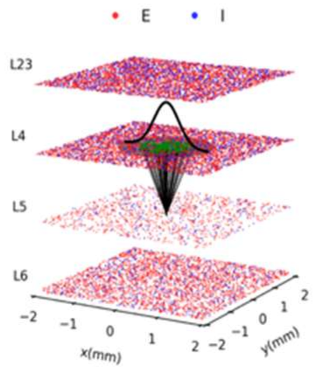
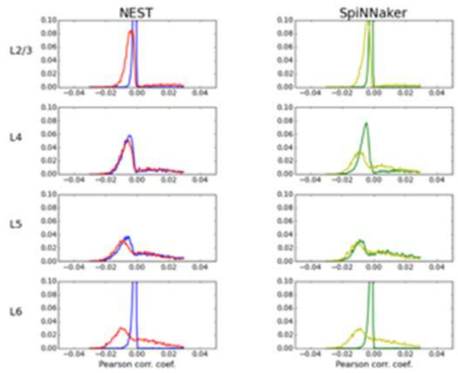
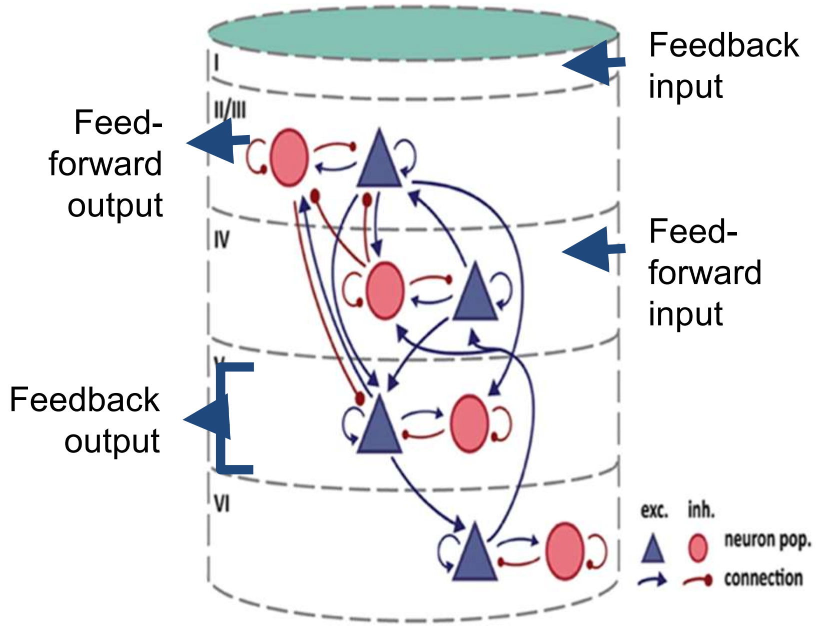
SpiNNaker applications

Computational
Neuroscience

Cortical microcircuit







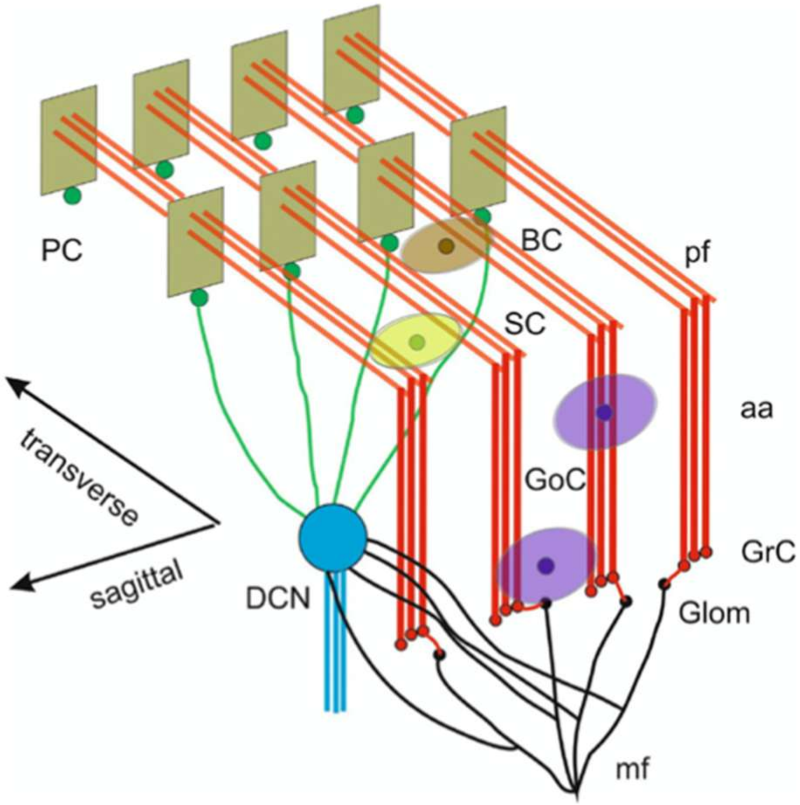
- ***Realtime execution of cortical model***
  - $1mm^2$ cortex
    - 77k neurons
    - 285M synapses
    - 0.1 ms time-step
- ***Best previous versions of this model***
  - HPC: 3x slow-down
  - GPU: 2x slow-down
- ***Will scale to $100mm^2$ without slow-down***
  - on current machine, simply by using more boards

S.J. van Albada, A.G. Rowley, A. Stokes, J. Senk, M. Hopkins, M. Schmidt, D.R. Lester, M. Diesmann, S.B. Furber, "*Performance comparison of the digital neuromorphic hardware SpiNNaker and the Neural network simulation software NEST for a full-scale cortical microcircuit model*", Frontiers 2018.

Oliver Rhodes, Luca Peres, Andrew G. Rowley, Andrew Gait, Luis A. Plana, Christian Brenninkmeijer & Steve.B. Furber, "*Real-time cortical simulation on neuromorphic hardware*", Phil Trans Roy Soc A, December 2019.

Towards a bio-inspired real-time neuromorphic cerebellum

- HBP collaboration with U. Pavia
- 97,000 neurons
- 4.2 million synapses
- SpiNNaker model validated against NEST

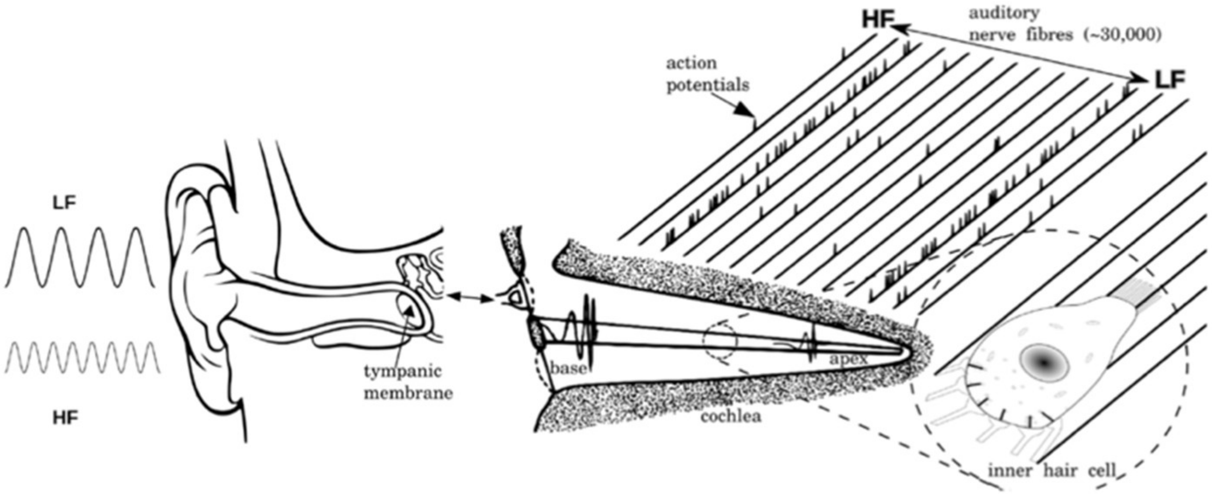


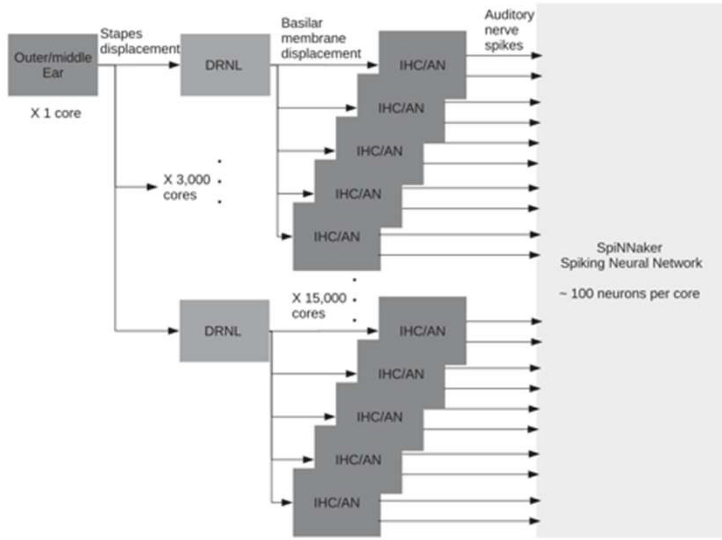
mf	mossy fibres
Glom	Glomerulus
GrC	Granule cell
GoC	Golgi cell
SC	Stellate cell
BC	Basket cell
PC	Purkinje cell
DCN	Deep Cerebellar Nucleus
aa	ascending axons
pf	parallel fibres

Bogdan, P., Marcinno, B., Casellato, C., Casali, S., Rowley, A., Hopkins, M., Leporato, F., D'Angelo, E. & Rhodes, O., *Towards a bio-inspired real-time neuromorphic cerebellum,* Frontiers in Cellular Neuroscience 15:622870 (2021).

Inner Hair Cell and Auditory Nerve model

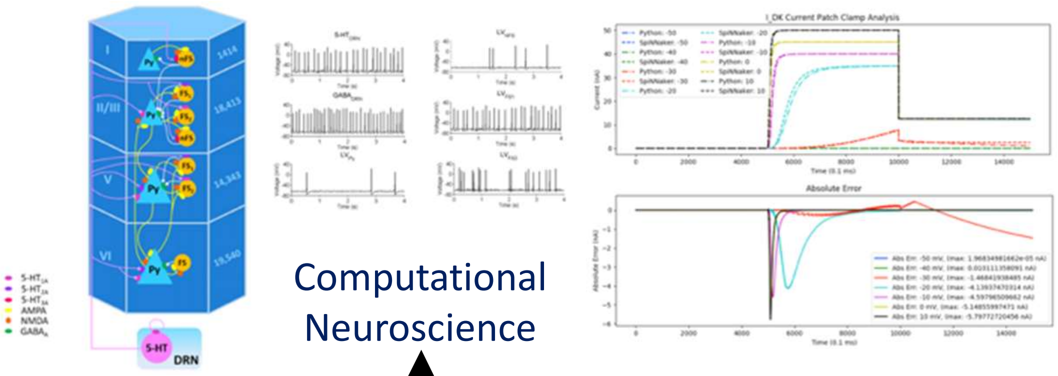
- Matlab Auditory Pathway (MAP) re-implemented on SpiNNaker
- 18,000 SpiNNaker cores
  - many running DSP code
  - lack of hardware floating-point on SpiNNaker1 hurts here!
- 1,500 SpiNNaker chips



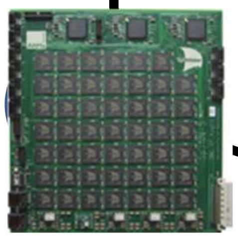


James, R., Garside, J., Plana, L., Rowley, A. & Furber, S., *Parallel Distribution of an Inner Hair Cell and Auditory Nerve Model for Real-Time Application,* IEEE Trans Biomedical Circuits & Systems 12(5) (2018).

