IST-2001-35271 Project SpikeFORCE: Real-time Spiking Networks for Robot Control

Project funded by the Future and Emerging Technologies arm of the IST Programme FET-Life-like Perception Systems (LPS) Proactive Initiative 2001 in Bionics

information society technologies

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SPIKEFORCE

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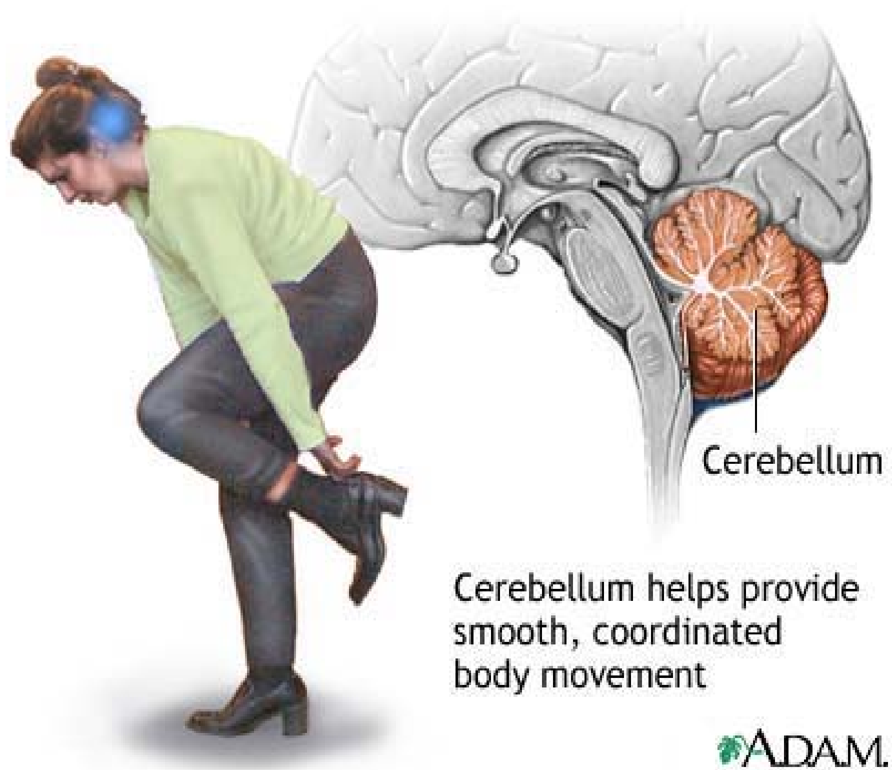
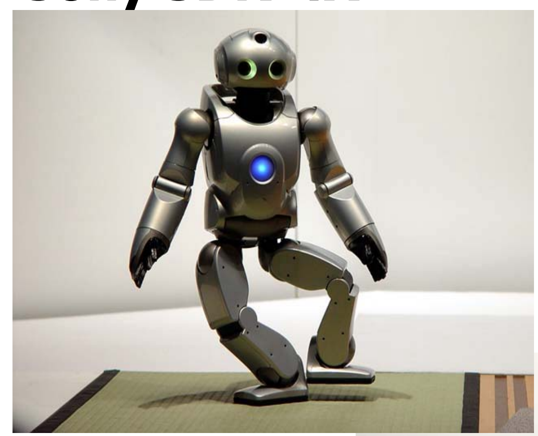
http://www.spikeforce.org

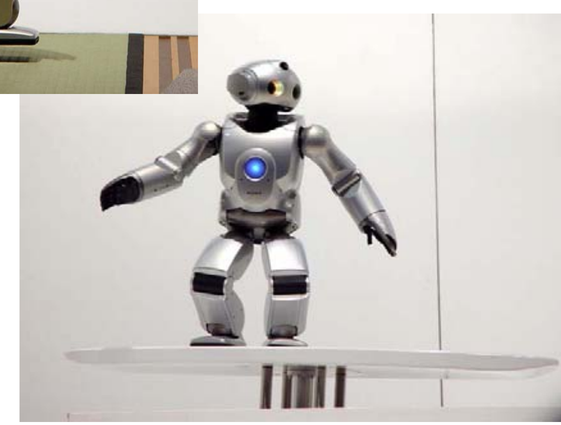
Project Objectives

Produce a model of the cerebellum based on known physiology and latest analytical and computational results that can be implemented efficiently in software/hardware for running real-time robotic experiments.



Sony SDR-4X





Real-time Spiking Network for Robot Control

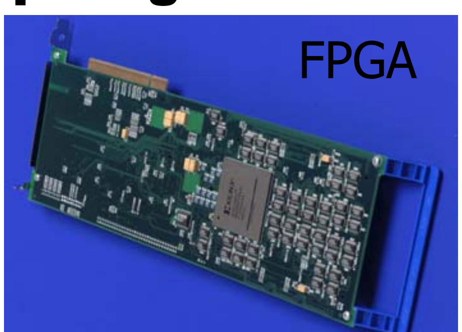
Spiking Cerebellar Model

Computer ↔ Computer

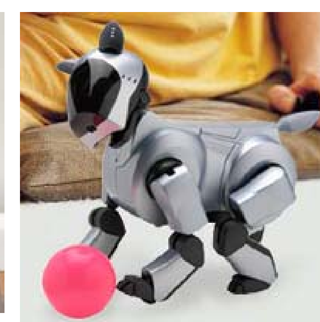
Computer ↔ Computer ↔ Computer

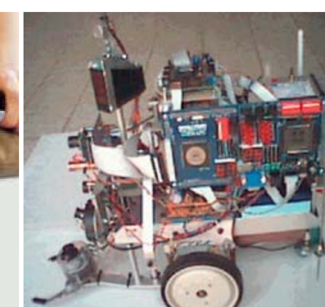
Tasks (simulated, real)

Spiking Hardware



Robots



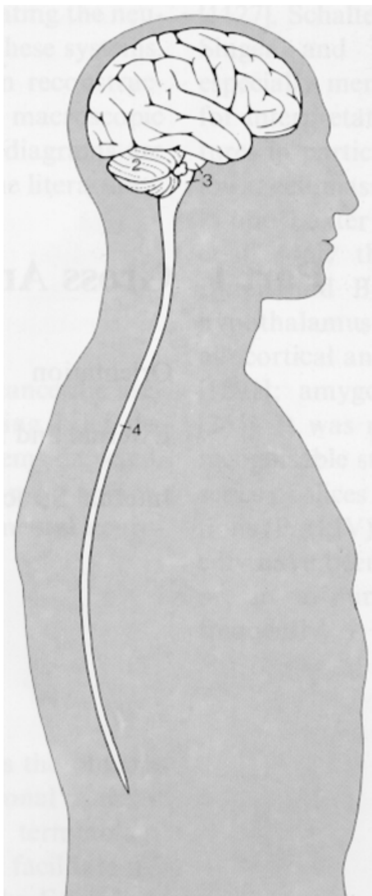


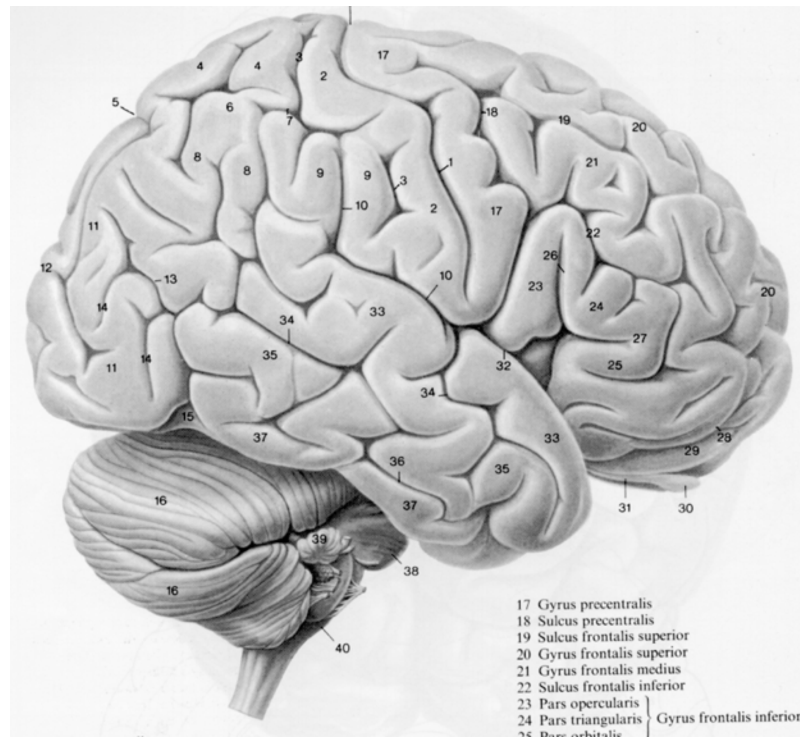
Impacts:

- Advances in robot learning
  fine response modulation/anticipation with context
- Improve cerebellar neurophysiological knowledge
- Spiking representation
- Improve knowledge of action-perception loop
  cerebellum participation
- Real-time spiking hardware technology
- Potential use in human rehabilitation

