Simulating the Brain without a Computer

Achievements and Challenges of Brain Inspired Computing

Simon Friedmann

Kirchhoff-Institute for Physics
Heidelberg University

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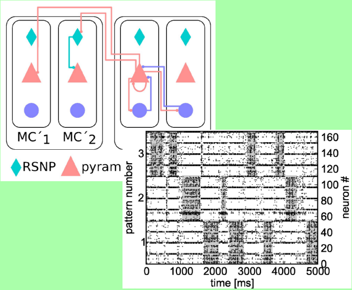
BrainScaleS

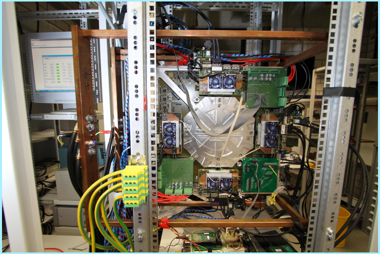
"Simulating the Brain"

Neuroscience



"Brain Inspired Computing"

Technology

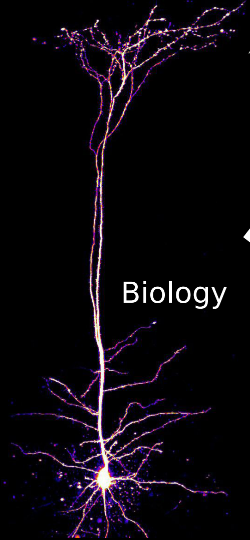


Computing with a Physical Model

$$C\,\frac{dV}{dt} = -g_L\,(V - E_L) + g_L\Delta_T\exp\left(\frac{V - V_T}{\Delta_T}\right) - w - I$$

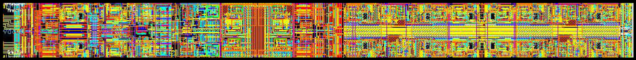
$$\tau_w\,\frac{dw}{dt} = a\,(V - E_L) - w$$

Mathematical model



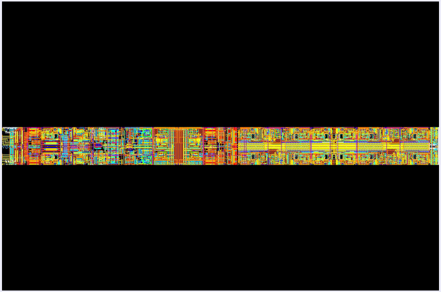
Biology

Hardware model



Physical model vs. software simulation

Physical model



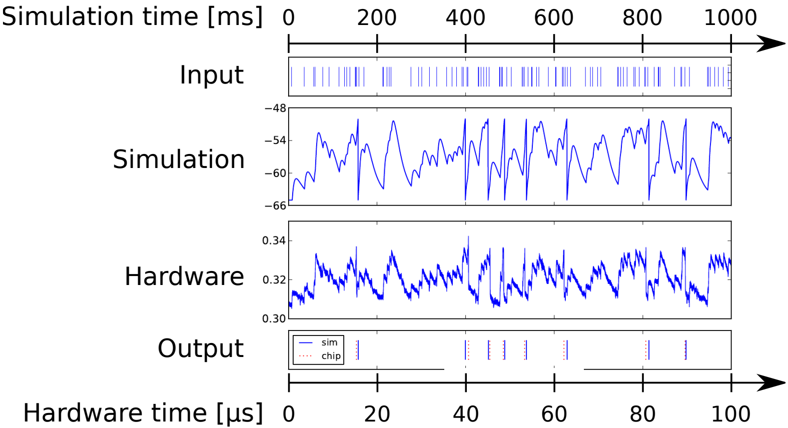
- Inherent dynamics perform computation
- Configurable dynamics

Classical computer

(Argonne National Laboratory, 2007)

- Numerically solve differential equations
- Programmable dynamics

Hardware model uses different scales



	Hardware	Biology
Voltage:	1 V	10 mV
Conductance:	100-1000 nS	10 nS
Capacitance:	1 pF	100 pF