SpiNNaker applications



Computational Neuroscience



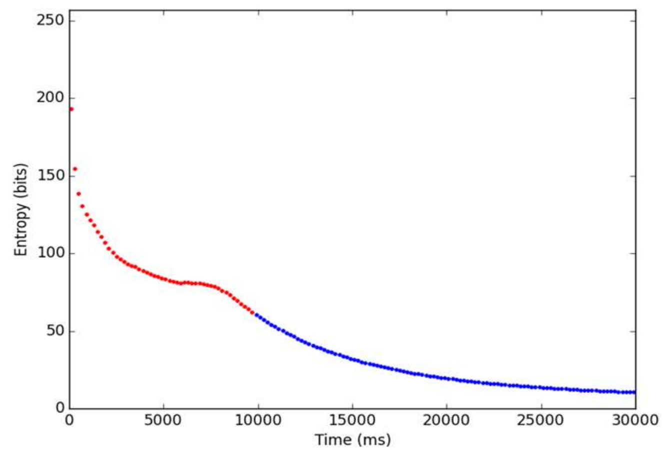
Theoretical Neuroscience

Constraint satisfaction problems

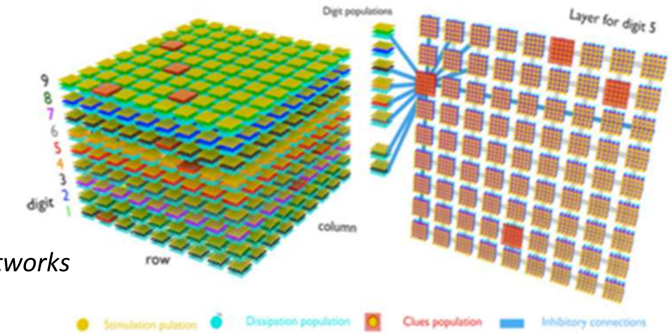
Stochastic spiking neural network:

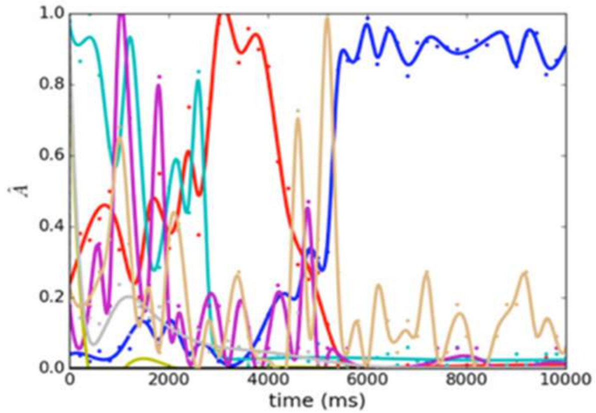
- Solves CSPs, e.g. Sudoku
  - 37k neurons
  - 86M synapses
- also
  - map colouring
  - Ising spin systems

4	6	1	9	5	8	6	7	3
3	8	5	6	7	7	4	9	1
7	8	9	3	3	1	6	8	5
6	9	6	8	1	3	5	5	7
5	3	8	7	9	2	1	4	6
1	2	4	7	6	5	8	3	9
3	5	3	1	8	6	9	9	4
8	1	6	4	4	9	3	6	2
9	4	2	5	3	6	7	1	8



work by: Gabriel Fonseca Guerra (PhD student)

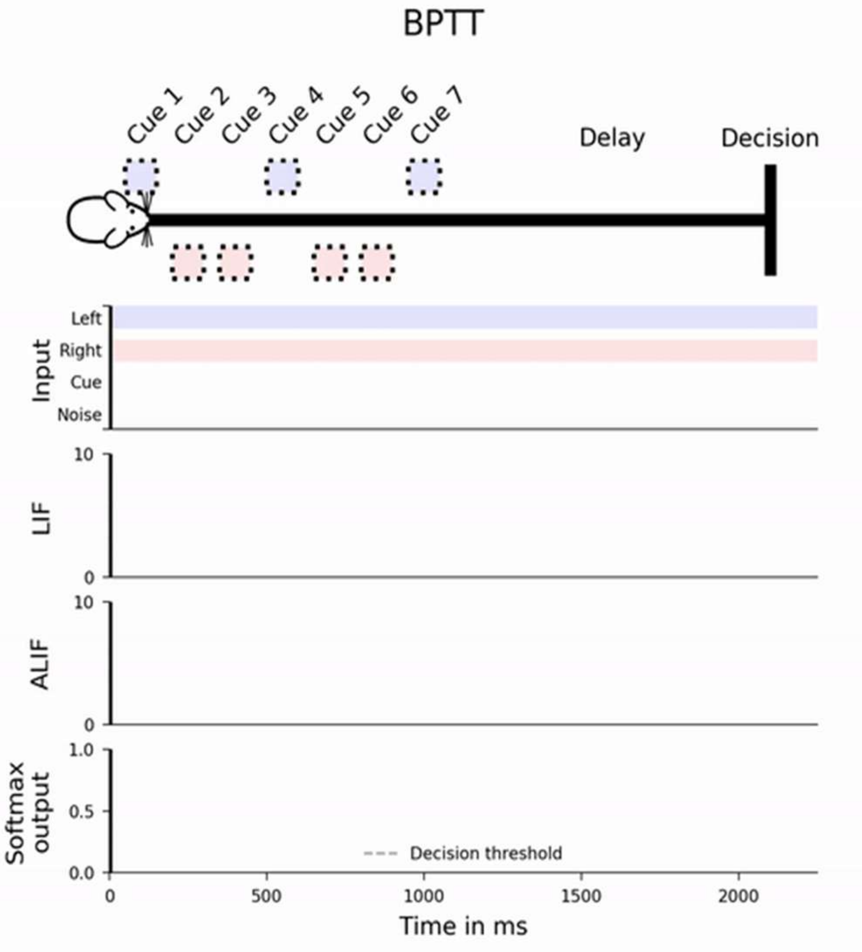




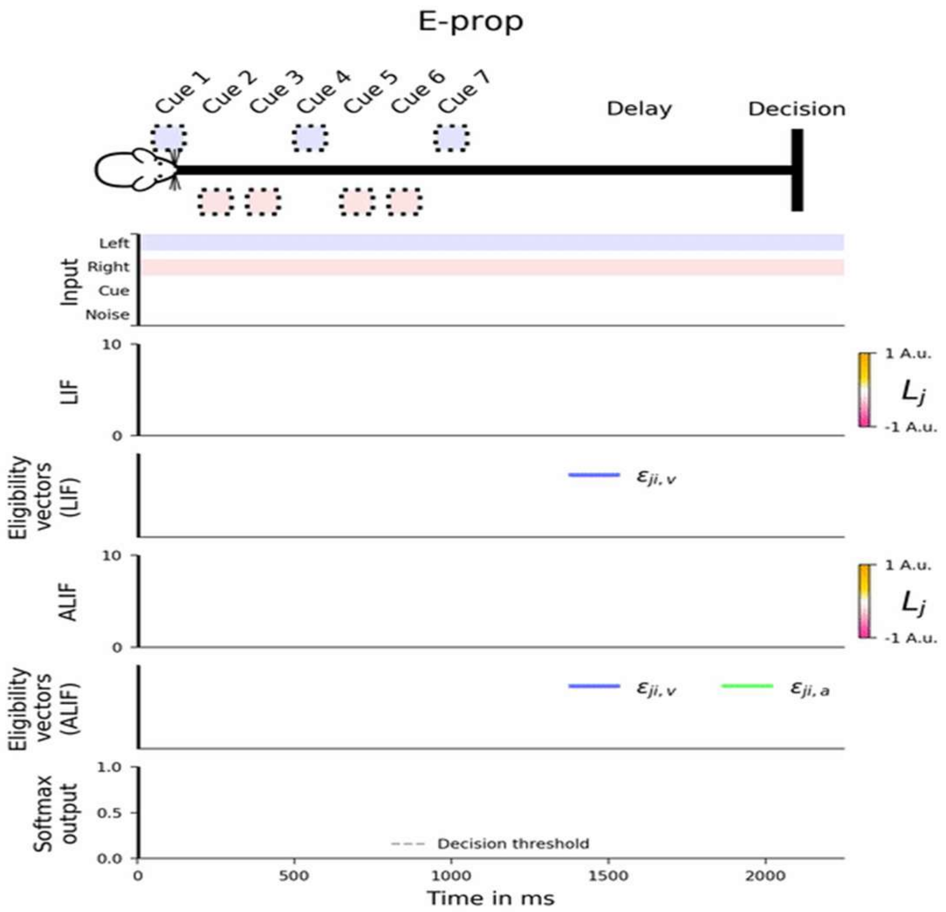
G. A. Fonseca Guerra and S. B. Furber, "*Using Stochastic Spiking Neural Networks on SpiNNaker to Solve Constraint Satisfaction Problems*", Frontiers 2018.

S. Habenschuss, Z. Jonke, and W. Maass, "*Stochastic computations in cortical microcircuit models*", PLOS Computational Biology, 9(11):e1003311, 2013.

e-prop on *SpiNNaker*

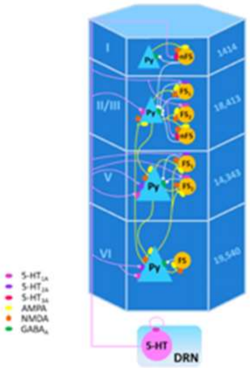


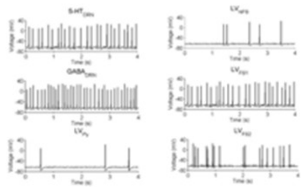
Bellec, G., Scherr, F., Subramoney, A., Hahek, E, Dalaj, D, Legenstein, R. & Maass, W., *A solution to the learning dilemma for recurrent networks of spiking neurons*, Nature Communications 11, 1 (2020).

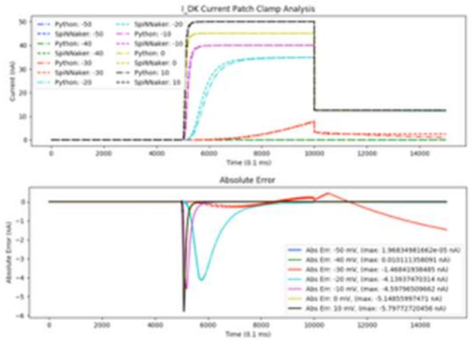


Perrett, A., Summerton, S., Gait, A. & Rhodes, O., *Online learning in SNNs with e-prop and neuromorphic hardware*, NICE 2022.