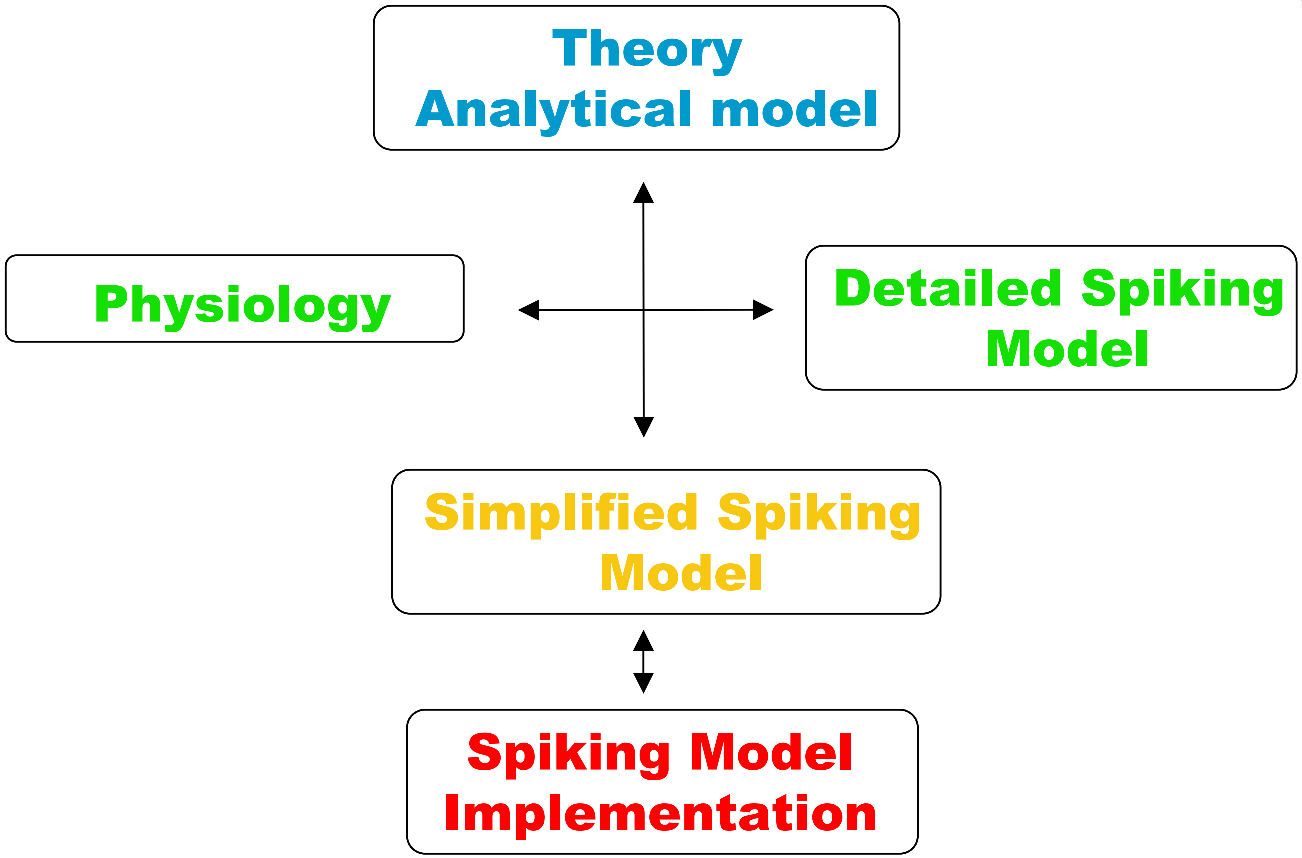
The Cerebellum

The human central nervous system, Nieuwenhuys *et al.*, 1988



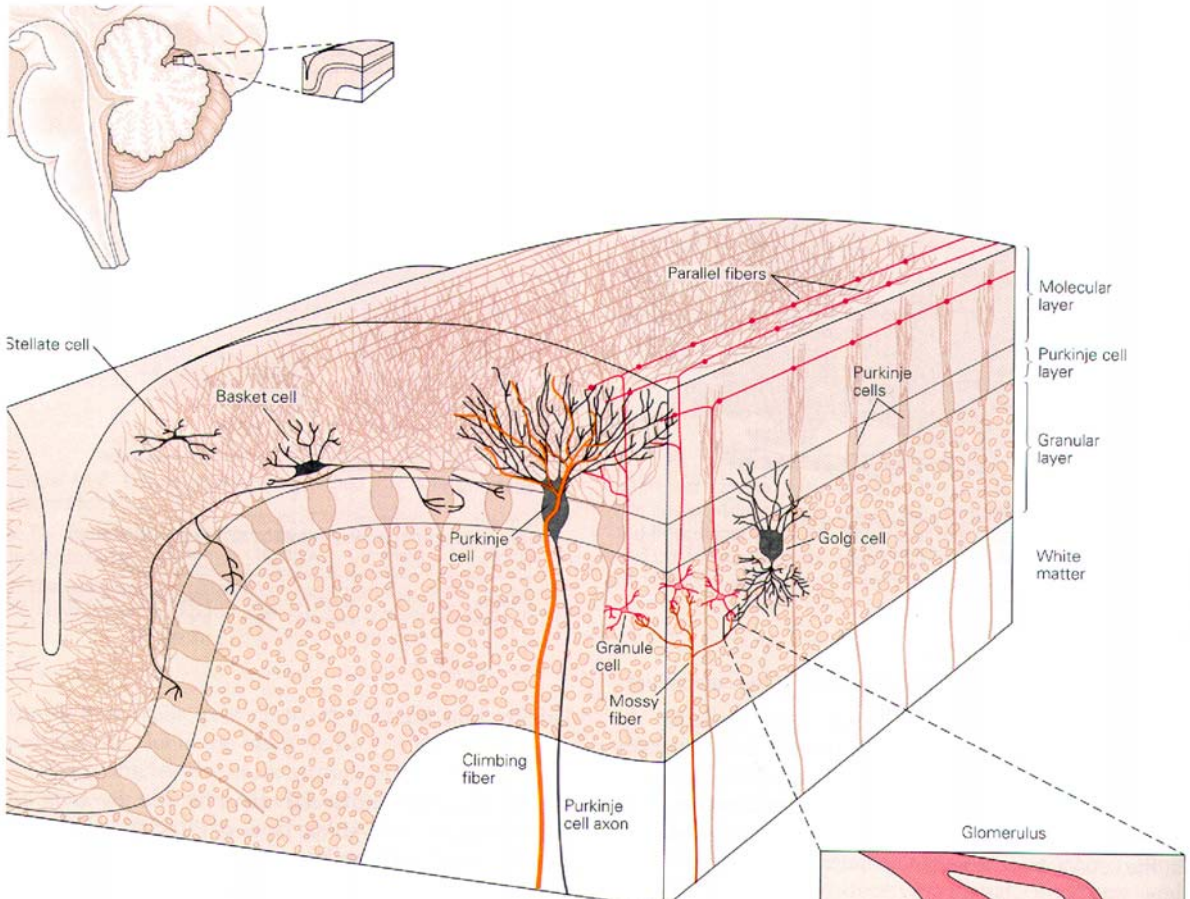


Route to a spiking cerebellar model



The Cerebellum

Principles of Neural Science, Kandel *et al.*, 4th Ed., 2000



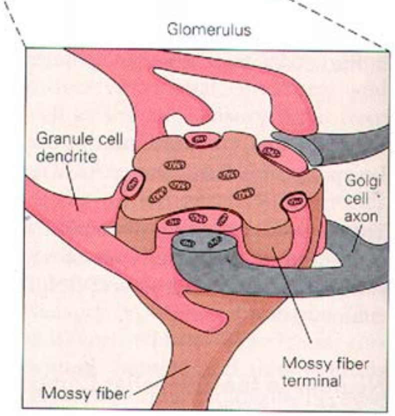
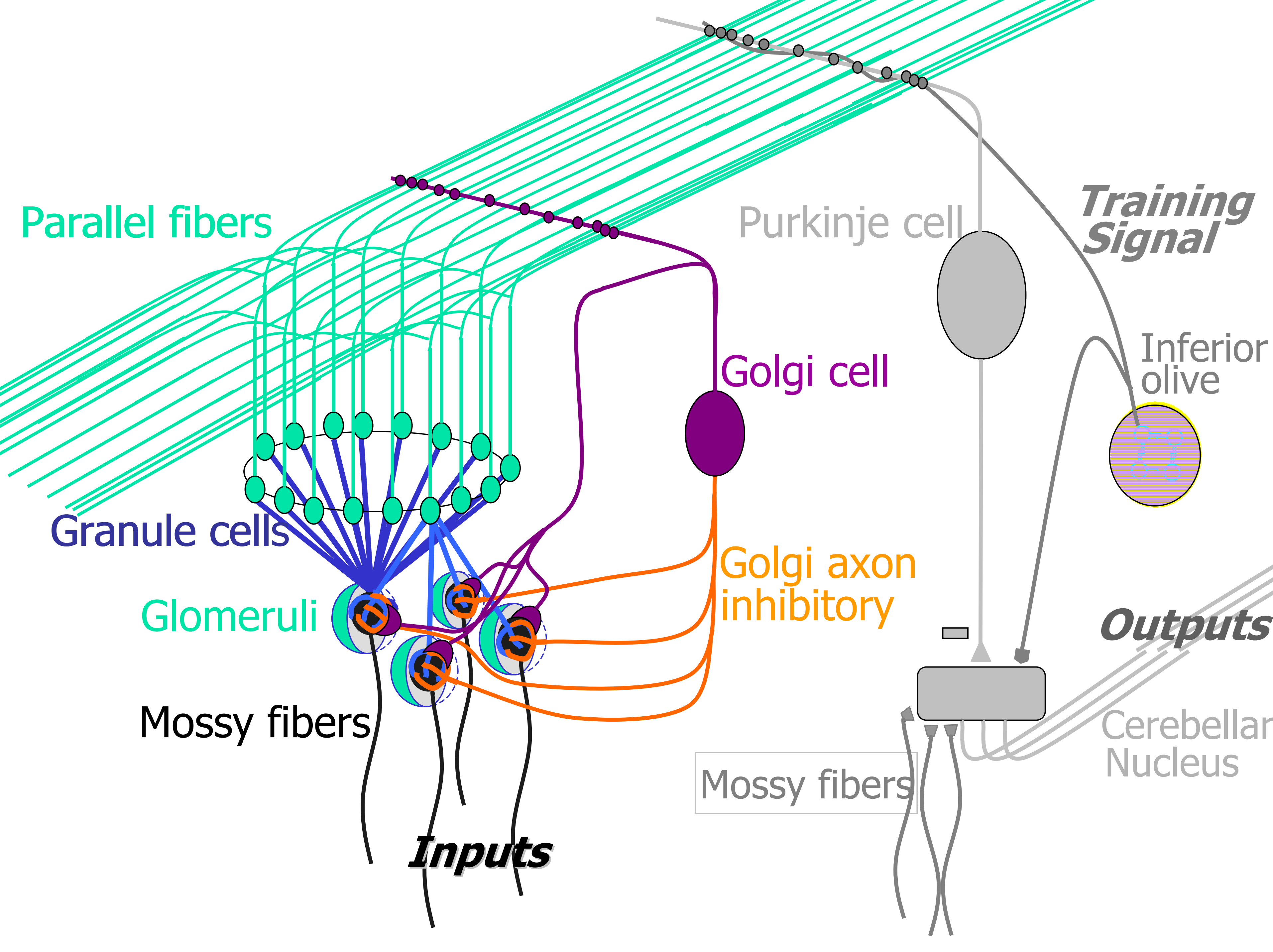


Figure 42-4 **The cerebellar cortex is organized into three layers and contains five types of neurons.** A vertical section of a single cerebellar folium, in both longitudinal and transverse planes, illustrates the general organization of the cerebellar cortex. The detail of a cerebellar glomerulus in the granular layer is also shown. A glomerulus is a clear space where the bulbous terminal of a mossy fiber makes synaptic contact with Golgi and granule cells.

Granular layer

Outline:

- **Physiology**
- **Computer models**
- **Theoretical models**


Parallel fibers
Purkinje cell
Training Signal
Inferior olive
Golgi cell
Granule cells
Golgi axon inhibitory
Glomeruli
Outputs
Mossy fibers
Cerebellar Nucleus
Mossy fibers
Inputs

Modeling: from physiological complexity to simplified harware implementation retaining the salient biophysical properties of neurons and synapses

Physiology → **detailed models of neurons and synapses** → **detailed network models**

detailed models of neurons and synapses ↓ **simplified models of neurons and synapses**

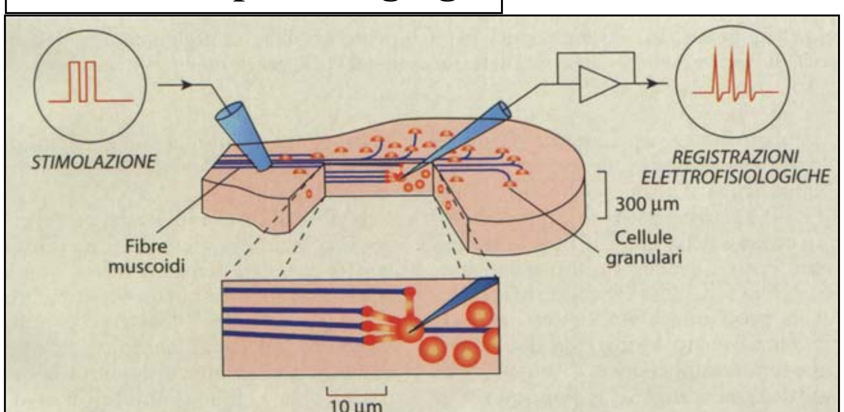
detailed network models ↓ **simplified network models**

simplified models of neurons and synapses → **simplified network models**

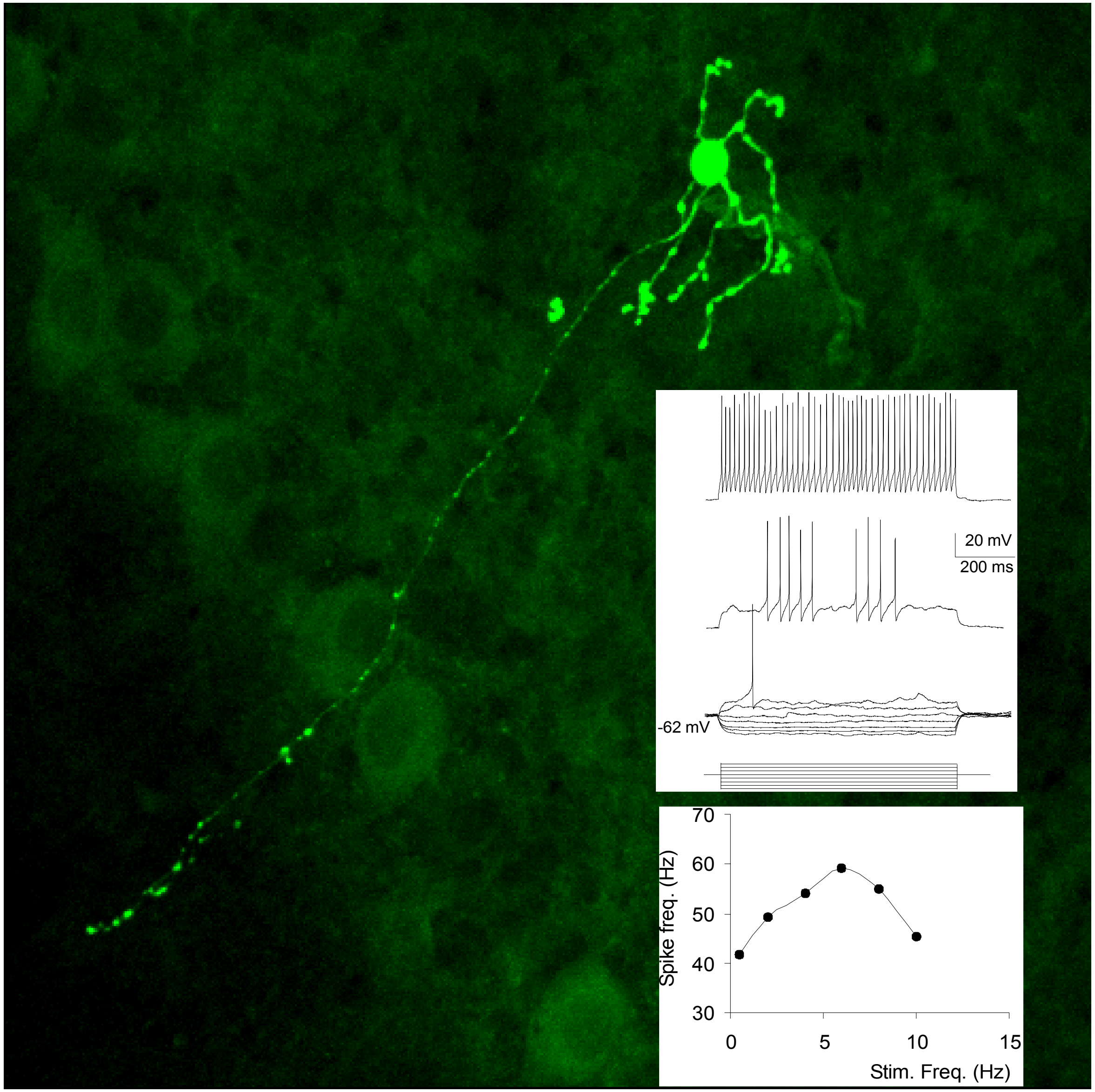
simplified network models ↓ **Hardware implementation**