→ Different time constants: Hardware is faster than biology

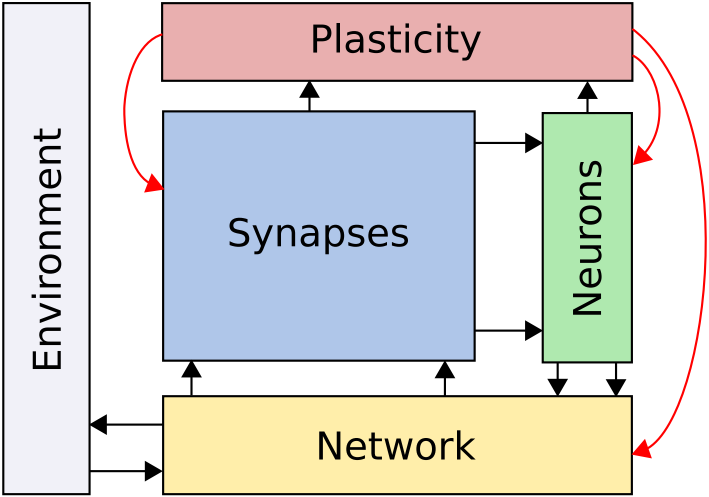
Accelerated time enables long-term learning studies

Time scales

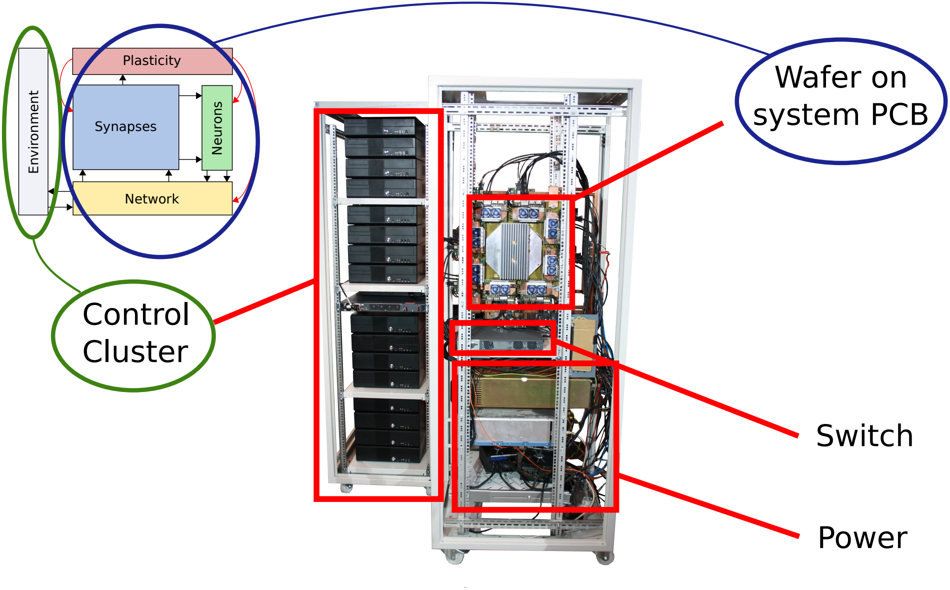
	Biological time	Hardware time ($\times 10^4$)
Plasticity	1 ms	0.1 μs
Learning Trial	1 min	1 ms
Training	1 h	100 ms
Development	1 month	1 min