SpiNNaker applications



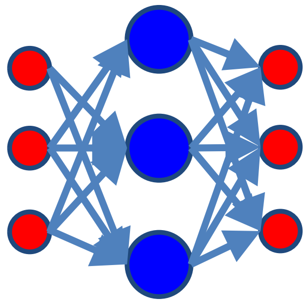


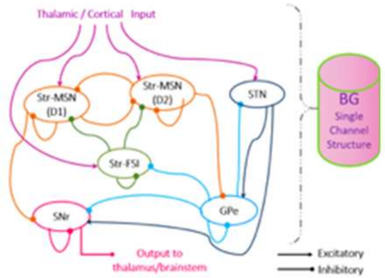


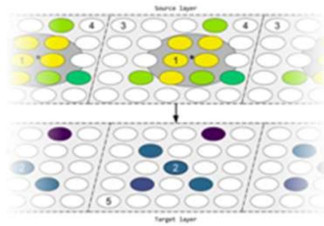
Computational
Neuroscience

Neurorobotics

Theoretical
Neuroscience

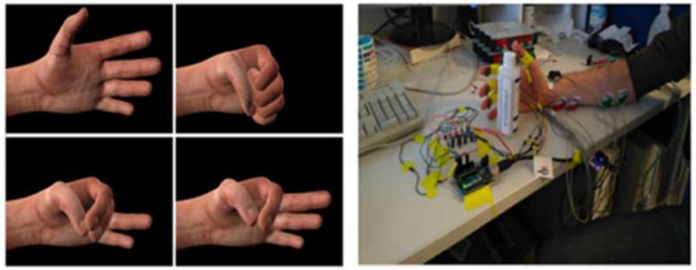


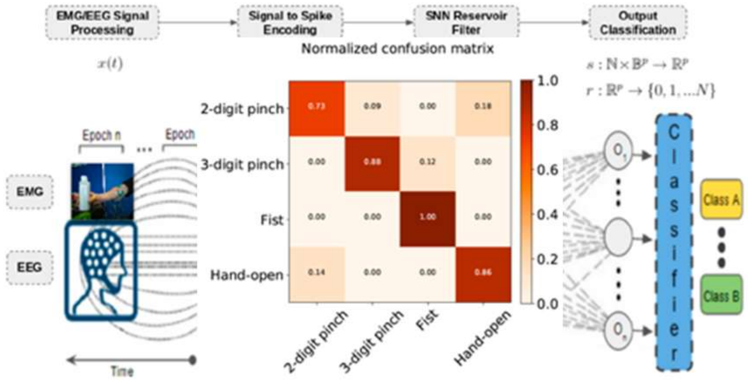


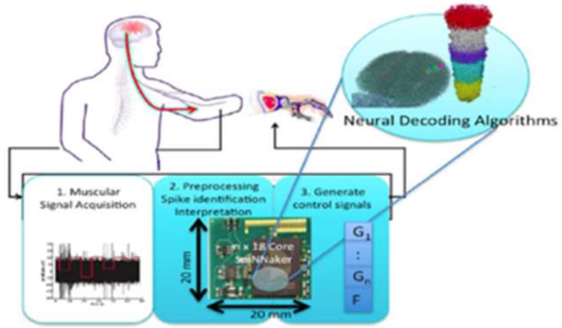


Prosthetic control

- Classification of electrical signals
  - real-time control of active prosthetics
  - low power
- Record electrical activity of participants during prescribed hand movements
- Classification with reservoir of spiking neurons
  - encode signals into spikes
  - train network (unsupervised)
  - readout to classify



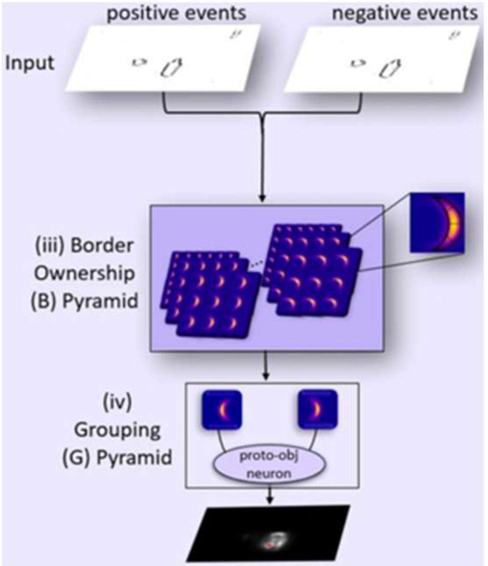




Behrenbeck, J. et al. *Classication and Regression of Spatio-Temporal Signals using NeuCube and its realization on SpiNNaker Neuromorphic Hardware.* Journal of Neural Engineering. 2018

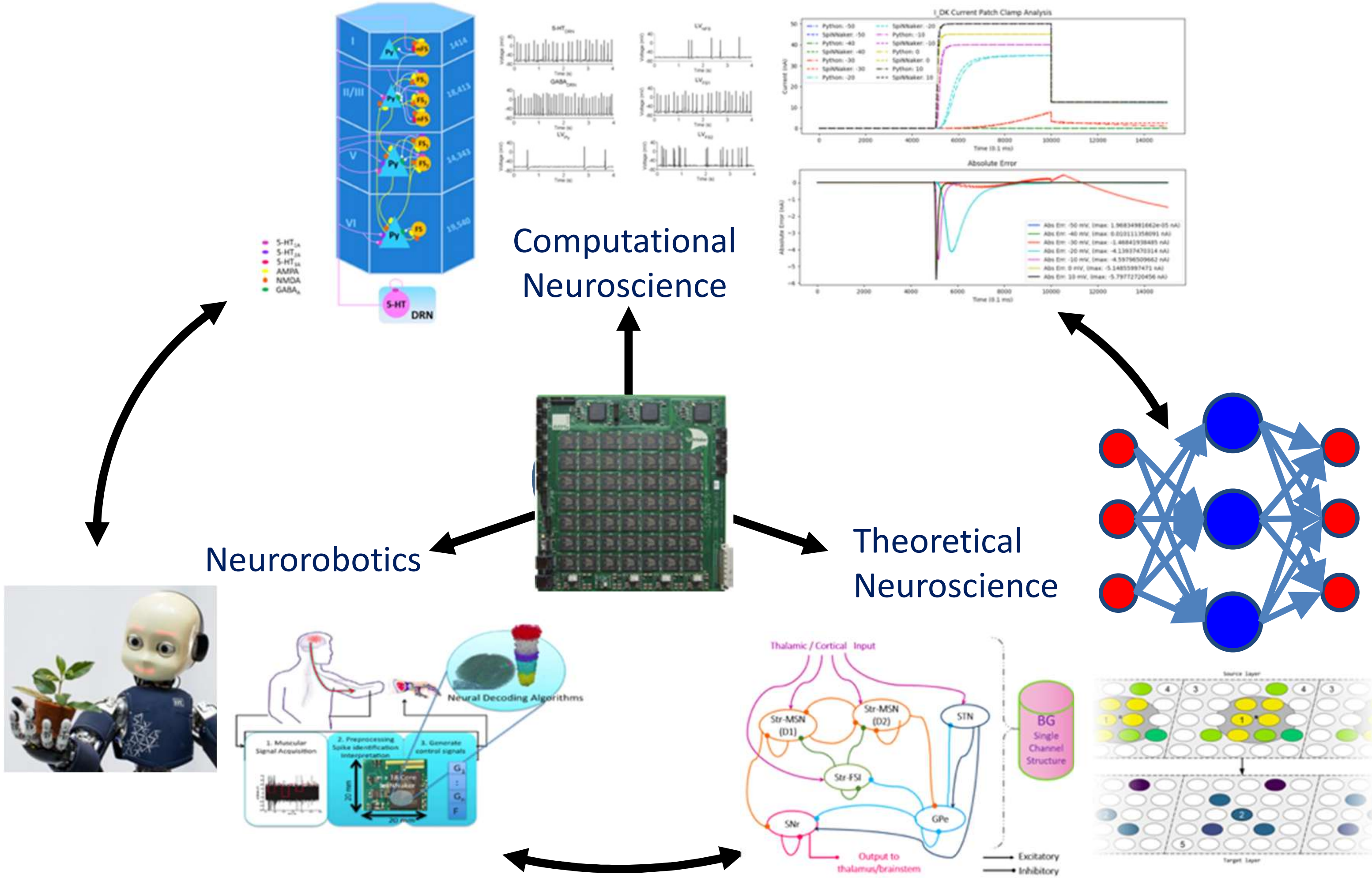
Robot vision

- Event-driven attentive system on iCub
  - SpiNNaker as neural substrate
- Event-driven vision sensors
- Produces saliency maps
- Average 16ms latency to produce a usable saliency map



D'Angelo, G., Perrett, A., Iacono, M., Furber, S & Bartolozzi, C, *Event driven bio-inspired attentive system for the iCub humanoid robot on SpiNNaker.* IOP Neuromorphic Computing and Engineering 2 (2022).

SpiNNaker applications



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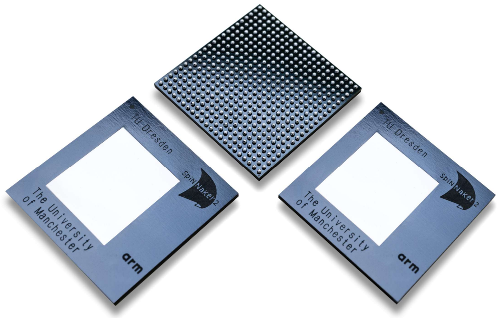
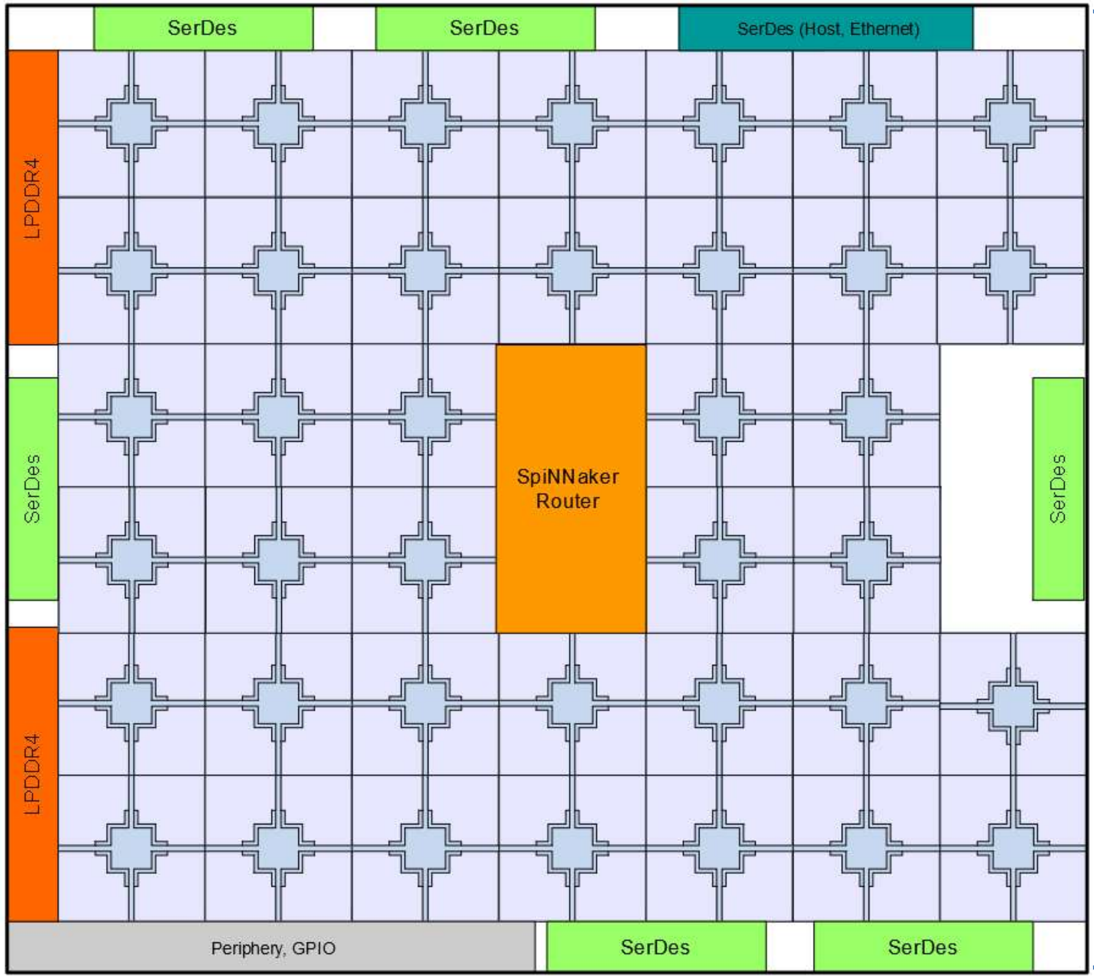
SpiNNaker2