Acute slice recordings

Patch-clamp / imaging



Granule cell



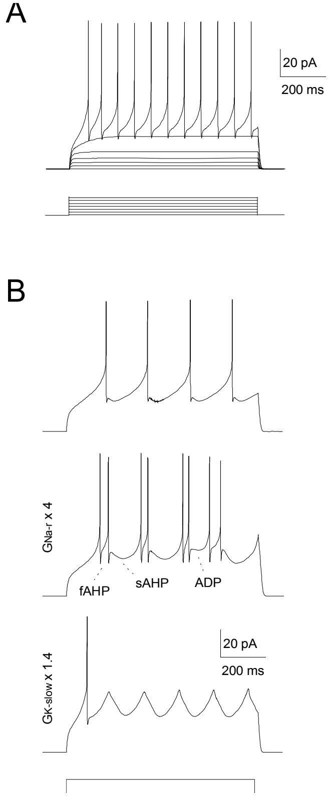
1) Repetitive firing

2) Inward rectification

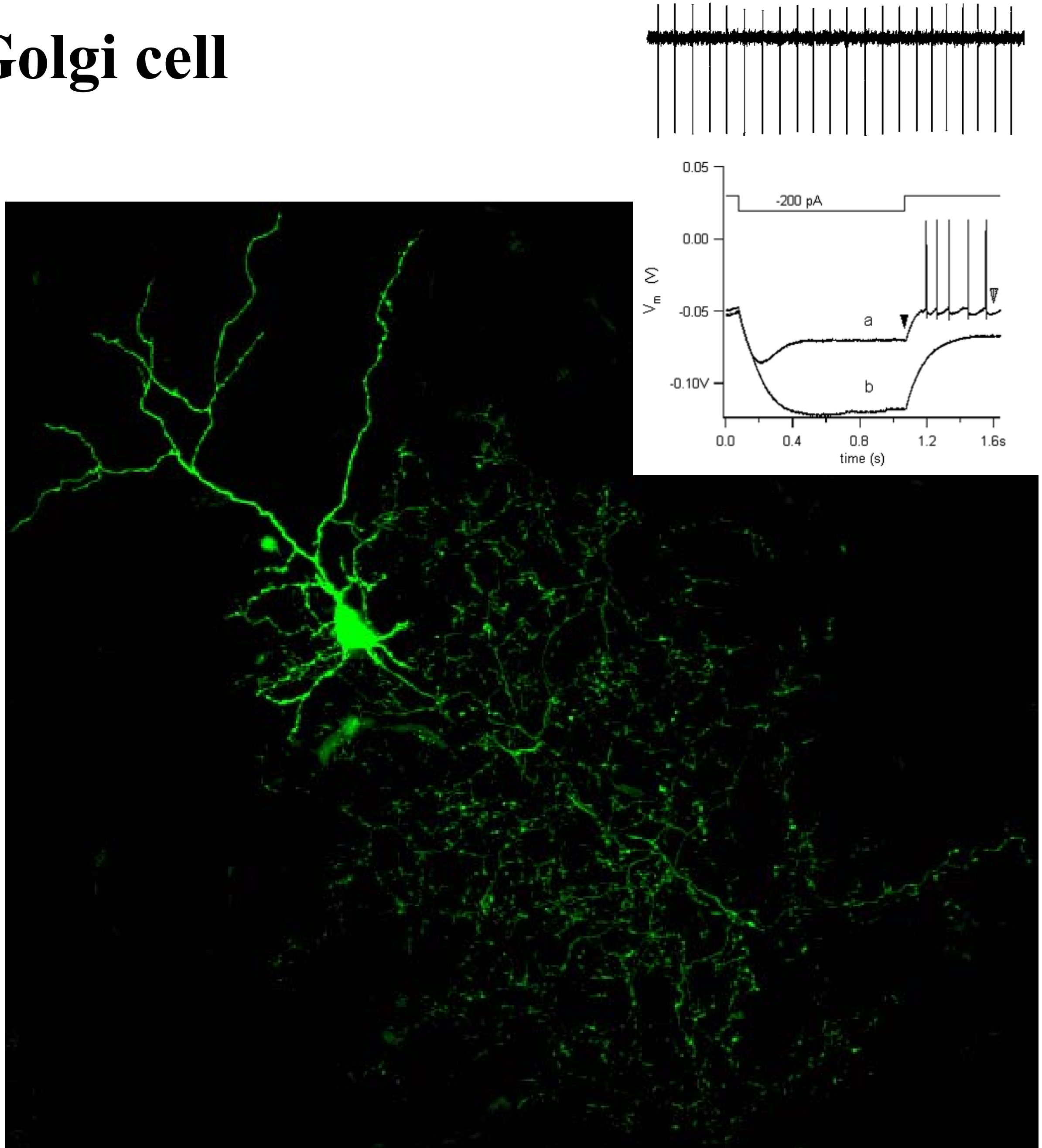
3) Bursting

4) Resonance

model



Golgi cell



1) Autorhythmic firing

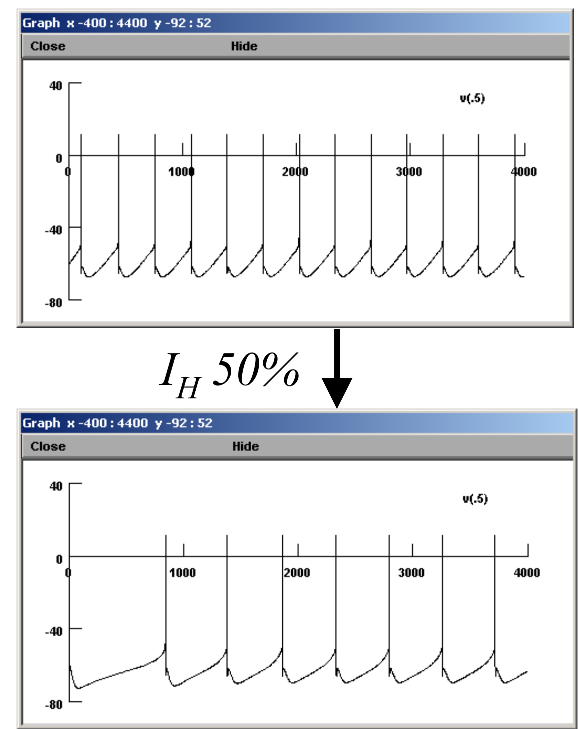
2) Subthreshold oscillations

3) Postinhibitory rebound

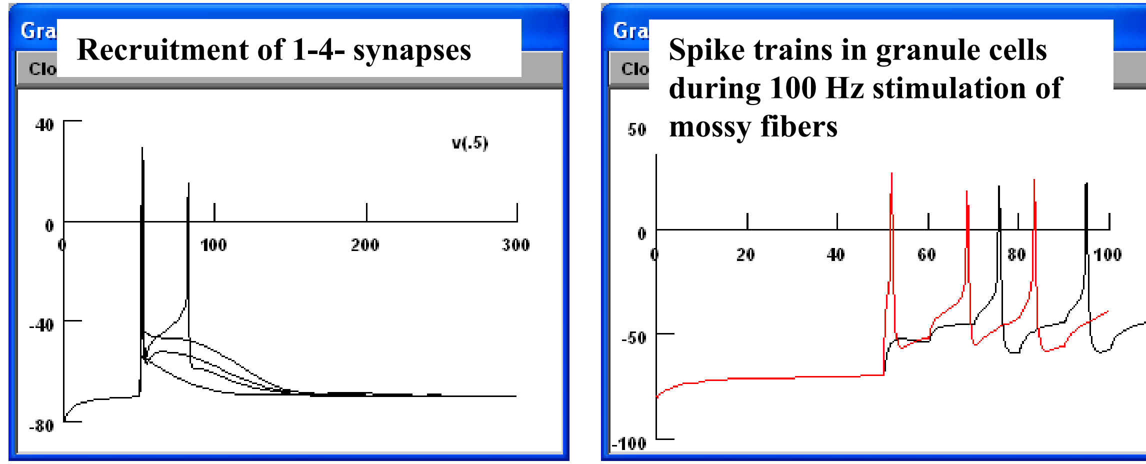
4) Post-burst pause

5) Inward rectification

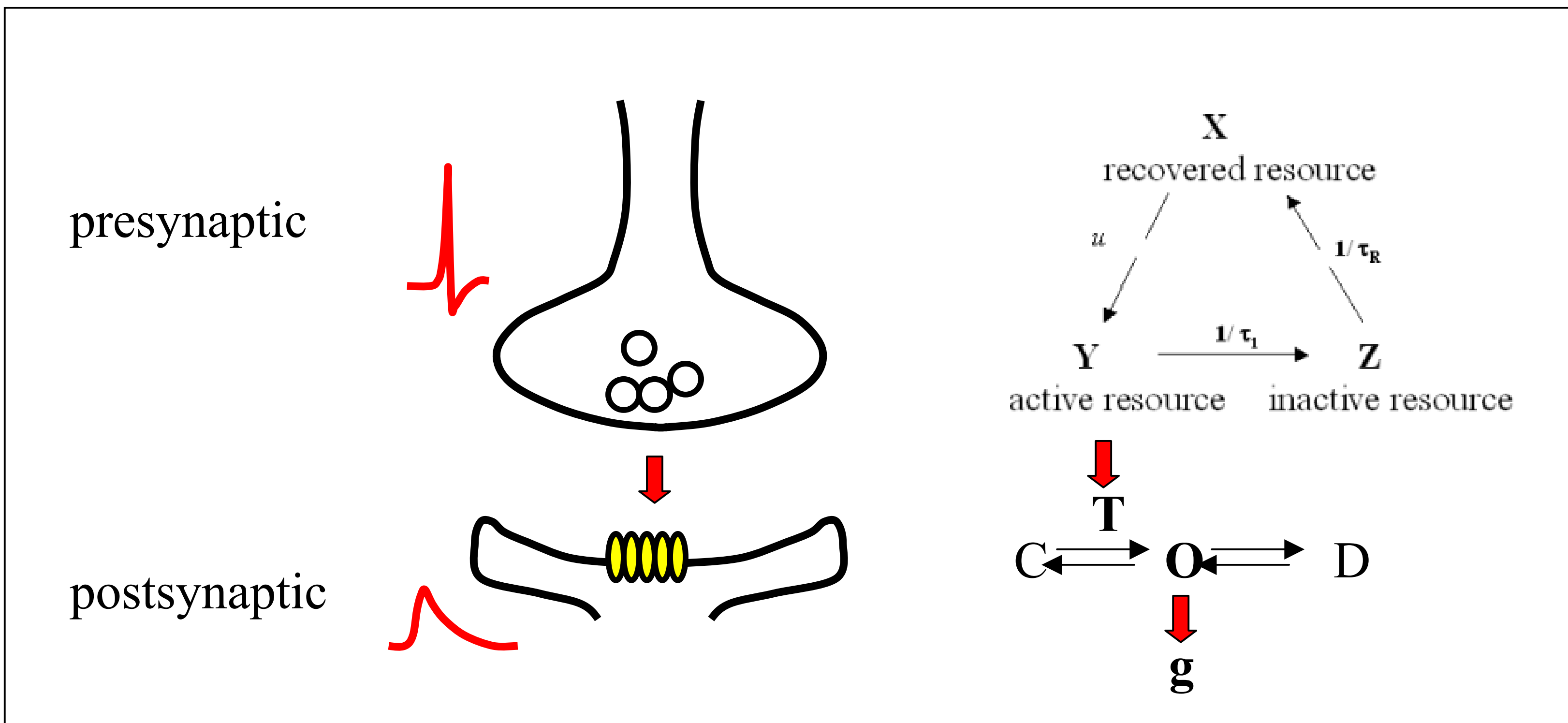
model



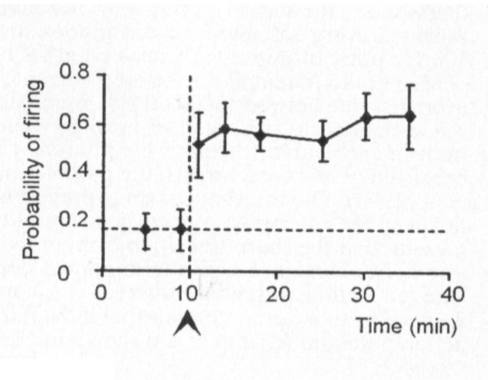
Modeling neurotransmission dynamics by conductance-based models