- Large-scale software simulations typically slower than biological time

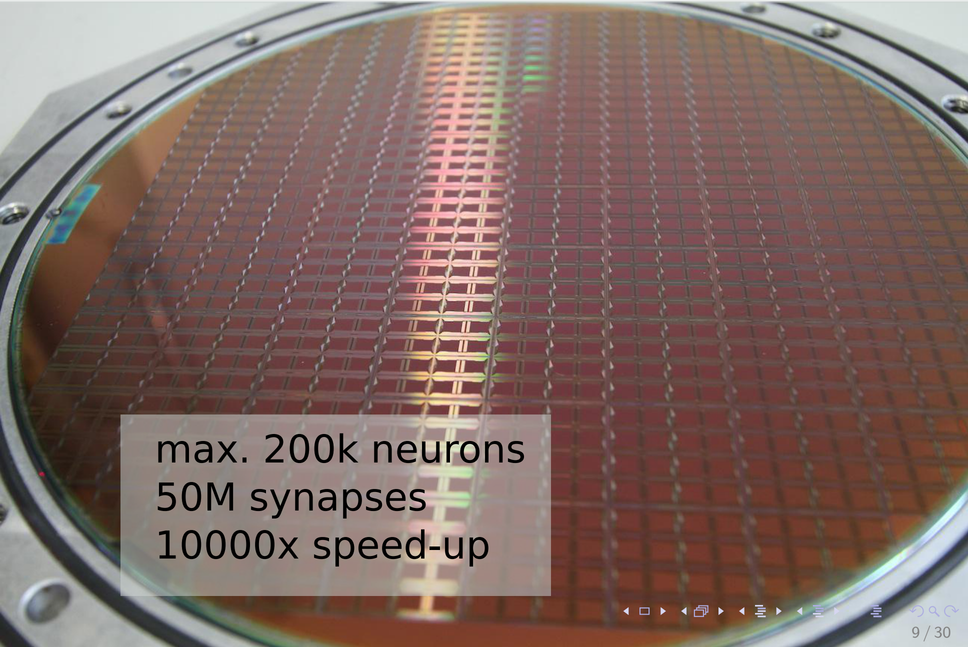
Structure of a hardware system



The BrainScaleS wafer-scale system

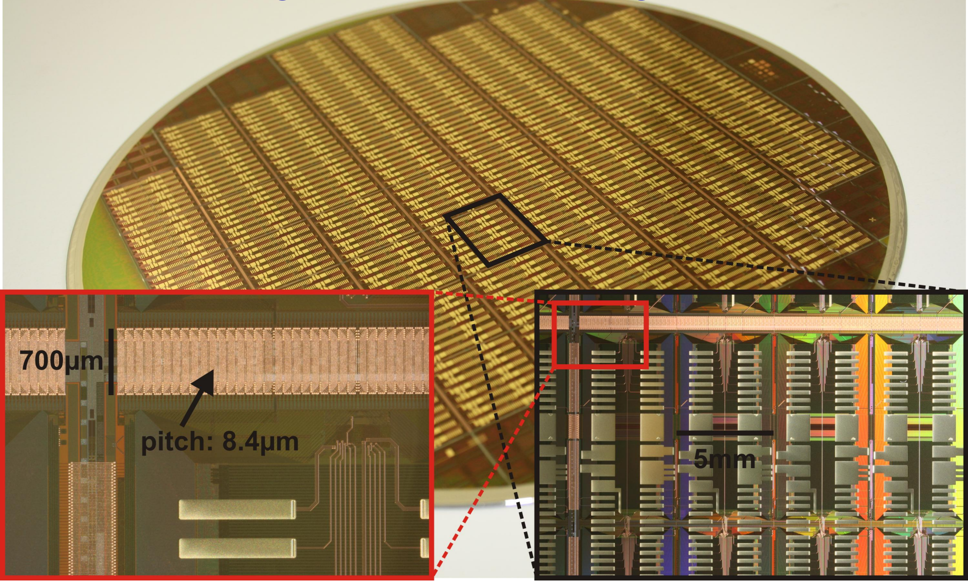


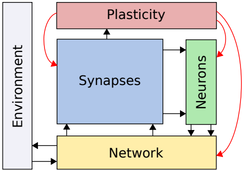
Wafer-scale integration

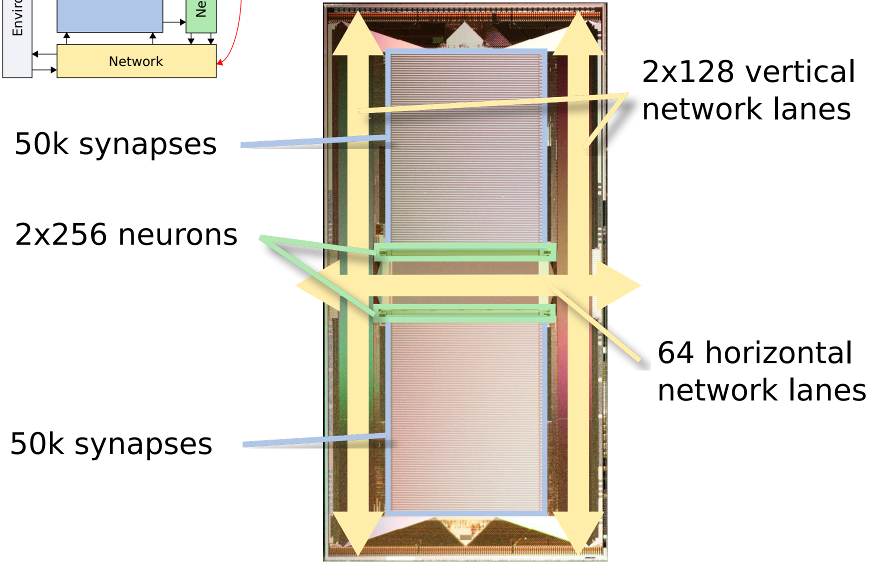