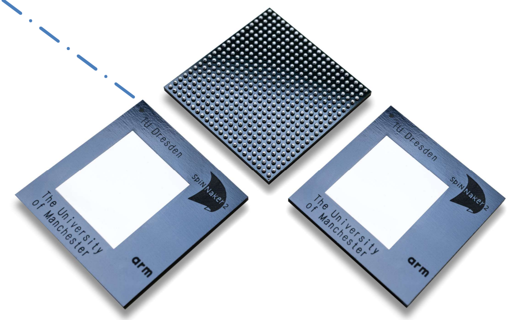
- 152 Arm-based processing elements in a low-power mesh
- High-speed infrastructure to connect chip-to-chip
- Light-weight and event-based Network-on-Chip
- Globally Asynchronous Locally Synchronous architecture
- Native accelerators for neuromorphic (Exp/Log/TRNG) and Machine Learning (Custom MACs)
- Adaptive Body Biasing (ABB) in 22FDX using reverse body bias
- Patented Dynamic Voltage Frequency Scaling at core-level



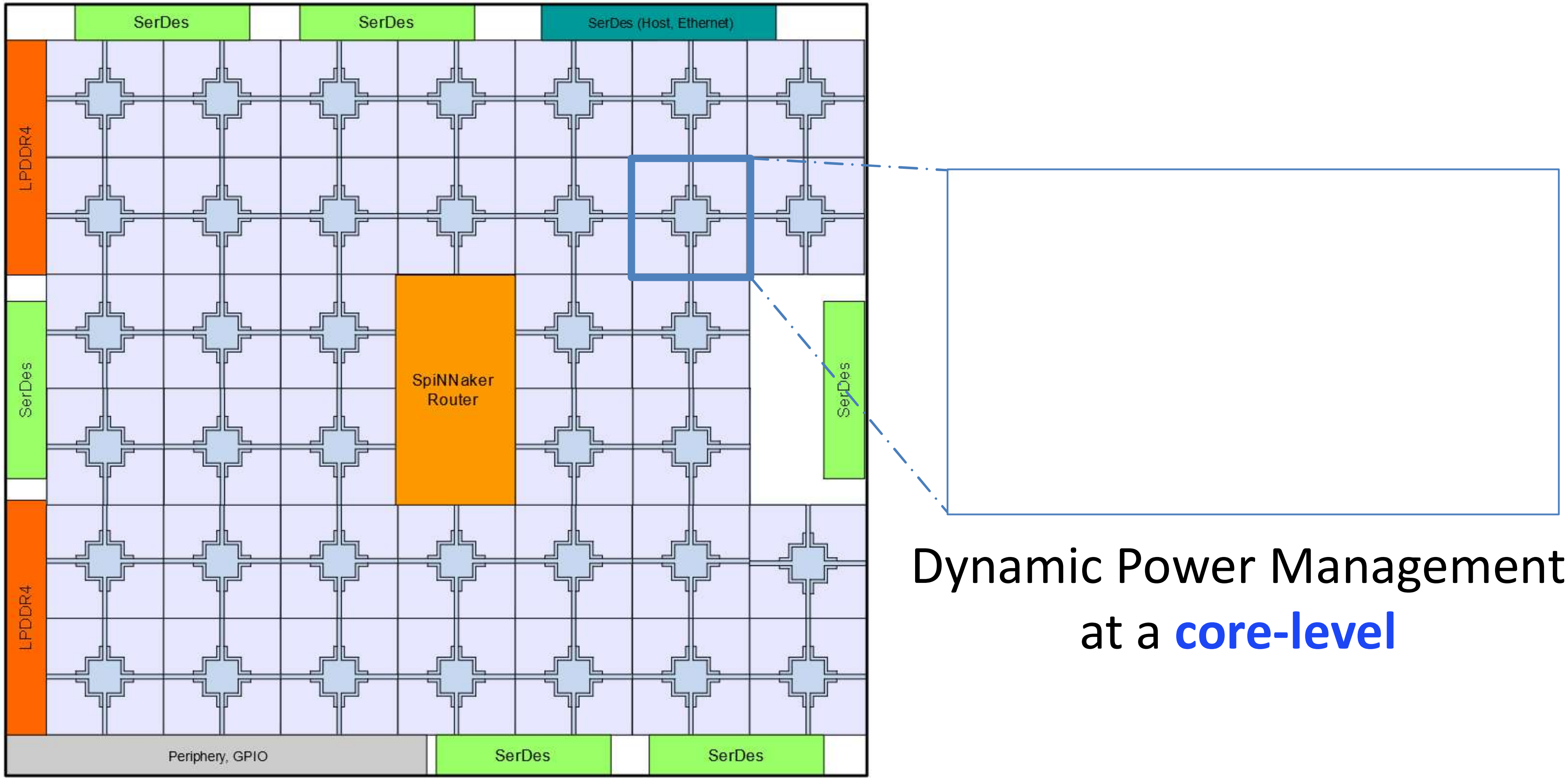
SpiNNaker2



SerDes
SerDes
SerDes (Host, Ethernet)
LPDDR4
SerDes
SpiNNaker Router
SerDes
LPDDR4
Periphery, GPIO
SerDes
SerDes



SpiNNaker2



Dynamic Power Management at a **core-level**

SpiNNaker2 Processing Element

Dynamic Power Management for enhanced energy efficiency

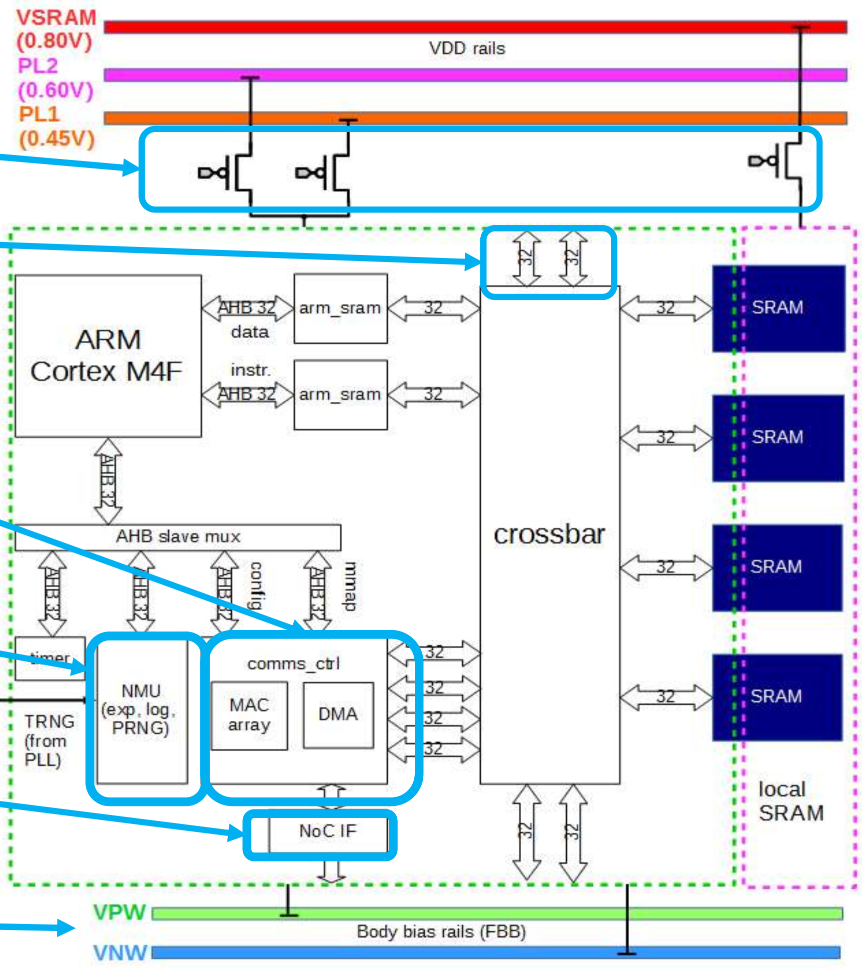
Memory sharing for flexible code, state and weight storage

Multiply-Accumulate accelerator for machine learning

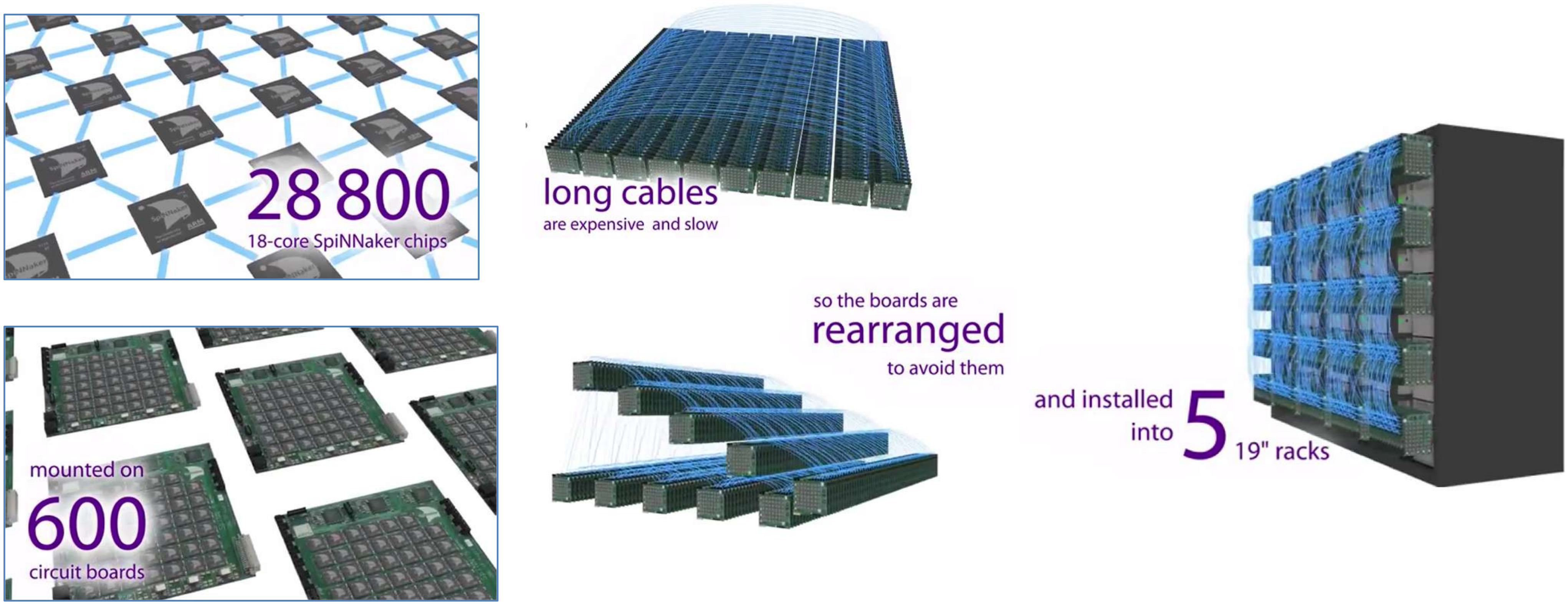
Neuromorphic accelerators and random generators for synapse and neuron computation