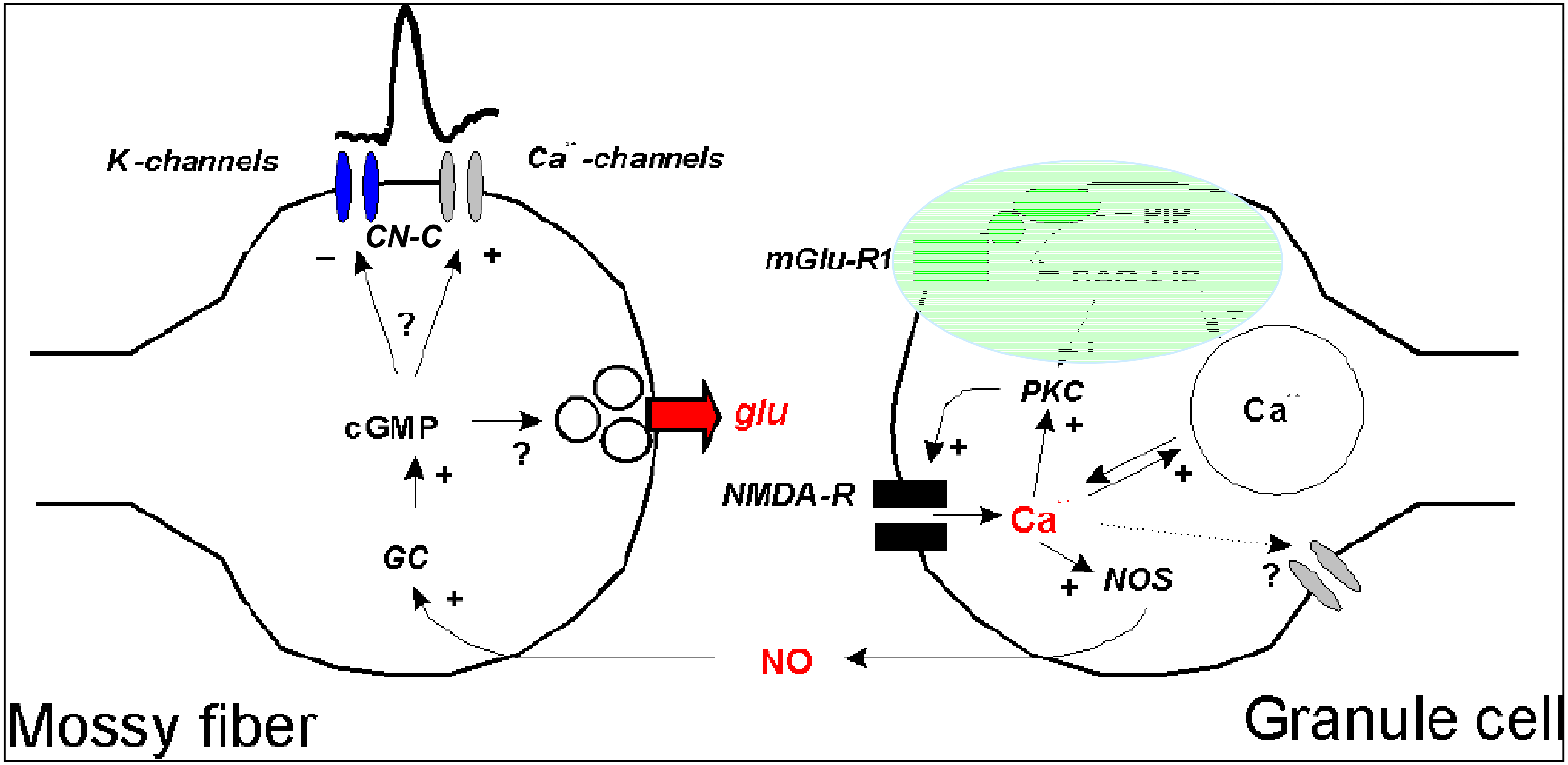


Mossy fiber - granule cell neurotransmission

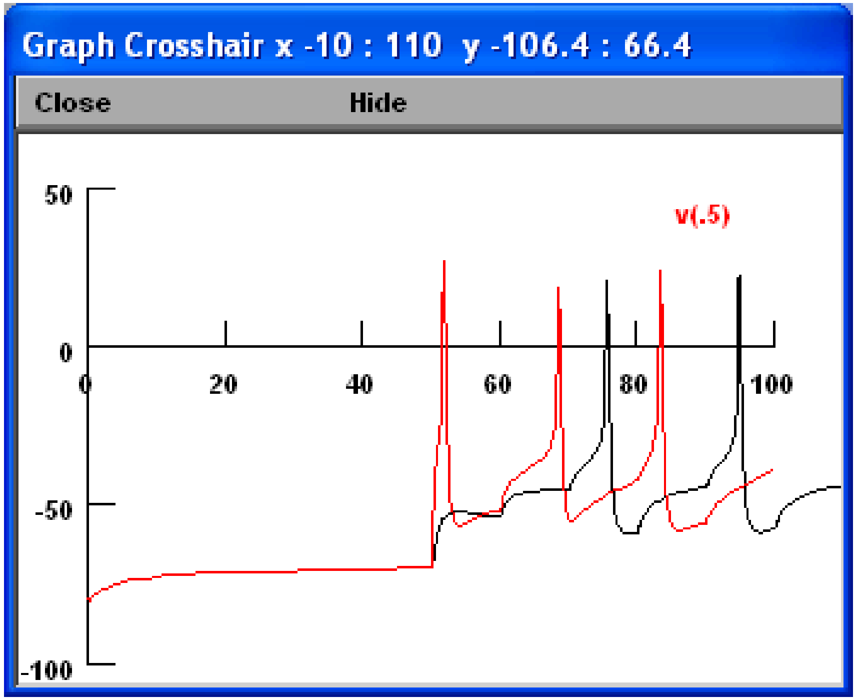


Mossy fibre – granule cell LTP





The presynaptic expression mechanism implies that neurotransmission dynamics are modified during LTP



Control of spike initiation in the model by changing release probability

p = 0.1

p = 0.5

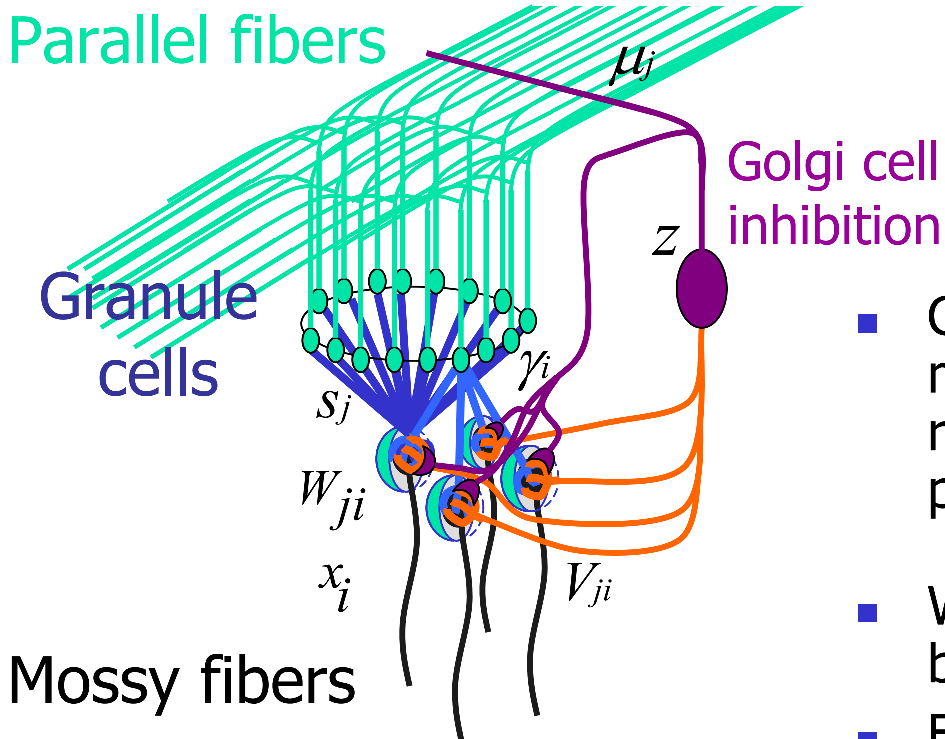
The infuence of dynamics changes caused by LTP are currently under testing in a detailed model network comprising 2000 Granule Cells.

Granular layer

Outline:

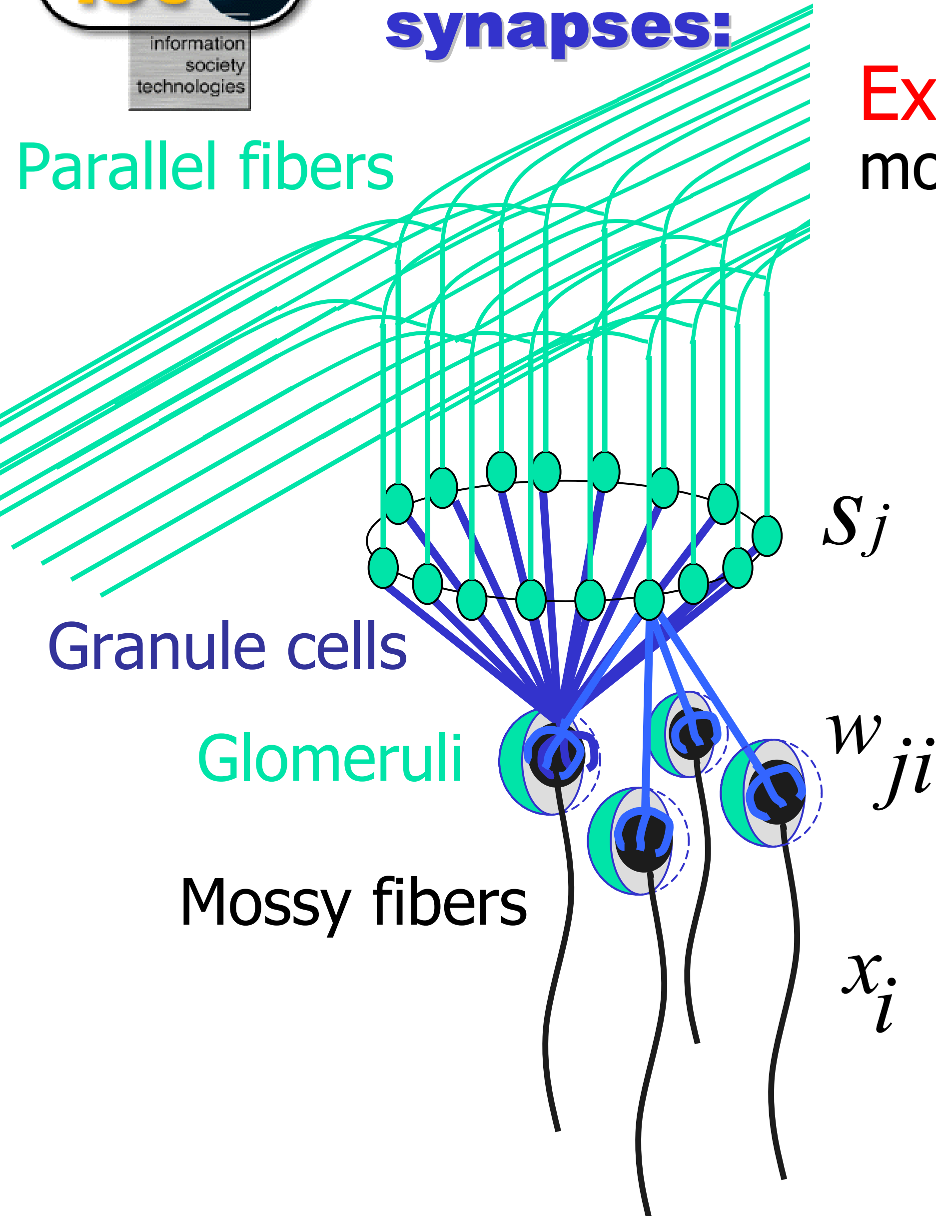
- **Physiology**
- **Computer models**
- **Theoretical models**

Denoising: A new role for the Golgi cells



- Granule cells perform a recoding of the mossy fibers inputs into a sparse representation using a biologically plausible ICA (Coenen *et al.*, 2001; Eagleman *et al.*, 2001)
- Which permits optimal noise reduction by the Golgi cell &
- Facilitates learning in the Purkinje and molecular layer of the cerebellum (simplifies credit assignment problem)

Plasticity at granule cell synapses:



Experimental evidence:

mossy fiber-granule cell synaptic weight changes:

Long-term potentiation (LTP)

synaptic weight increase

EPSPs, presynaptic currents

Long-term depression (LTD)

synaptic weight decrease

(D'Angelo, 1999; Maffei *et al.*, 2002; etc.)

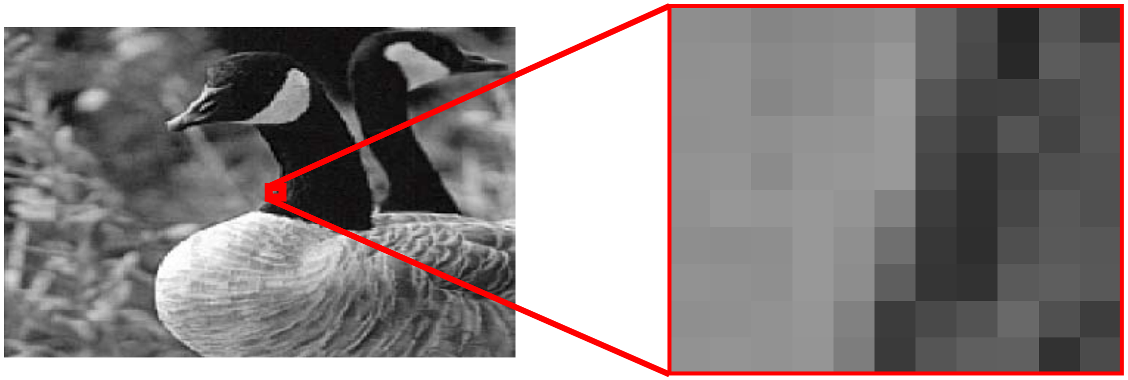
Changes in cell excitability

intrinsic cell properties

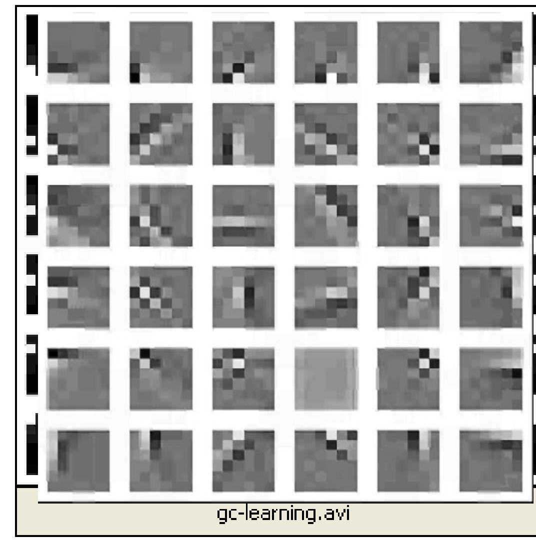
(Armano *et al.*, 2000)