max. 200k neurons
50M synapses
10000x speed-up

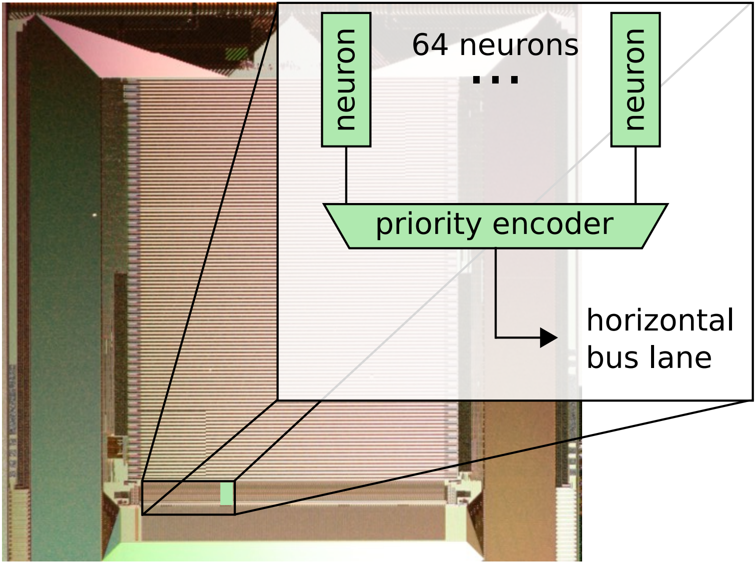
Wafer-scale integration: Post-processing



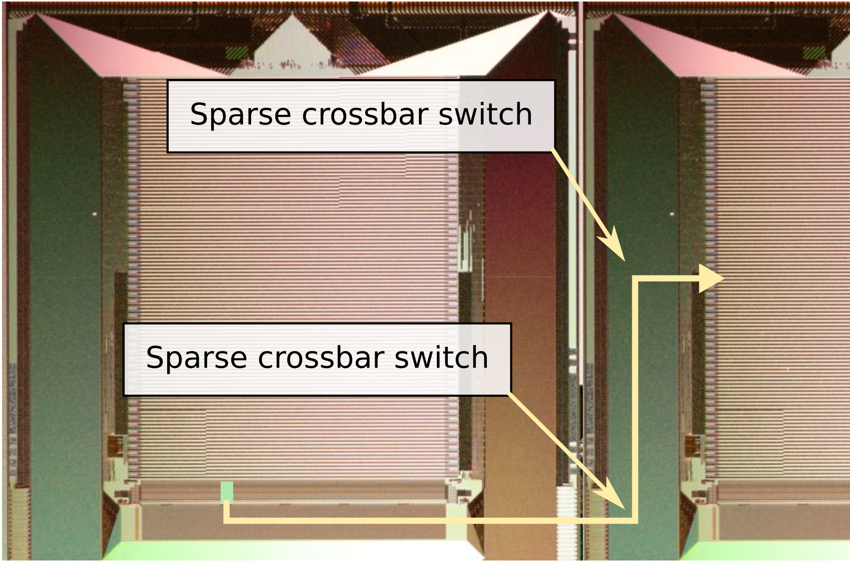

Plasticity
Environment
Synapses
Neurons
Network


2x128 vertical network lanes
50k synapses
2x256 neurons
64 horizontal network lanes
50k synapses