Network-on-Chip for efficient spike communication

Adaptive Body Biasing for energy efficient low voltage operation

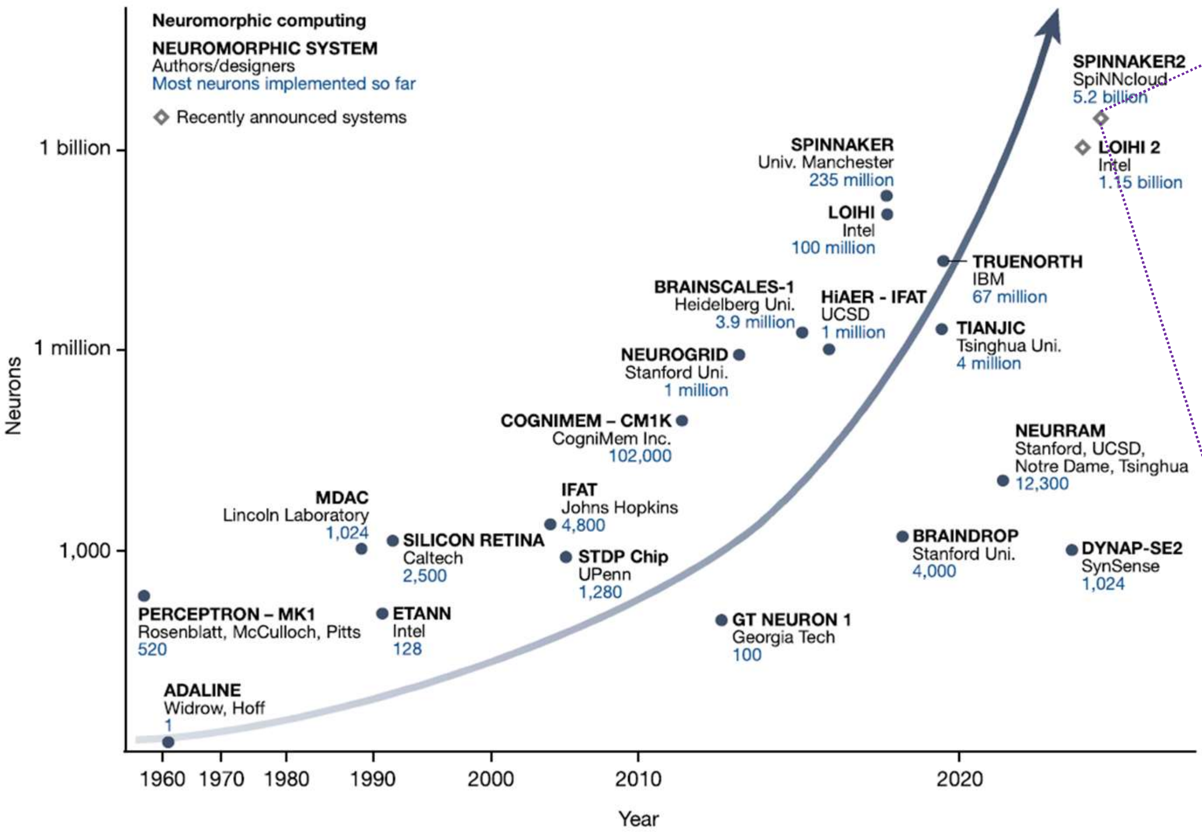


SpiNNaker concept



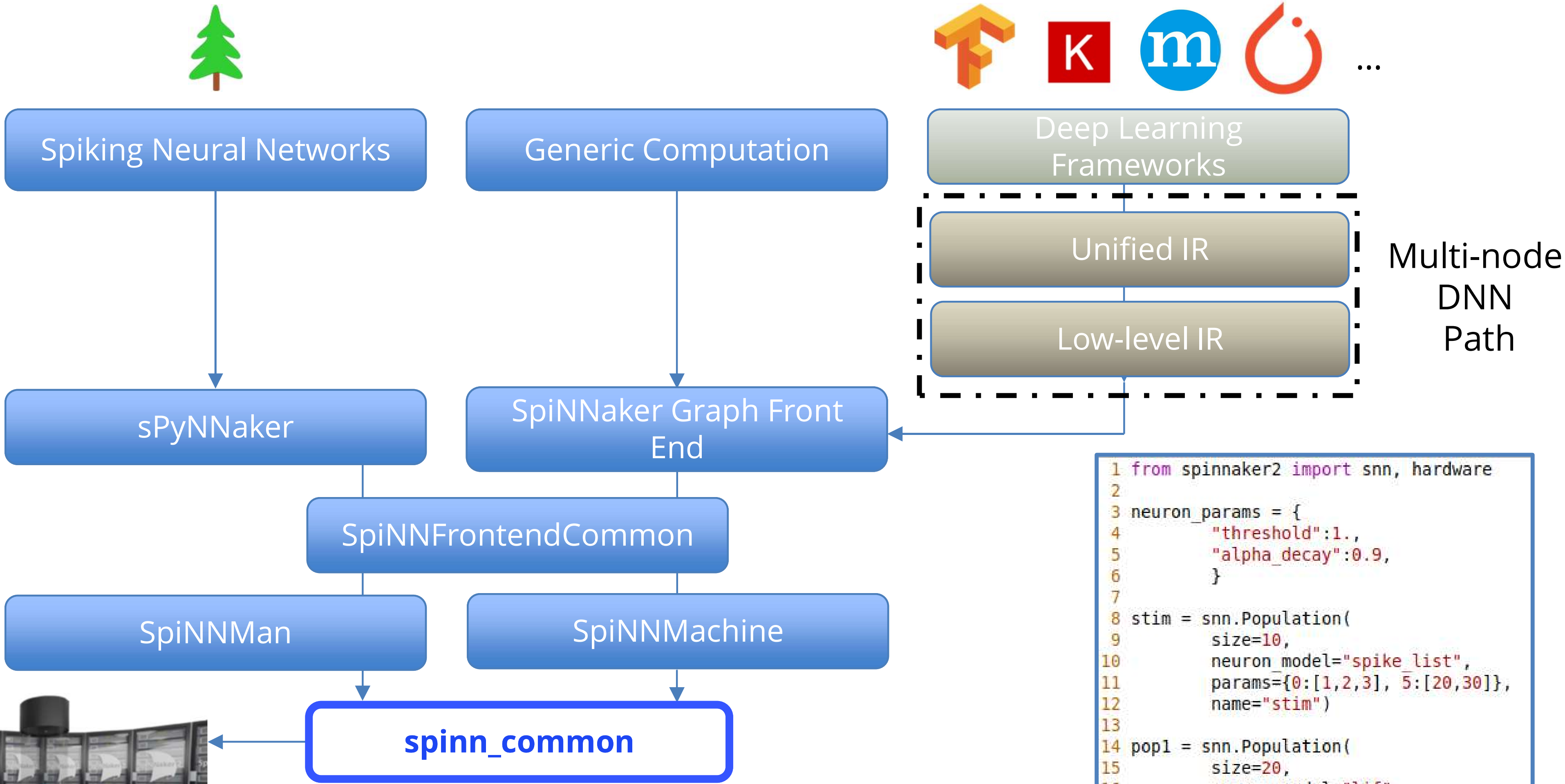
Source: [University of Manchester at HBP Education]()

Large-scale neuromorphic systems



Source: https://www.nature.com/articles/s41586-024-08253-8

High-level software flow



```python
from spinnaker2 import snn, hardware

neuron_params = {
        "threshold":1.,
        "alpha_decay":0.9,
        }

stim = snn.Population(
        size=10,
        neuron_model="spike_list",
        params={0:[1,2,3], 5:[20,30]},
        name="stim")

pop1 = snn.Population(
        size=20,
        neuron_model="lif",
        params=neuron_params,
        name="pop1")
```

Outline

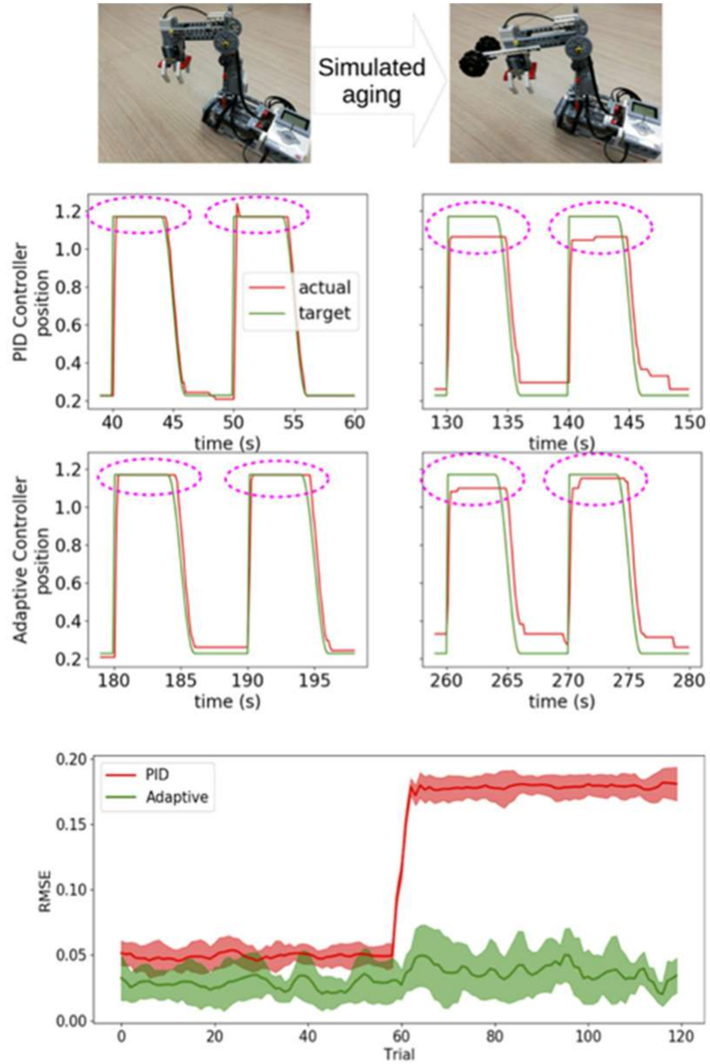
- Neuromorphic computing
- The SpiNNaker project
- SpiNNaker applications
- SpiNNaker2
- SpiNNaker2 applications
- Project leadership
- Conclusions

Comparing Loihi with SpiNNaker2

Table 1. Comparison of the SpiNNaker 2 prototype (SpiNN) and Loihi for the keyword spotting task.