Images as mossy fiber inputs to illustrate putative 'statistical structure'

granule cell receptive field



one pixel = one mossy fiber input



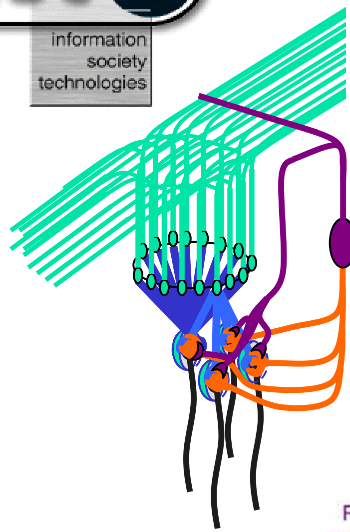
granule cell weights adapt to become independent as much as possible using the mossy fibers statistical structure

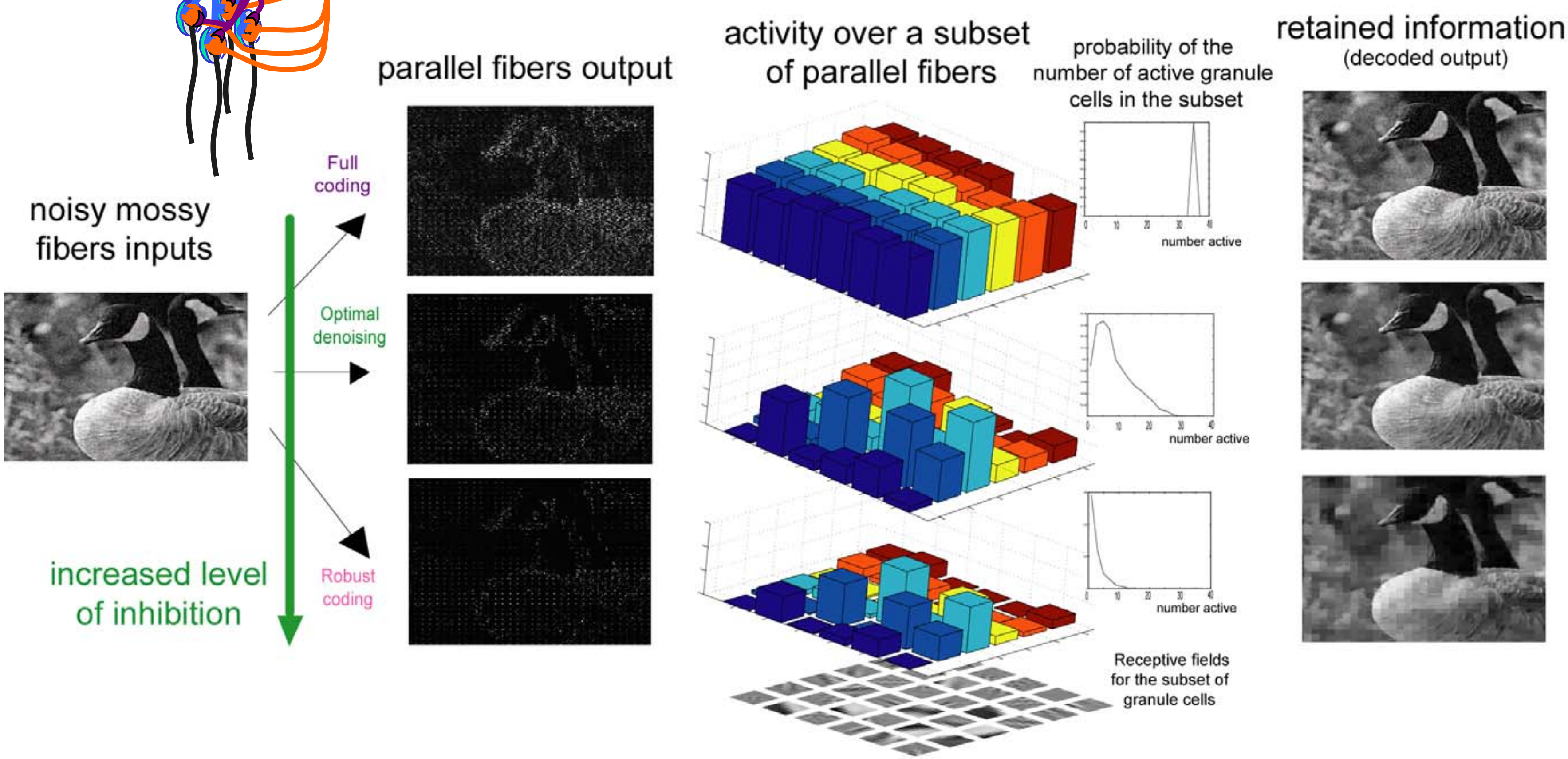
Cerebellar inputs will contain noise:

original image

noisy mossy fibers inputs

Encoding by granule cells with Golgi cell inhibition

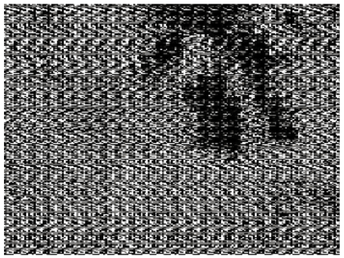




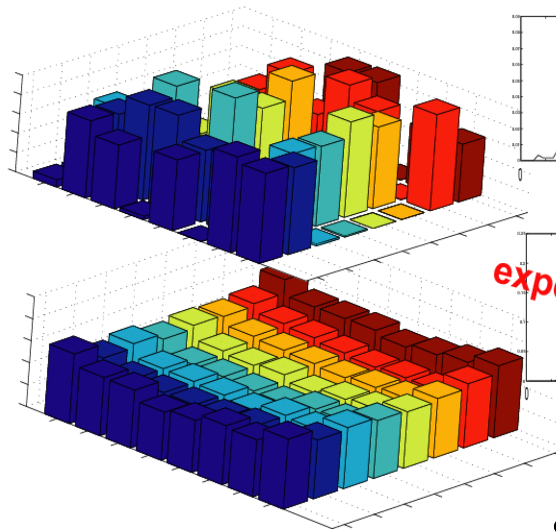
Encoding by granule cells: robust coding?

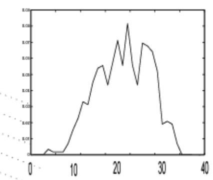
Other models:

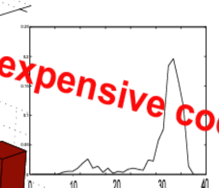
Random weights



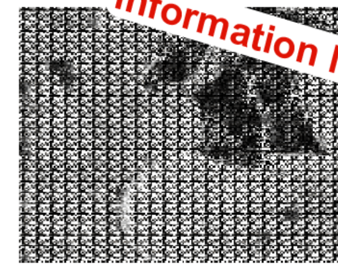
Decorrelating weights

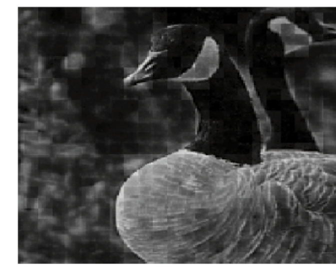






Kettner *et al.*, JNeurophys., 1997

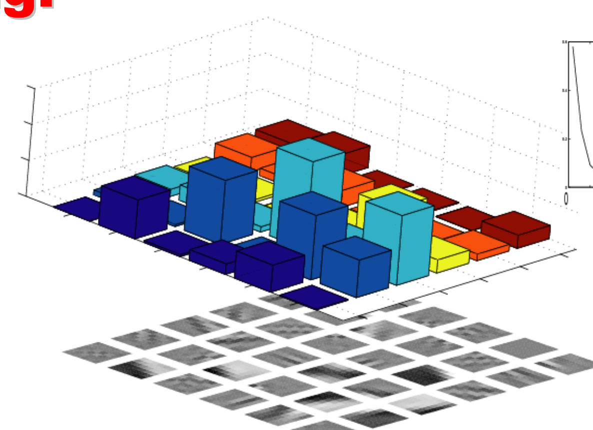


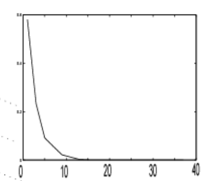


Schweighofer *et al.*, Neurosci., 2001
Chauvet, 1986; Jonker *et al.*, 1998

Robust sparse coding:

Robust coding





Receptive fields for the subset of granule cells

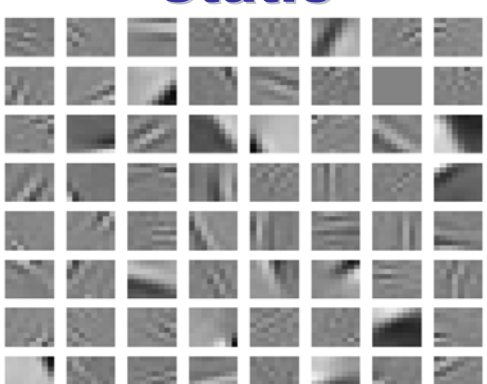
Spatiotemporal coding

Granule cells display facilitating and depressing synapses
(D'Angelo, personal communication)

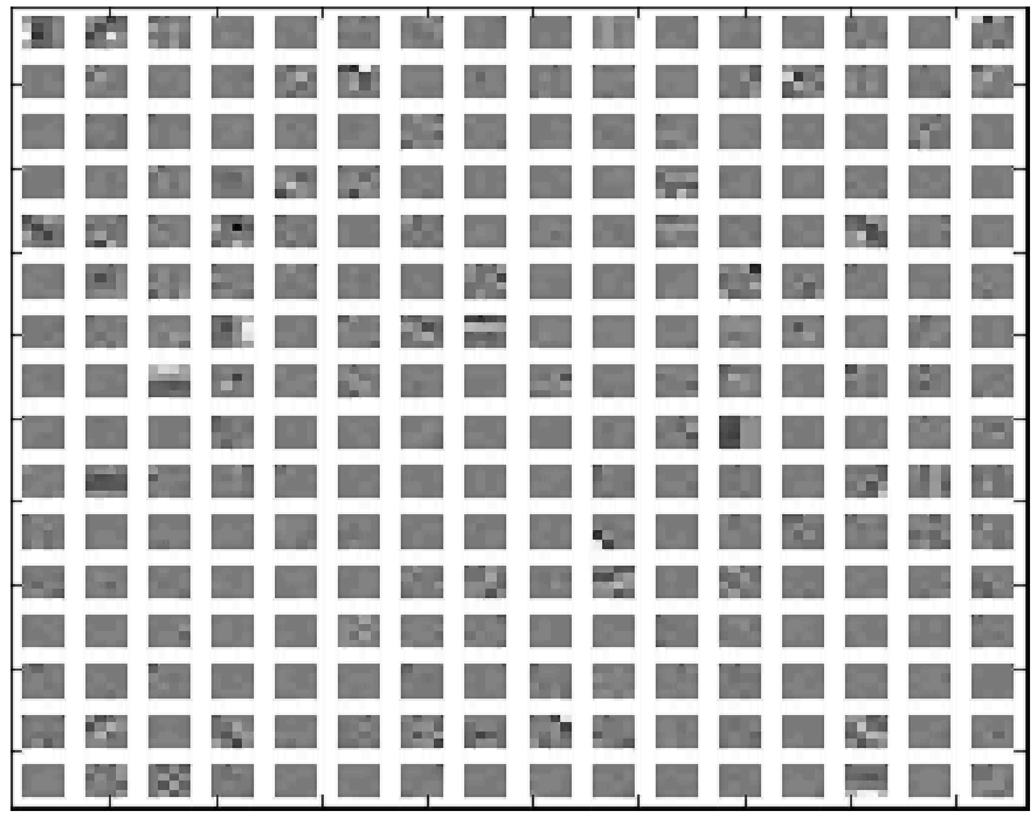
Constructing temporal basis function from experience

(Bell & Sejnowski, 1995; Lewicki, 2002; Olshausen, 2002;
van Hateren & Ruderman, 1998)

Static



Preferred mossy fibers stimulus for a set of granule cells



$$s_j(t) = \sum_n \sum_i w_{ji}(n) x_i(t-n)$$

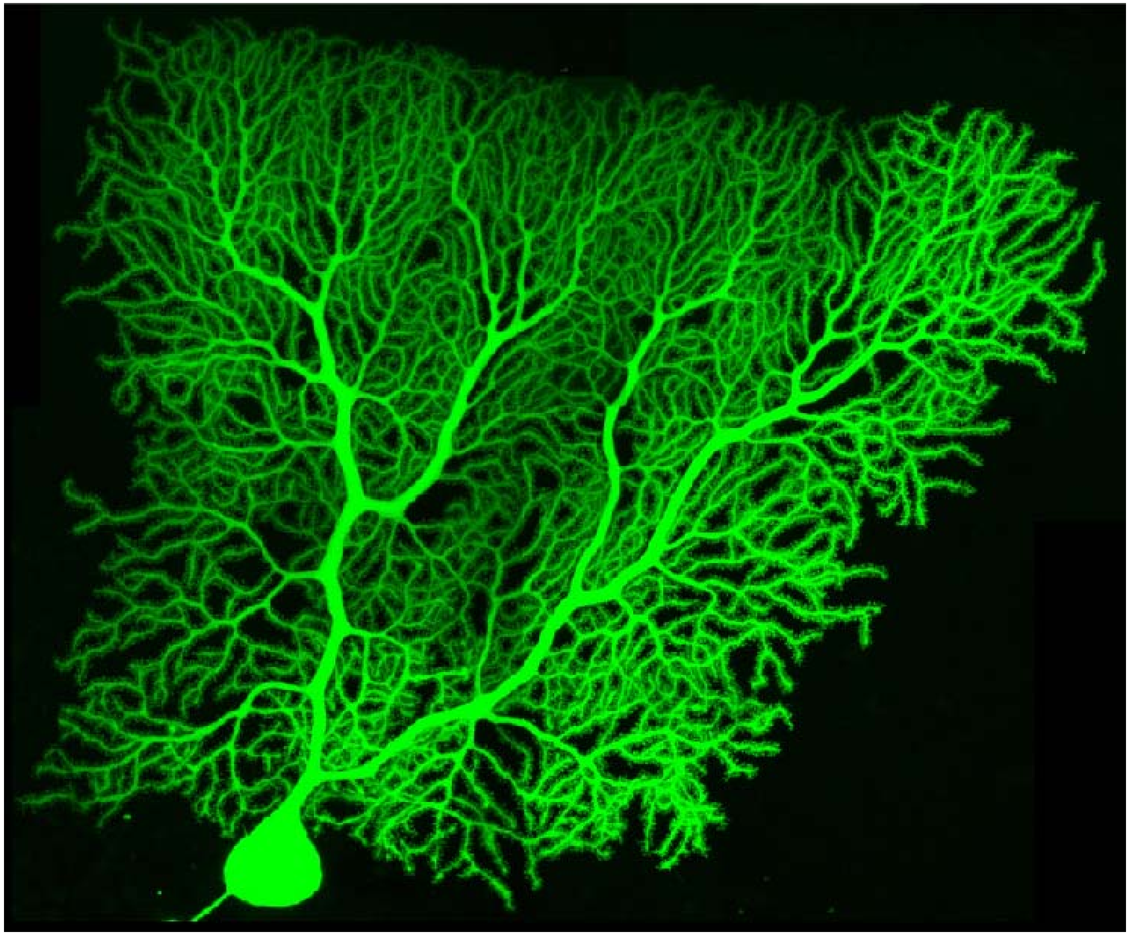
Purkinje/molecular layer

Outline:

- **Physiology**
- **Theoretical models**

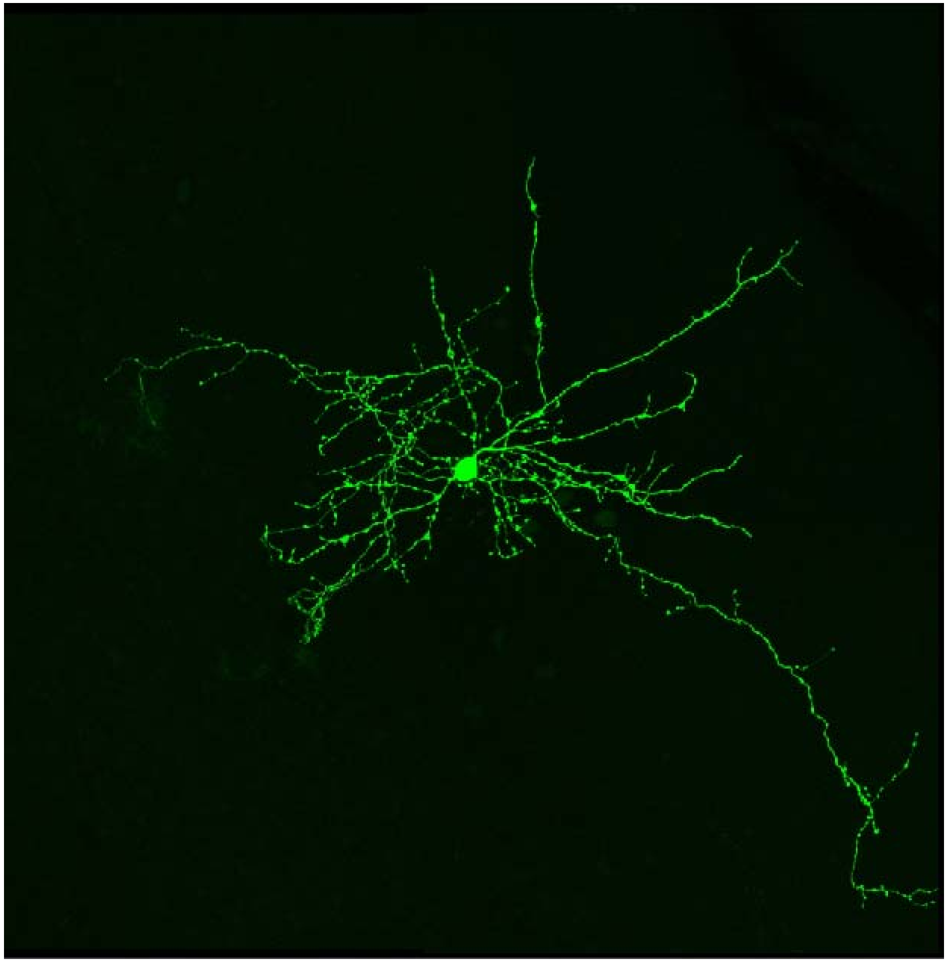
Purkinje cell

High resolution fluorescence confocal image stacks (3D)

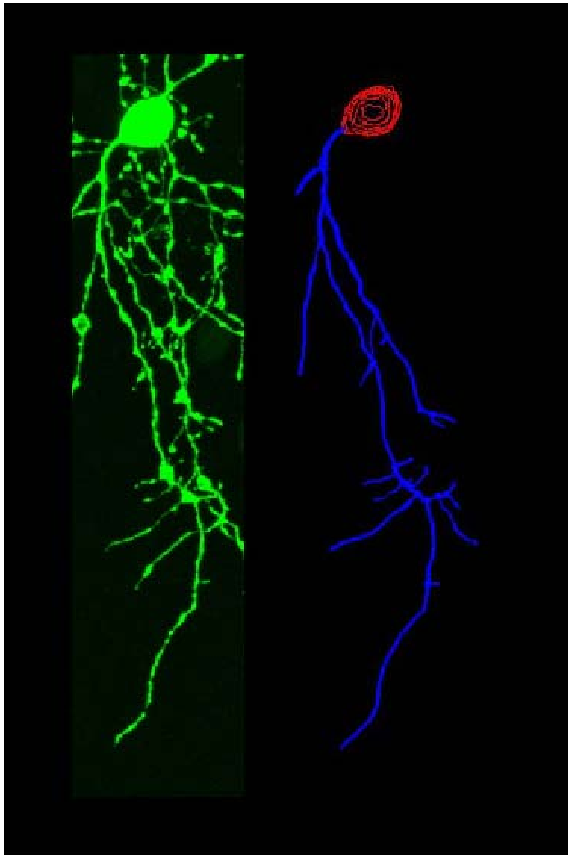


Inhibitory interneuron

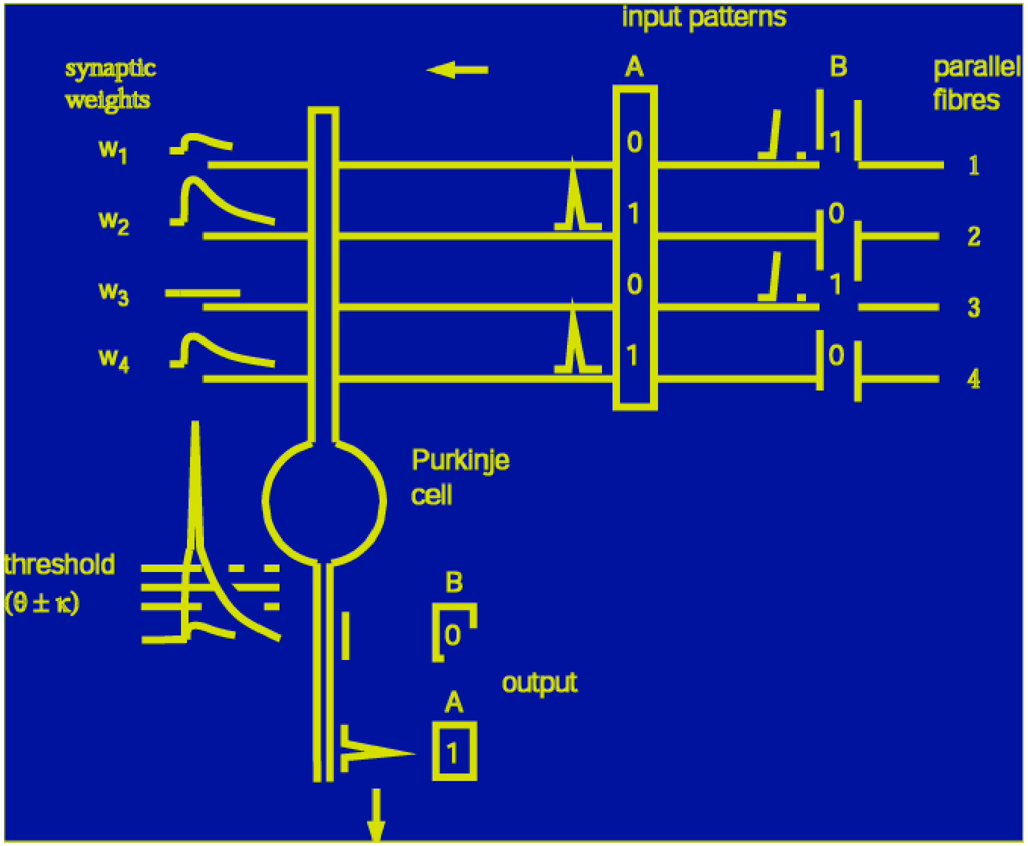
High resolution fluorescence confocal image stacks (3D)



Reconstruction



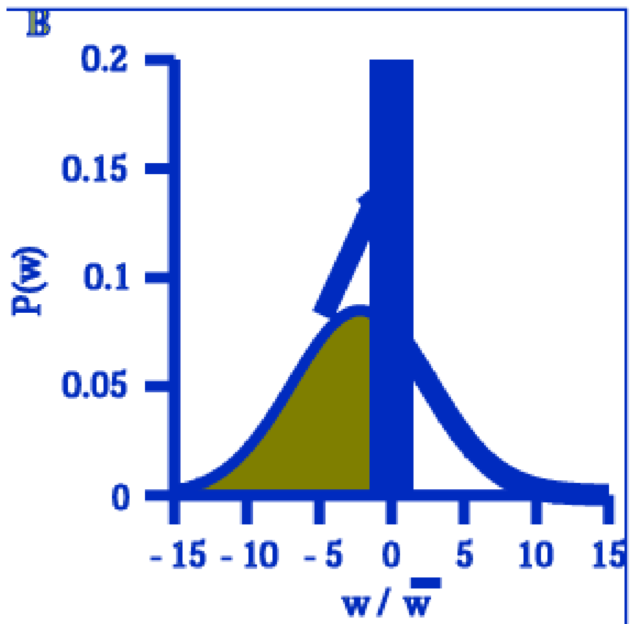
Purkinje cell as a perceptron



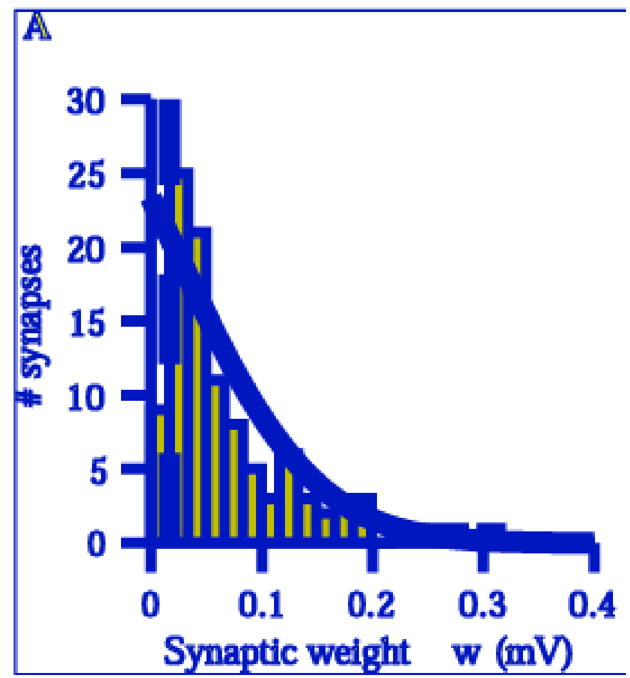
Brunel *et al.*, submitted

Purkinje weight distributions & silent synapses

Perceptron weight distrib.



Experimental vs Theoretical



Capacity analysis: ~50000 patterns/Purkinje cell

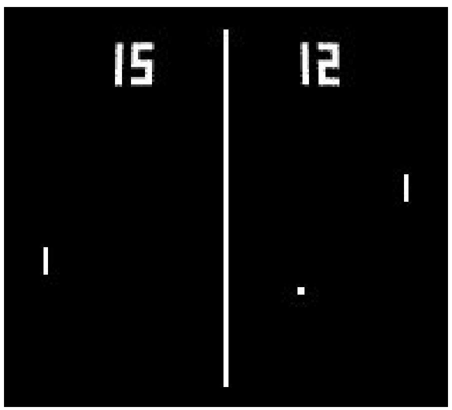
Cerebellar Task Development

Outline:

- **Task description**
- **Cerebellar simulation results**

Task description: cerebellar plong player

Pong - 1972



Computer

Simulated sensory systems:
visual, auditory, touch

Spiking cerebellar model

Computer, FPGA

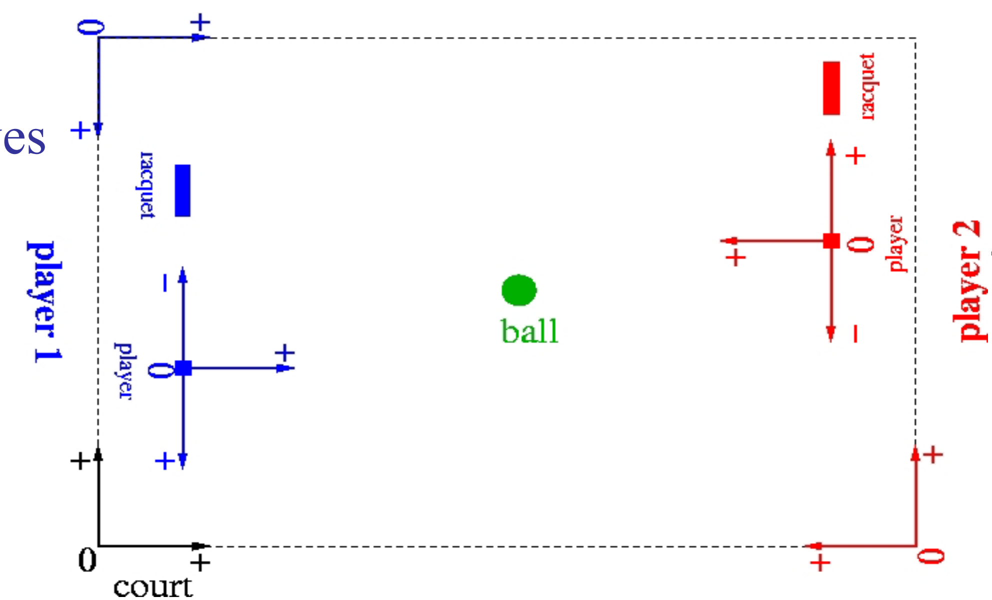
Movement,motor actions

Task description: cerebellar pong player

One player
-racquet move with player

Different configurations possible:
- ball dynamics (speed, spin, rebound effects)
- racquet dynamics
- racquet in 1D, 2D or 3D
- control strategies:
  - tracking/pursuit
  - colliding trajectory
  - controller imitation
- etc.