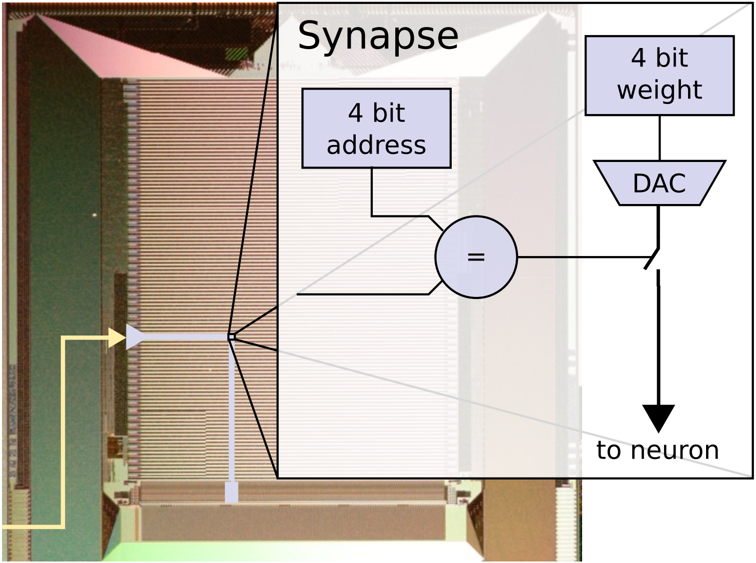
Event processing: Neuron output



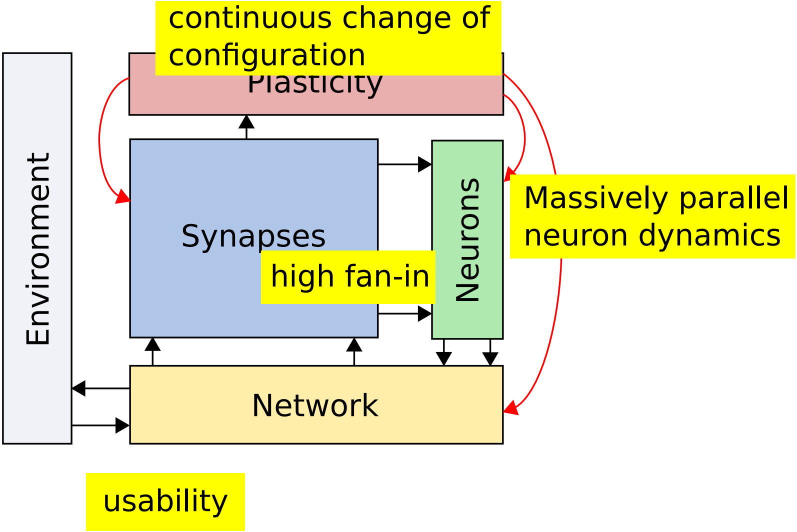
Event processing: Network



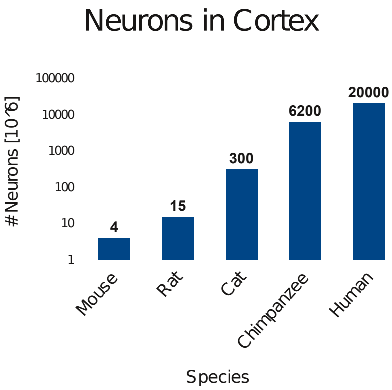
Event processing: Synapses



Challenges for hardware implementation



Challenge: Massively parallel neuron dynamics



Challenge

- About $20 \cdot 10^9$ neurons in cortex
- Neurons show complex dynamics
- Need area & power efficient solution

Approach

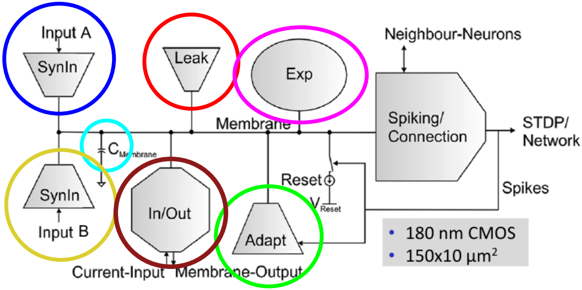
- Neurons as physical model
- Analog computing

BrainScaleS neurons

$$-C_m \frac{dV}{dt} = g_l\left(V - E_l\right) - g_l \Delta_t e^{\left(\frac{V-V_t}{\Delta_t}\right)} + w + I + g_e(t)\left(V - E_e\right) + g_i(t)\left(V - E_i\right)$$

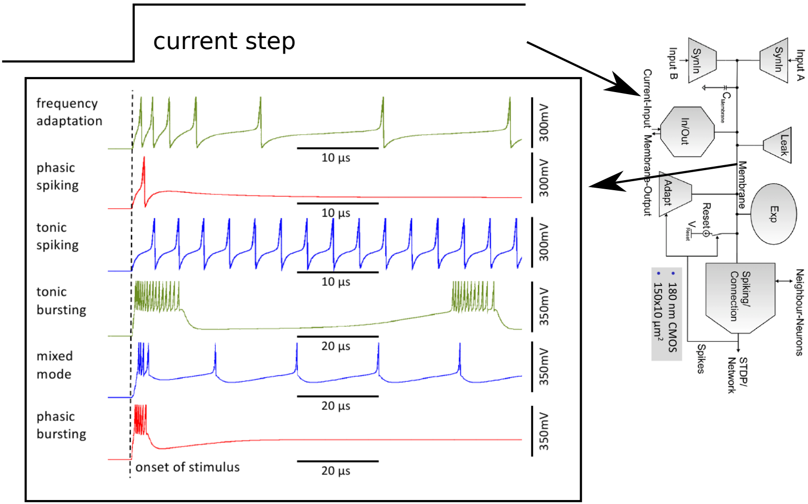
$$-\tau_w \frac{dw}{dt} = w - a\left(V - E_l\right)$$

Adaptive Exponential Integrate & Fire neuron model
(Brette & Gerstner, 2005)



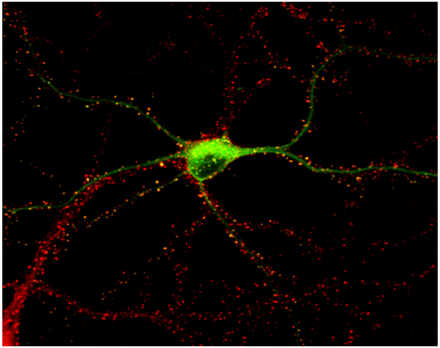
Hardware model
(Millner, 2012)