Hardware	Inference/s	Energy/inference (μJ)
SpiNN	1000	7.1
Loihi	296	37

- Two applications compared:
  - Low-latency keyword spotting
  - Simulated aging of a robot arm
- Loihi shows better efficiency for less complicated vector-matrix multiplication
- SpiNNaker2 (prototype) shows better efficiency for high-dimensional vector-matrix multiplication



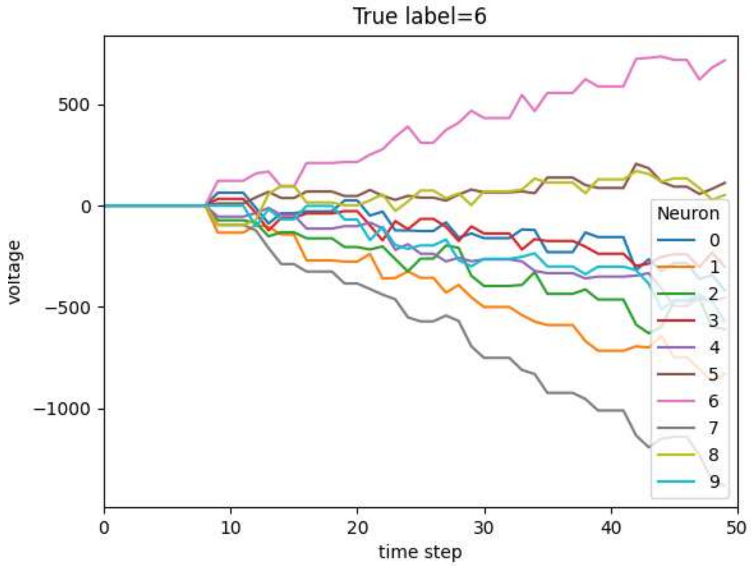
Yan, Y., Stewart, T., Choo, X., Vogginger, B., Partzsch, J., Hoppner, S., Kelber, F., Eliasmith, C., Furber, S. & Mayr, C., *Comparing Loihi with a SpiNNaker2 prototype on low-latency keyword spotting and adaptive robot control.* IOP Neuromorphic Computing and Engineering 1 (2021) 014002.

Hybrid Examples

Neural Apps on ARM core

conv2d_if_neuron_rate

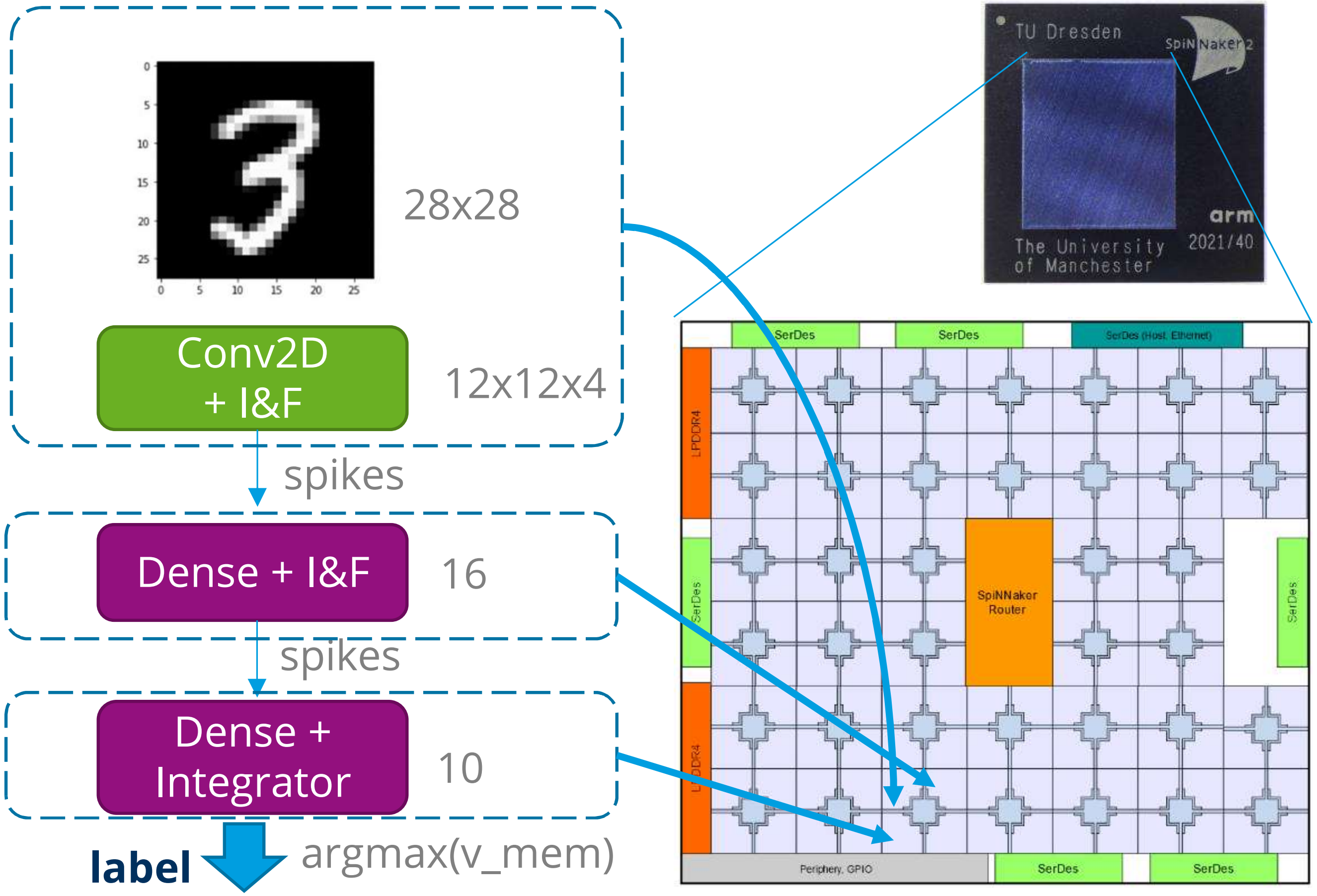
lif_neuron



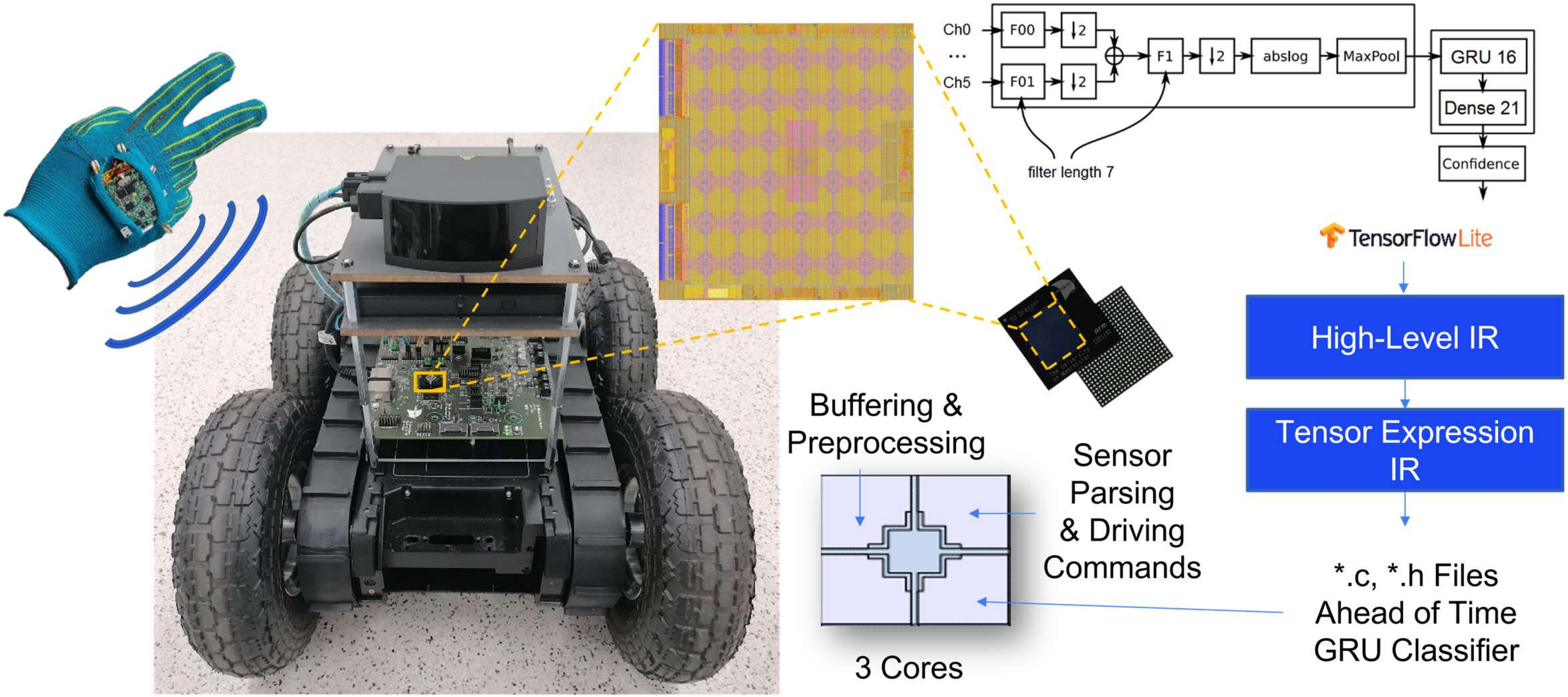
Accuracy of 97.5 % identical to DNN in Tensorflow