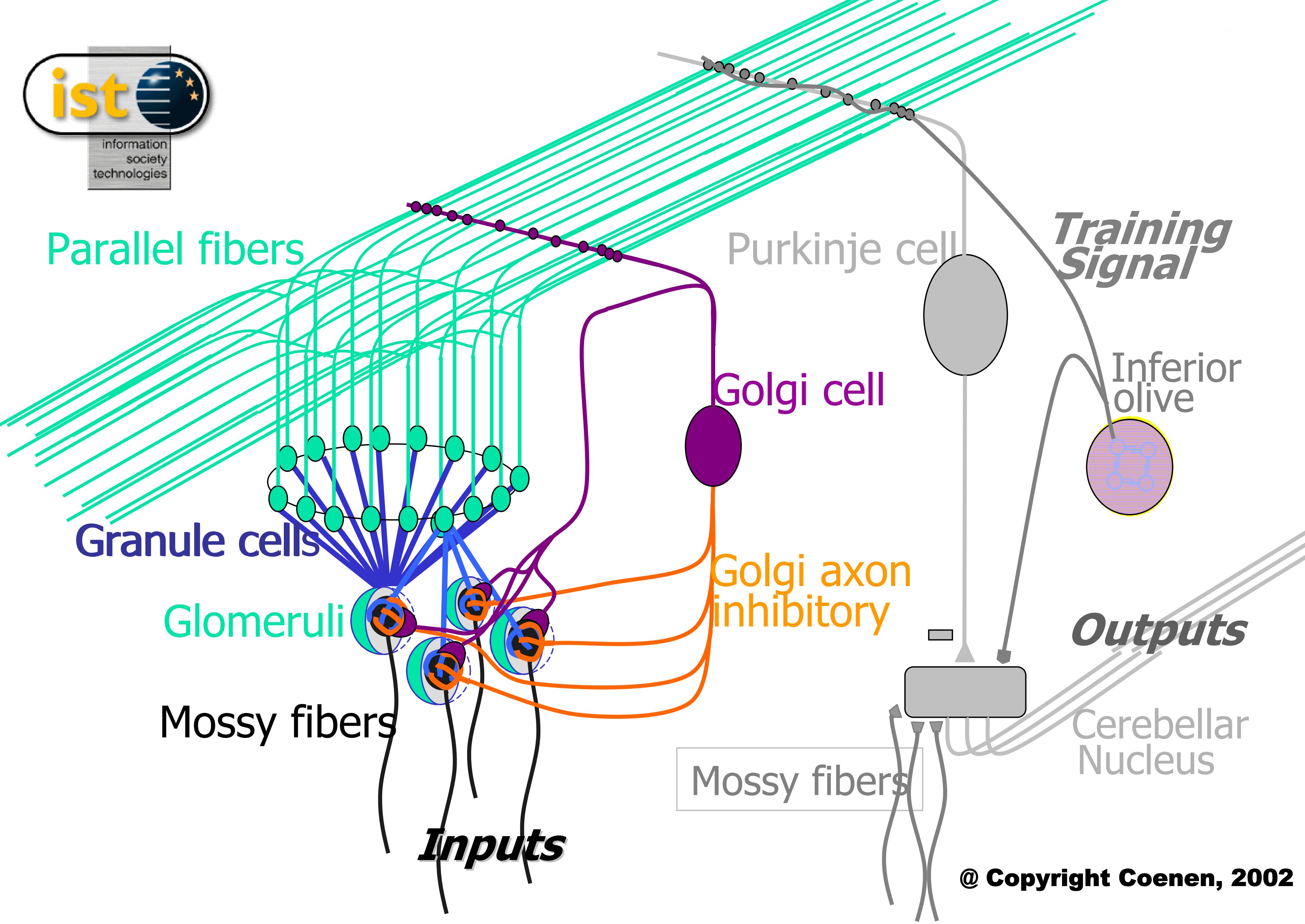
Two players
-racquet moves wrt player



Cerebellar pong player

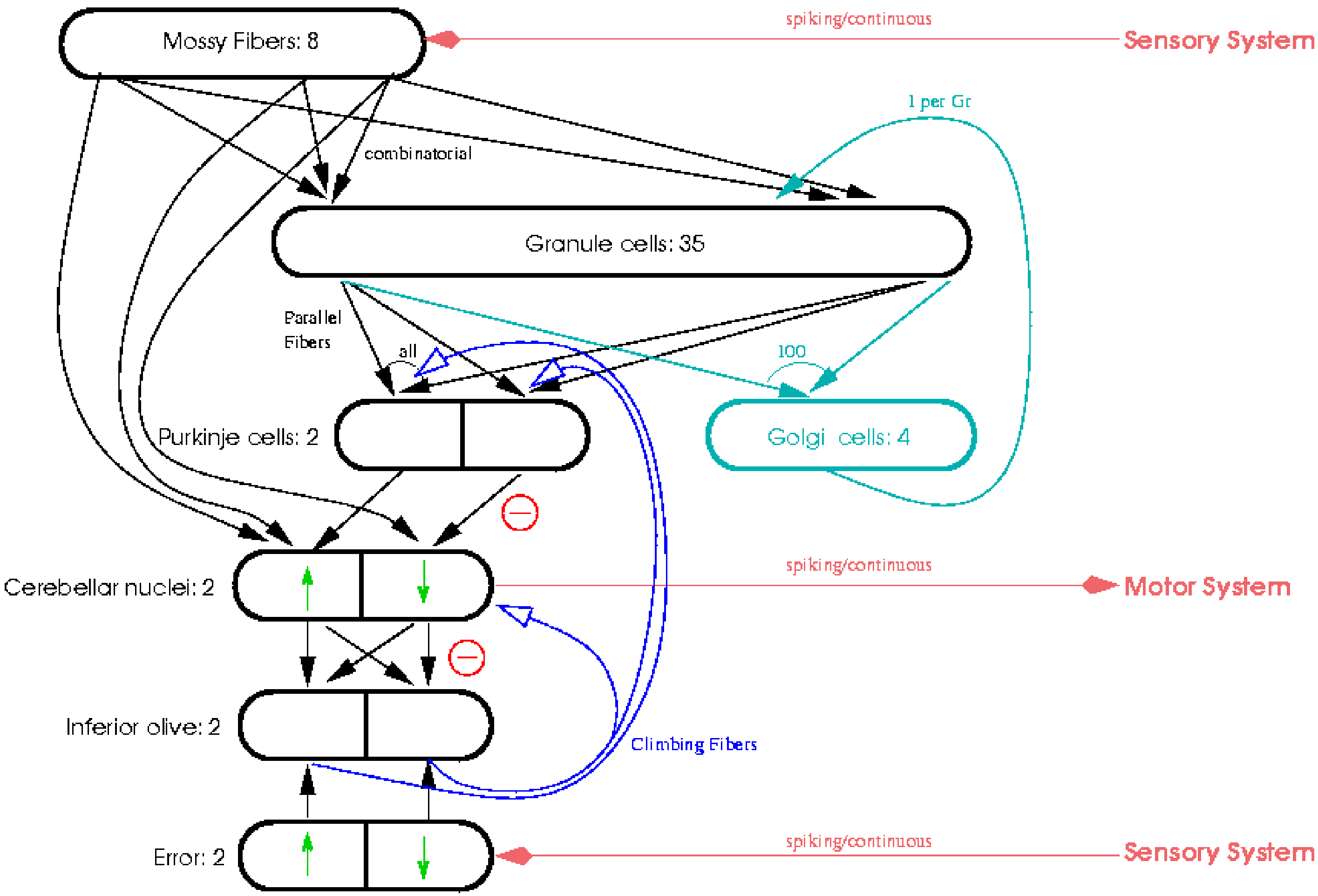
Look for:

- Learning multiple tasks -> learning multiple games
  or one game with different dynamics
- Min interference -> fast switching/modulation btw games
  with no need to relearn
- Flexible, possibly large sensorimotor context
- Cerebellar encoding: useful for high numbers of games/dynamics to learn


information society technologies
Parallel fibers
Purkinje cell
Training Signal
Golgi cell
Inferior olive
Granule cells
Glomeruli
Golgi axon inhibitory
Outputs
Mossy fibers
Cerebellar Nucleus
Mossy fibers
Inputs

Cerebellar pong player: smooth pursuer

Tenns spiking neural network simulator (Altjira Software)



Cerebellar pong player: cell responses during tracking before learning

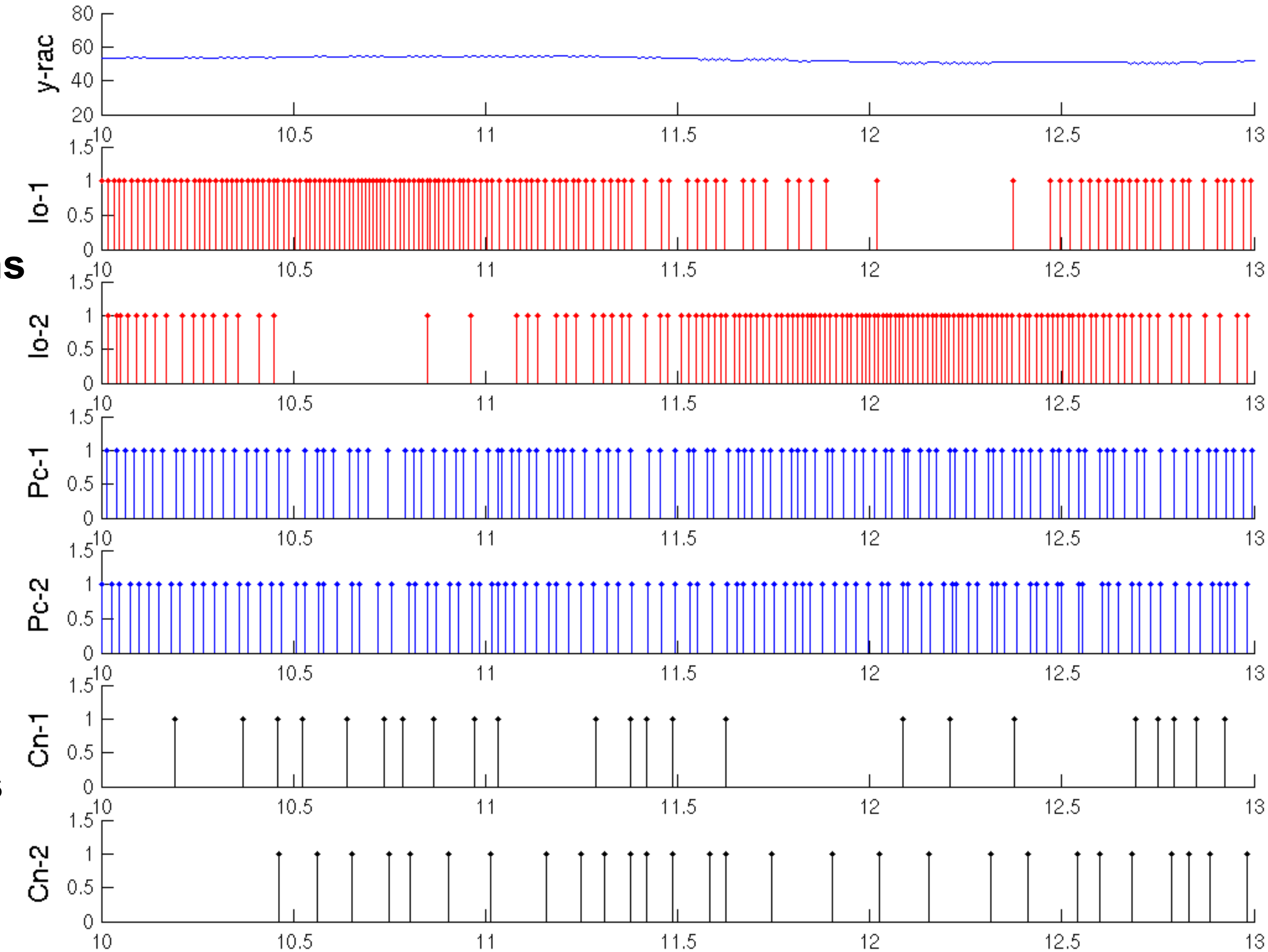
Tenns spiking neural network simulator (Altjira Software)