BrainScaleS neurons



- Configurable: Different firing modes
- Reproduce behavior from biology

Challenge: High synaptic input count



(Paul De Koninck, 2004)

Challenge

- 10^4 - 10^5 synapses per neuron in neocortex
- Much more synapses than neurons

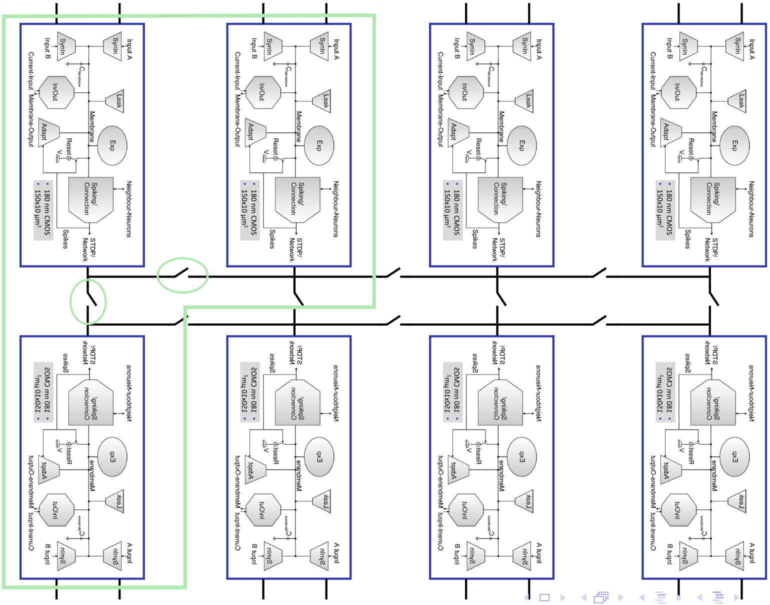
Approach

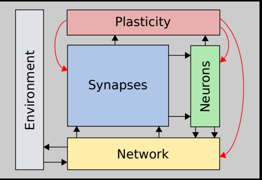
- Simple synapses
- Combinable neurons

BrainScaleS neurons

Building blocks

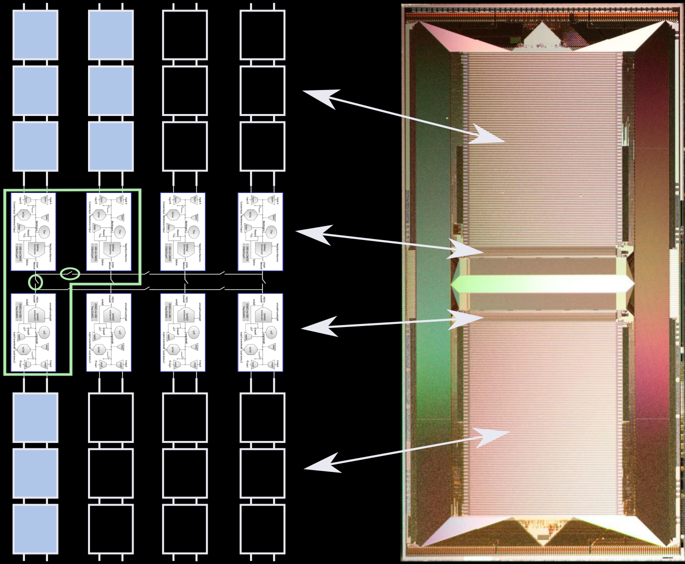
Combined neuron



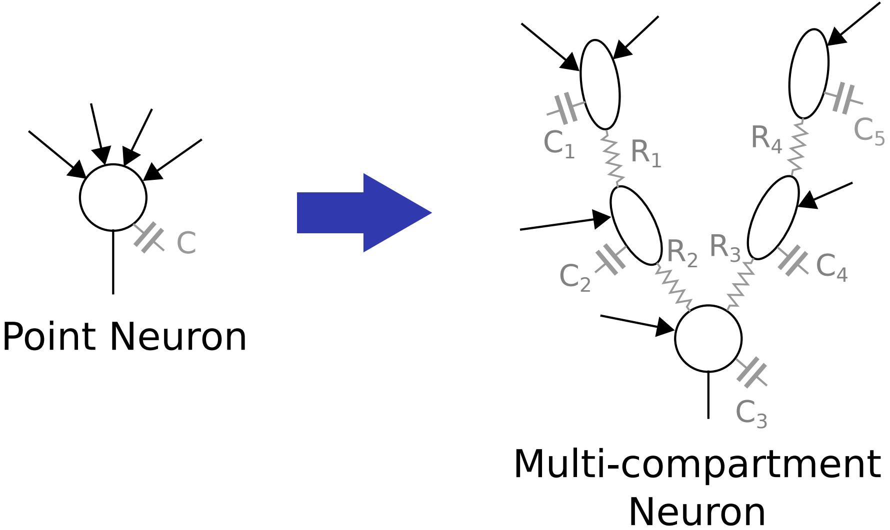


224 synapses per column

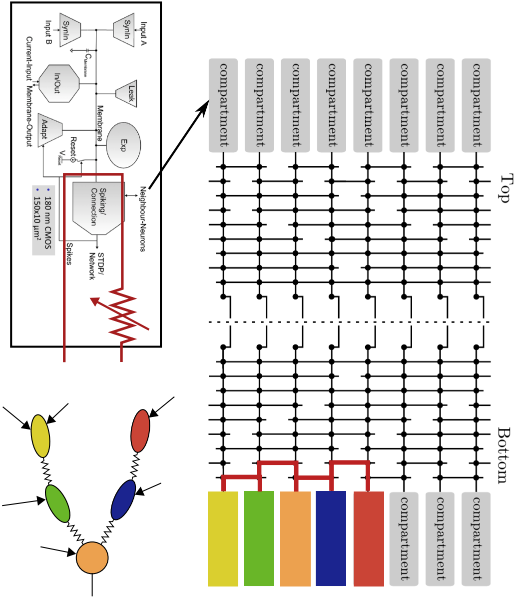
max. 14k synapses per neuron