Hybrid Network

Automatic Mapping



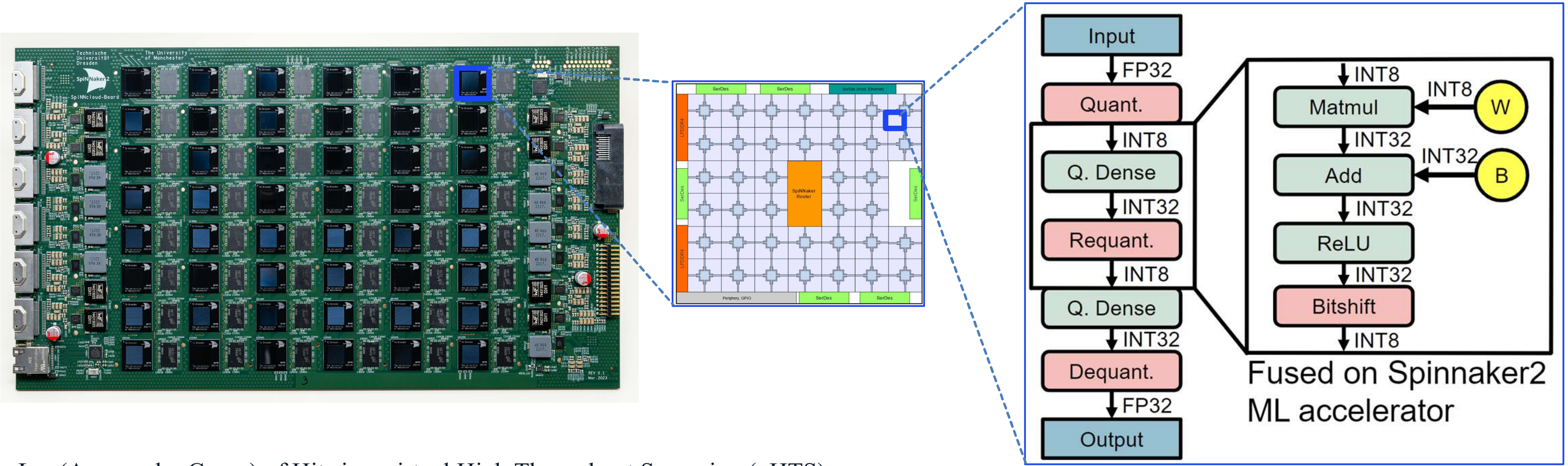
Edge Applications



SpiNNaker2

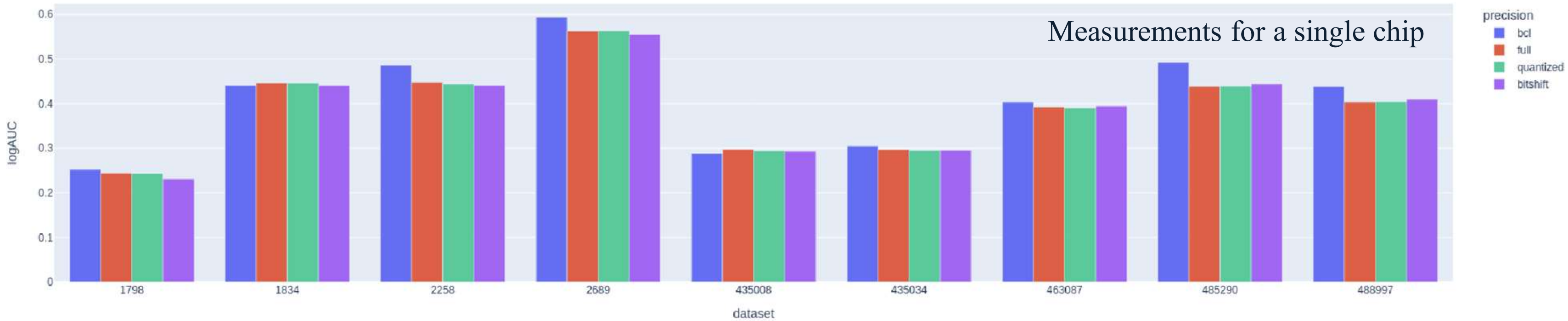
Universal Spiking Neural Network Architecture

Drug discovery



Log(Area under Curve) of Hits in a virtual High Throughput Screening (vHTS)

A Hit is a molecule/ligand with a positive reaction with the target molecule provided as input



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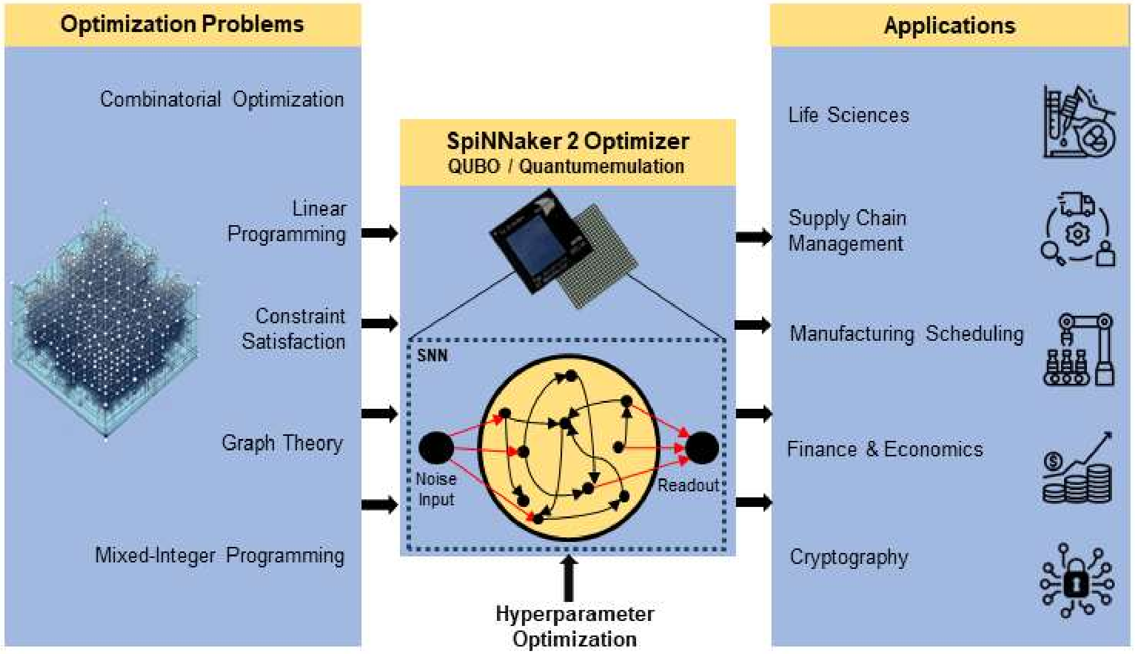
QUBO*

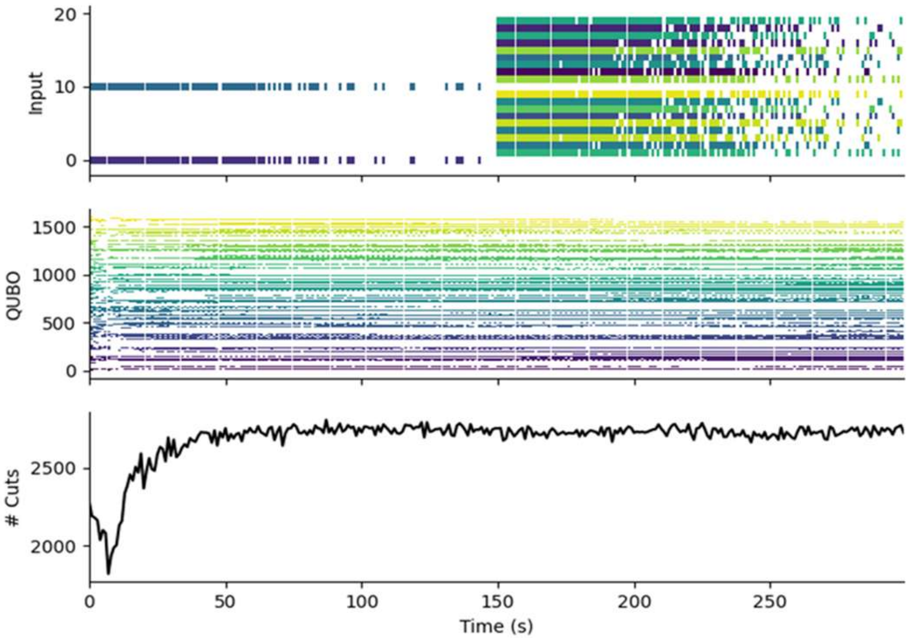
- Finds optimal solutions on small problems
  - currently fine-tuning neuronal dynamics and benchmarking on more complex problems
- Can reach sub-optimal solutions in a few milliseconds
  - This quickly-acquired sub-optimal solution can be used by other algorithms to reach an optimal solution
  - hybrid approach



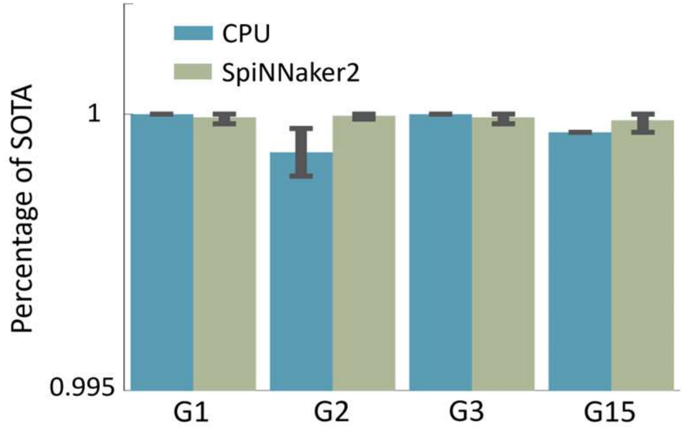
*Quadratic Unconstrained Binary Optimization

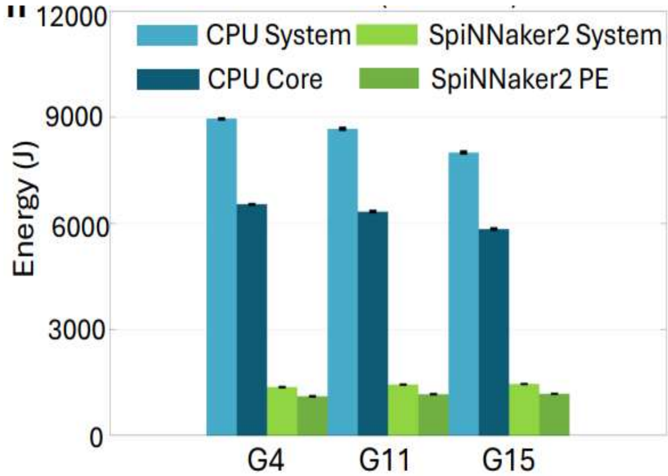
QUBO

SNN-based QUBO solvers on SpiNNaker2 achieve state-of-the-art performance at a fraction of the energy cost.



Maxcut **800-node graph** SpiNNaker solution

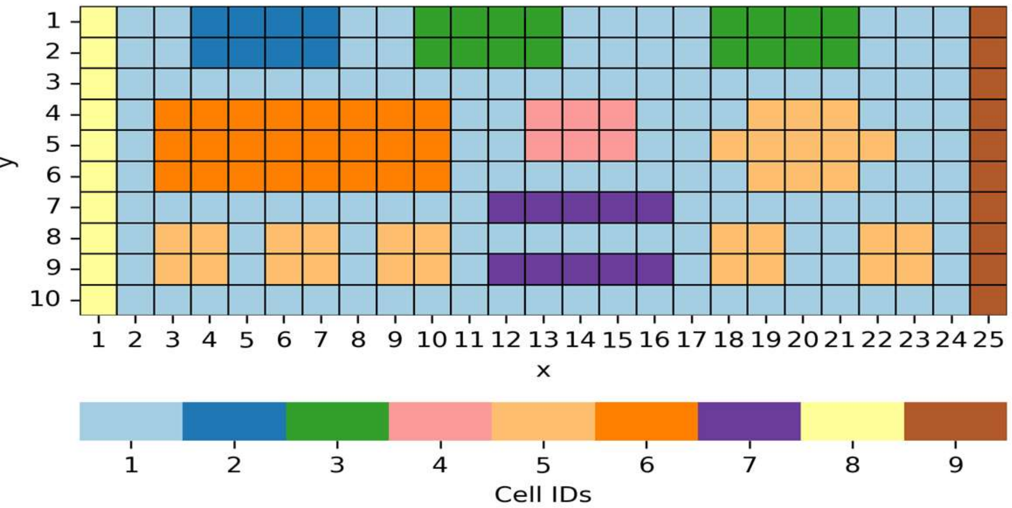


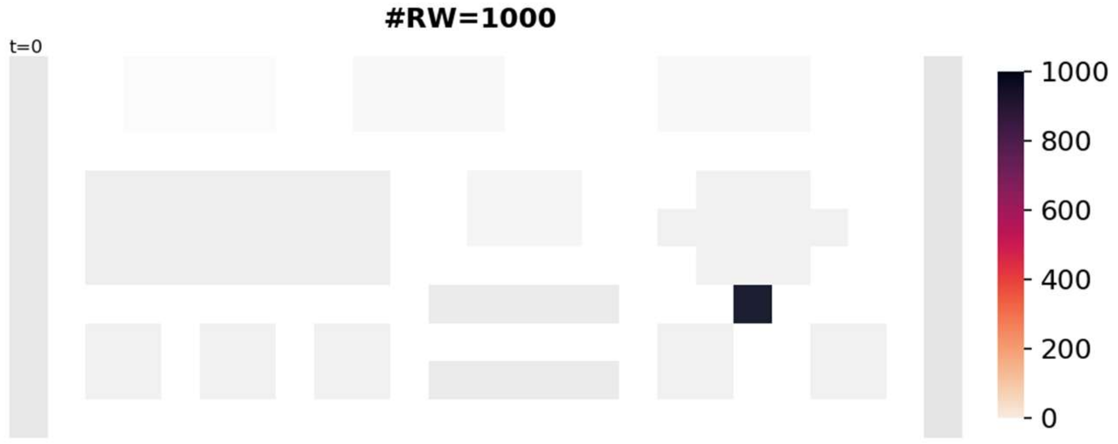


Chen, Z., Xiao, Z., Akl, M. *et al.* ON-OFF neuromorphic ISING machines using Fowler-Nordheim annealers. *Nat Commun* **16**, 3086 (2025). https://doi.org/10.1038/s41467-025-58231-5

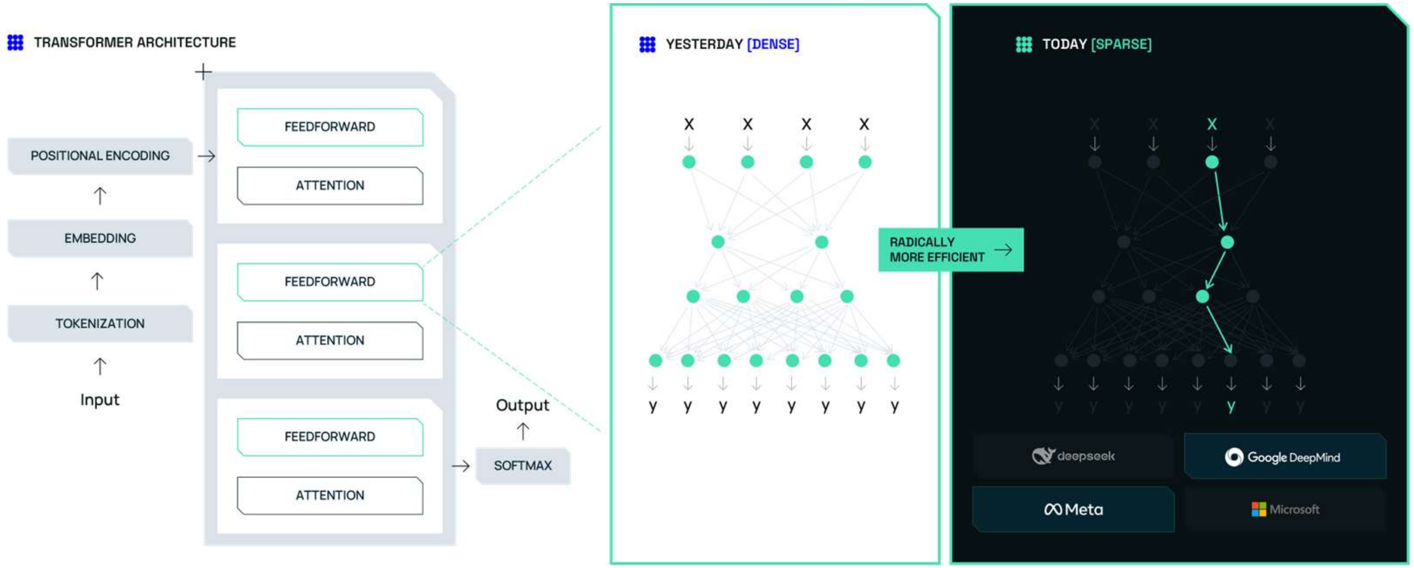
Random Walkers

Neural Random Walkers on SpiNNaker 2 simulate the stochastic process for solving heat flow across a circuit board with a cooling fan flow





Mainstream AI trends



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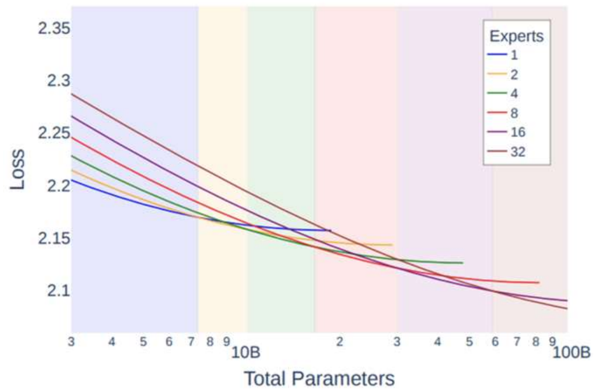

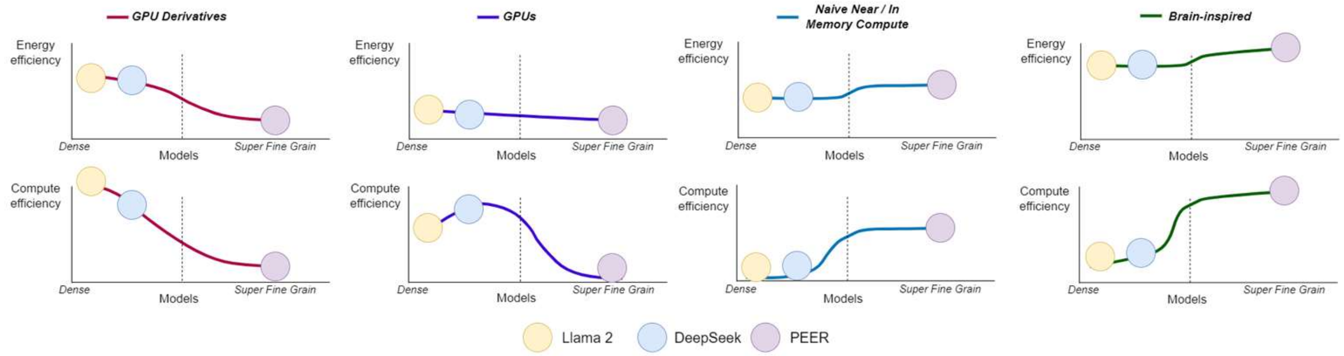

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Project leadership

- Running a large, multi-disciplinary research team
  - heterogeneous team:
    - academic staff, Research Fellows, post docs, PhD students, MSc projects, undergraduate projects
  - for a major academic engineering project:
    - core engineering work will be done by RFs & post-docs
    - academics advise and support
    - PhD students explore and add value around the core work
    - MSc & UG projects focus on (non-critical) specific details
    - there will be exceptions!
      - e.g. some core work done by academics

Project leadership

- Understand each team member's priorities:
    - academics: need to publish for career advancement
    - RFs: some want to publish, some just want interesting work
    - post-docs: generally want to publish for future prospects
    - PhD students: should be encouraged to publish!
    - MSc & UG students: need to generate a project report on time
    - all can have external (e.g. family) responsibilities that at times distract them from project work
- so project requirements must be balanced against other pressures

Project leadership

- Who does what?
  - an experienced team will self-organise with a little guidance
    - they all know each others' skills and strengths
  - meet, discuss problems, agree on who will look at each problem
- Design reviews
  - designer presents his/her design to their peers
  - peers offer criticism and suggestions for improvement
  - works brilliantly when done in the right spirit!

Project leadership

- Problems…
  - recruiting the right people
    - experienced chip designers are hard to find!
  - internal conflict
    - may arise from time to time
    - if serious, one of the parties will have to leave
    - this can be tricky in academia!
  - budget management
    - e.g. SpiNNaker chip tape-out
      - test first on MPW (multi-project wafer) for ~€100k?
      - go straight for production mask set for ~€250k?

ARM design team advantages

(according to Acorn founder, Hermann Hauser)

– No people
  - small team meant simplicity in design was an absolute requirement
– No money
  - everything was done in-house using simple, familiar home-grown tools
    – apart from VLSI design tools

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Conclusions

- **Industrial AI:**
  - is based on dense matrix operations:
    - computes everything all the time
    - "deathly embrace" of algorithms and GPU hardware

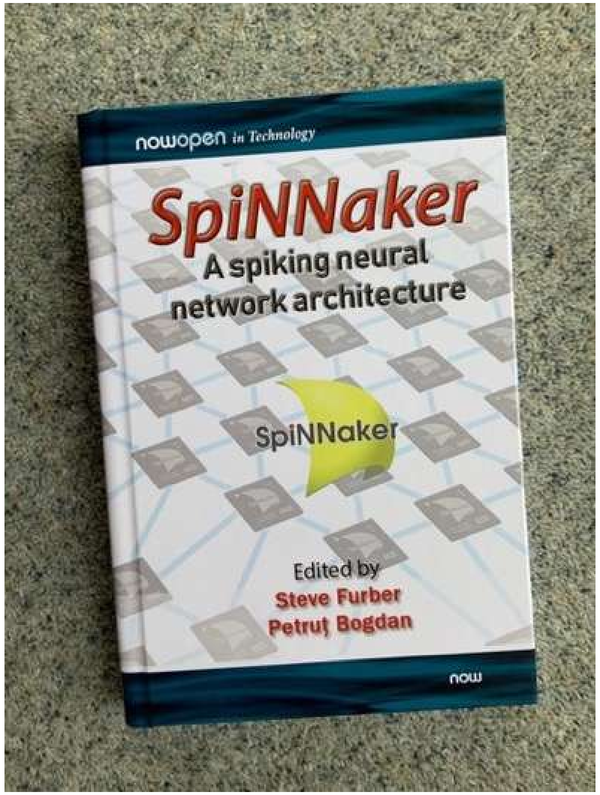
- ***SpiNNaker and SpiNNaker2:***
  - designed on brain-like principles:
    - support spatial & temporal sparsity
    - event-based software model

- Neuromorphics and AI are converging
  - brain-like principles will help address the unsustainable energy demands of AI

SpiNNaker book

- Open Access in PDF form (i.e. free!)
  - $90 on paper

20 years in conception and 15 in construction, the SpiNNaker project has delivered the world's largest neuromorphic computing platform incorporating over a million ARM mobile phone processors and capable of modelling spiking neural networks of the scale of a mouse brain in biological real time…



http://dx.doi.org/10.1561/9781680836523