Outlook: Multi-compartment neurons



Outlook: Multi-compartment neurons

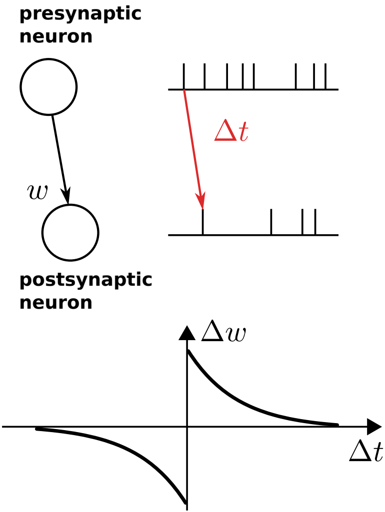


(Millner, 2012)

- Configurable resistances
- Routing matrix
- Implement dendritic tree

⇒ Biologically more realistic

Challenge: Synaptic plasticity



Spike Timing Dependent Plasticity

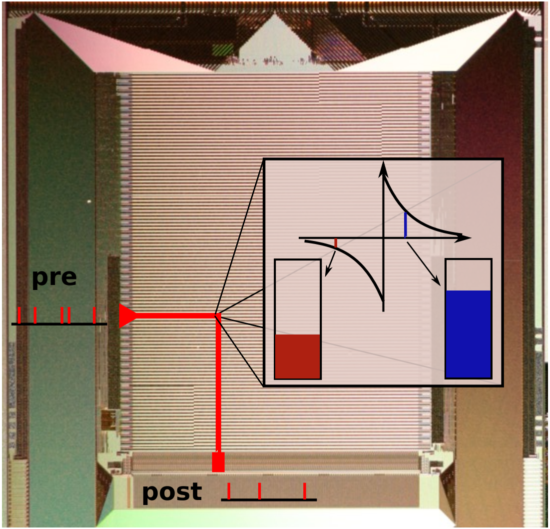
Challenge

- Every synapse subject to change
- Plasticity is foundation of learning
- Timing dependency with millisecond precision

Approach

- Analog timing measurement
- Digital weight modification

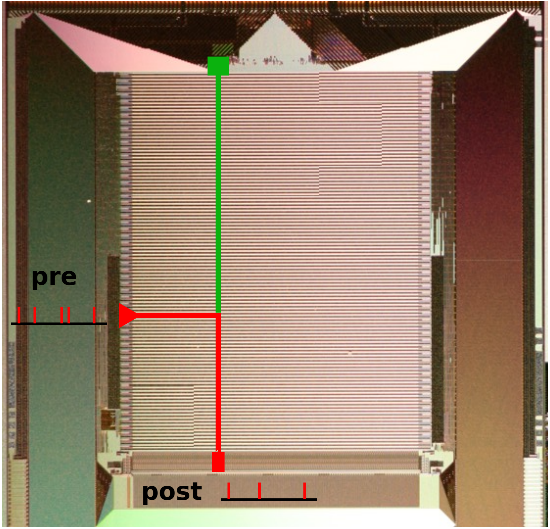
BrainScaleS STDP



Synapse:

- Measure spike timing
- Exponential weighting
- Local accumulation on capacitors

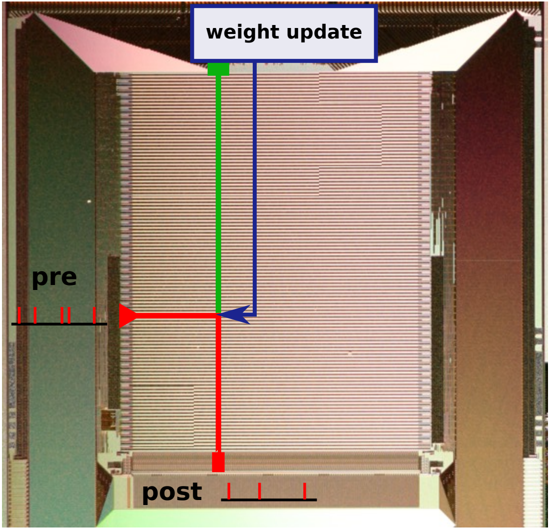
BrainScaleS STDP



Evaluation:

- Configurable comparison operation
- e.g. compare difference to threshold

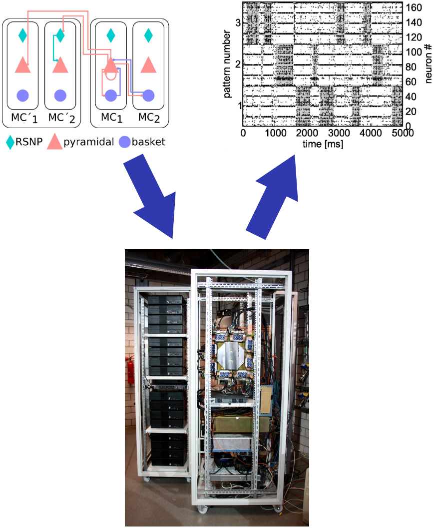
BrainScaleS STDP



Digital weight update:

- 4 bit weights
- Calculate new weight
- Uses look-up tables

Challenge: Usable by neuroscientists



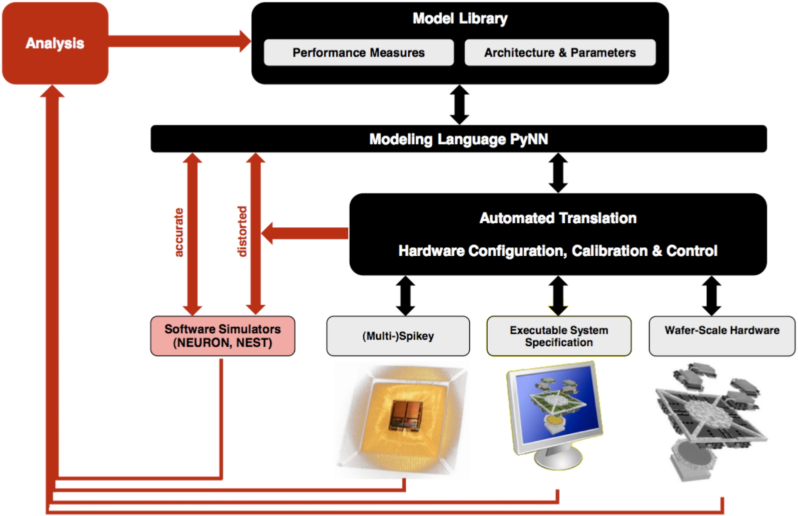
Challenge

- Large configuration space
- Lots of technical detail
- Neuroscientists are not hardware engineers

Approach

- Network described in biological terms
- Modeling language PyNN
- Automatic configuration

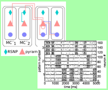
Usage Workflow



Conclusion

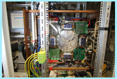
"Simulating the Brain"

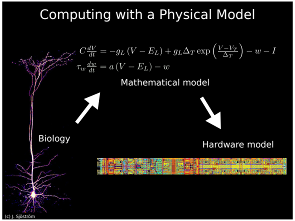
Neuroscience

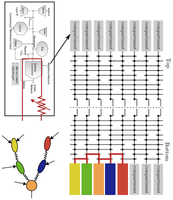


"Brain Inspired Computing"

Technology







(Millner, 2012)

- Goals: “Simulating the Brain” and “Brain inspired Computing”
- Workflow: Biology → Model → Hardware
- Acceleration: Important for studies of learning
- Improved neuron model in future systems