Racquet position

Inferior olive neurons

Purkinje cells

Cerebellar nucleus neurons



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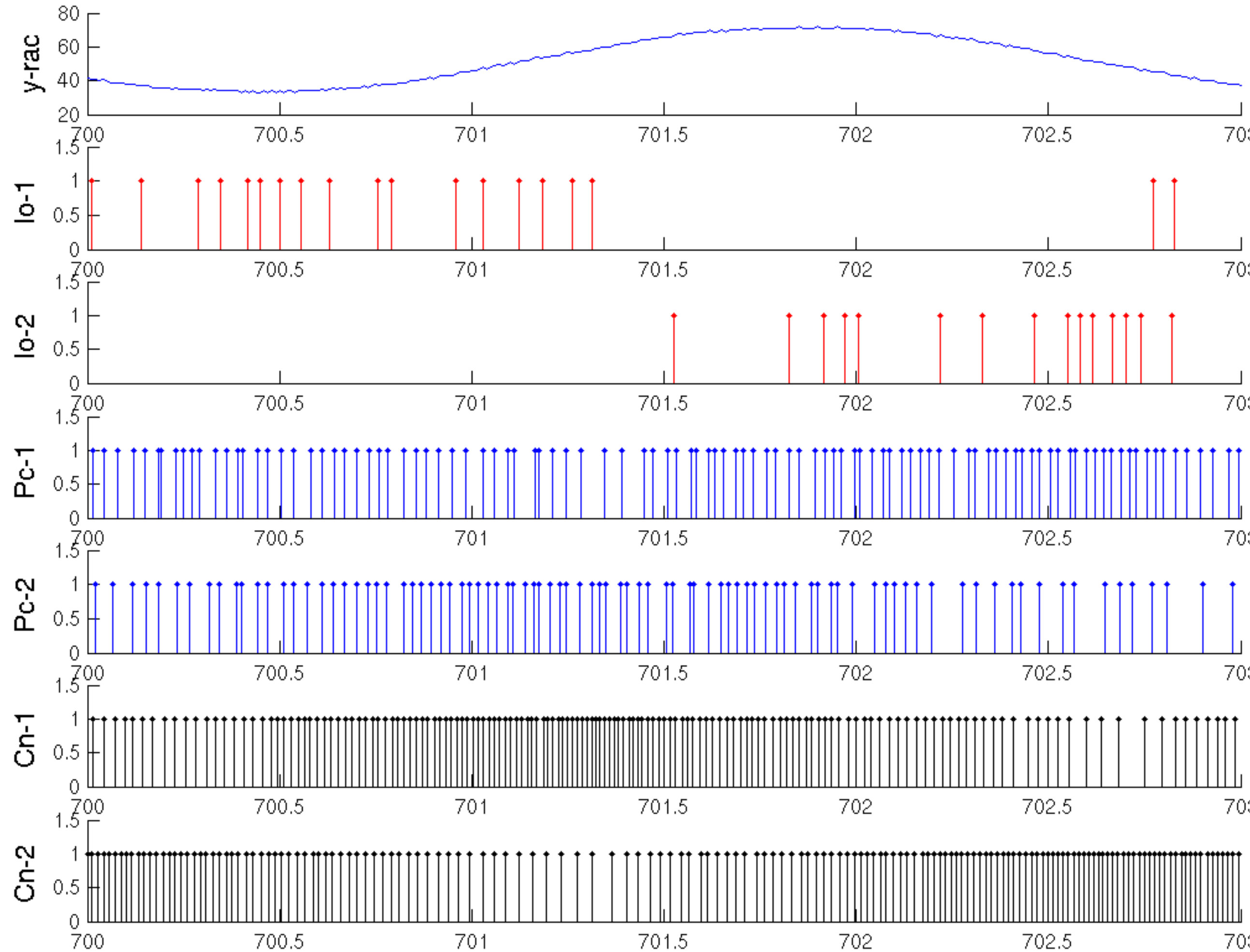
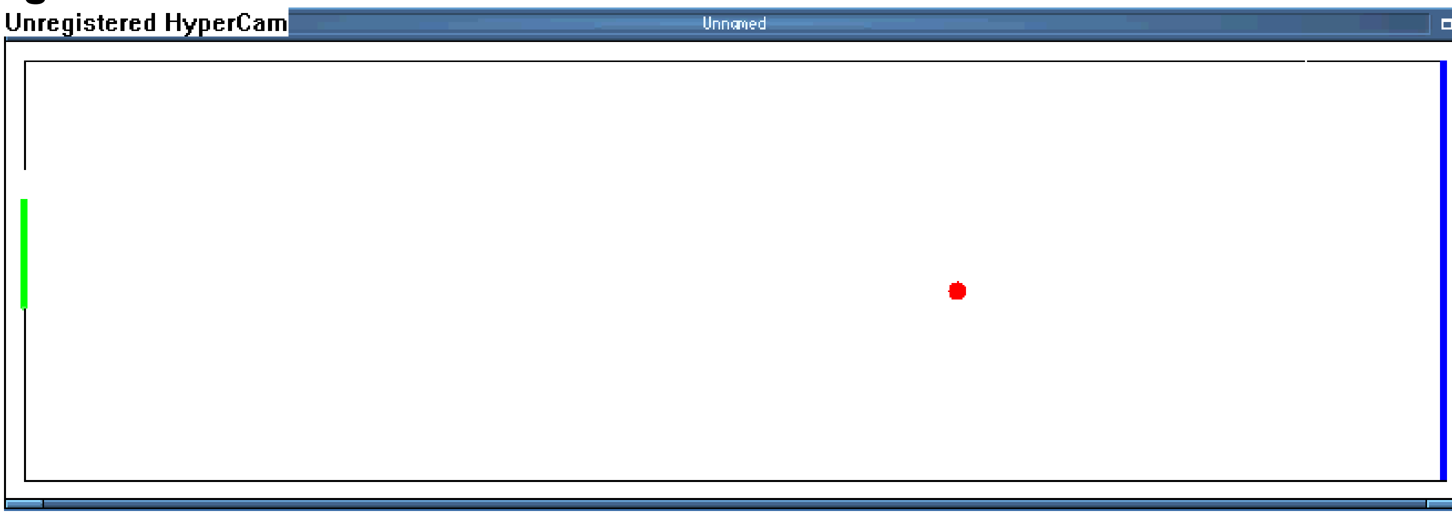
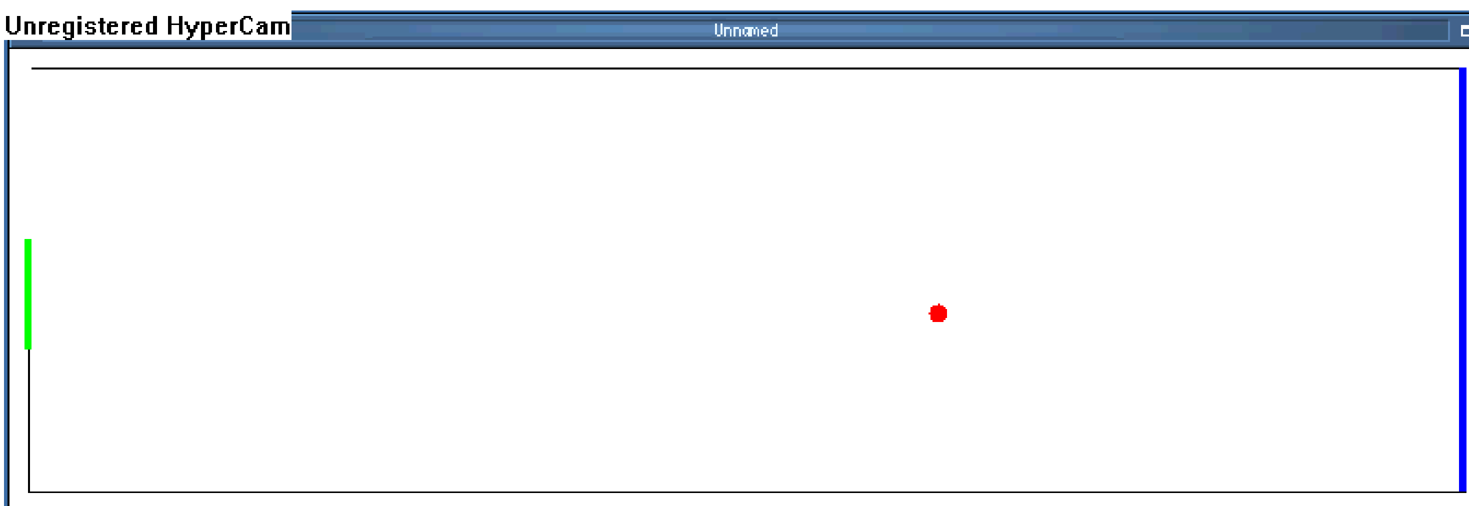


Cerebellar pong player

Before learning



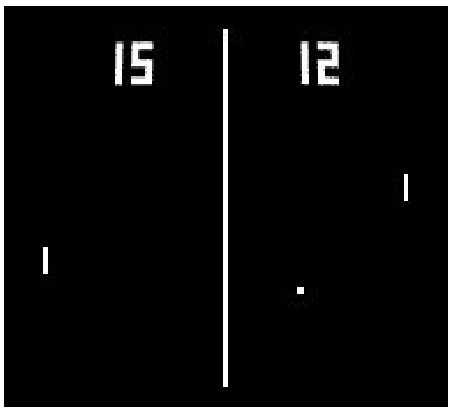
After



Task extension: mixing simulated with real

A robot playing videogames

Pong, 1972



Computer

simulated/ real systems: visual, auditory, touch →

Spiking cerebellar model

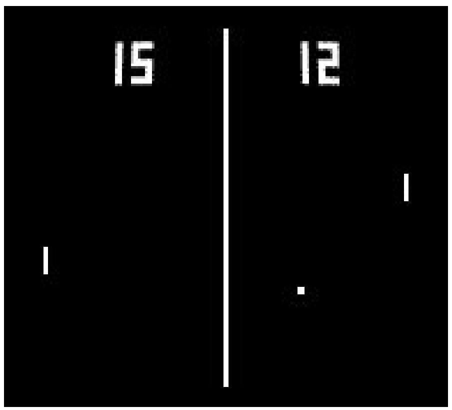
Computer, FPGA

↕

← Robot movement, action

Further extension: air-table hockey

Air-table hockey



real systems:
visual, auditory, touch →

Spiking cerebellar model

Computer, FPGA

← Robot movement, action

Efficient Implementation

Hardware

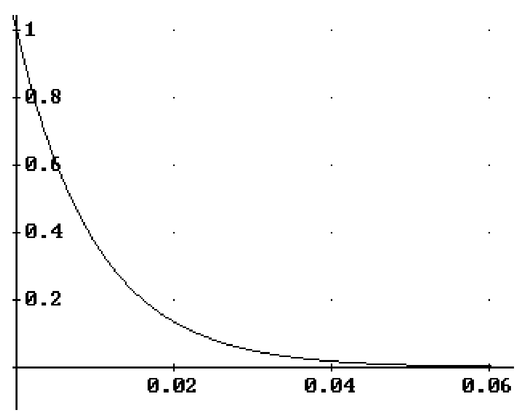
Natural Neuron characteristics incorporated in developed hardware

Synapses as conductances (shunting or multiplicative synapses)

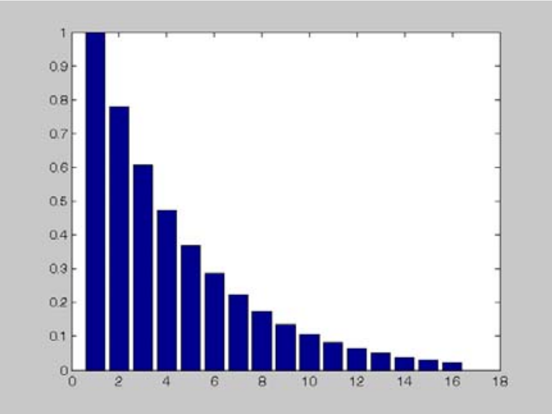
$$V_x = V_x + \left(E_{exc} - V_x\right) \cdot \sum I_i^{exc} \cdot \omega_{ij}^{exc} + \left(V_x - E_{inh}\right) \cdot \sum I_i^{inh} \cdot \omega_{ij}^{inh}$$

Time-dependent synaptic characteristic: gradual injection of charge.

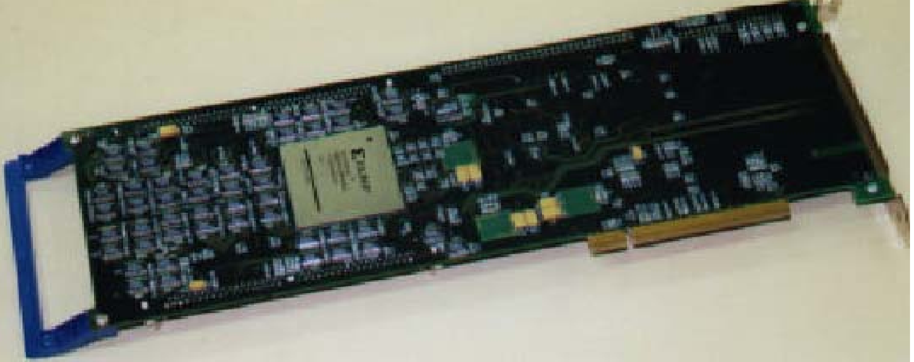
$$F_{syn} = \overline{F_{syn}} \cdot e^{-\left(t - t^{(f)}\right) / \tau}$$



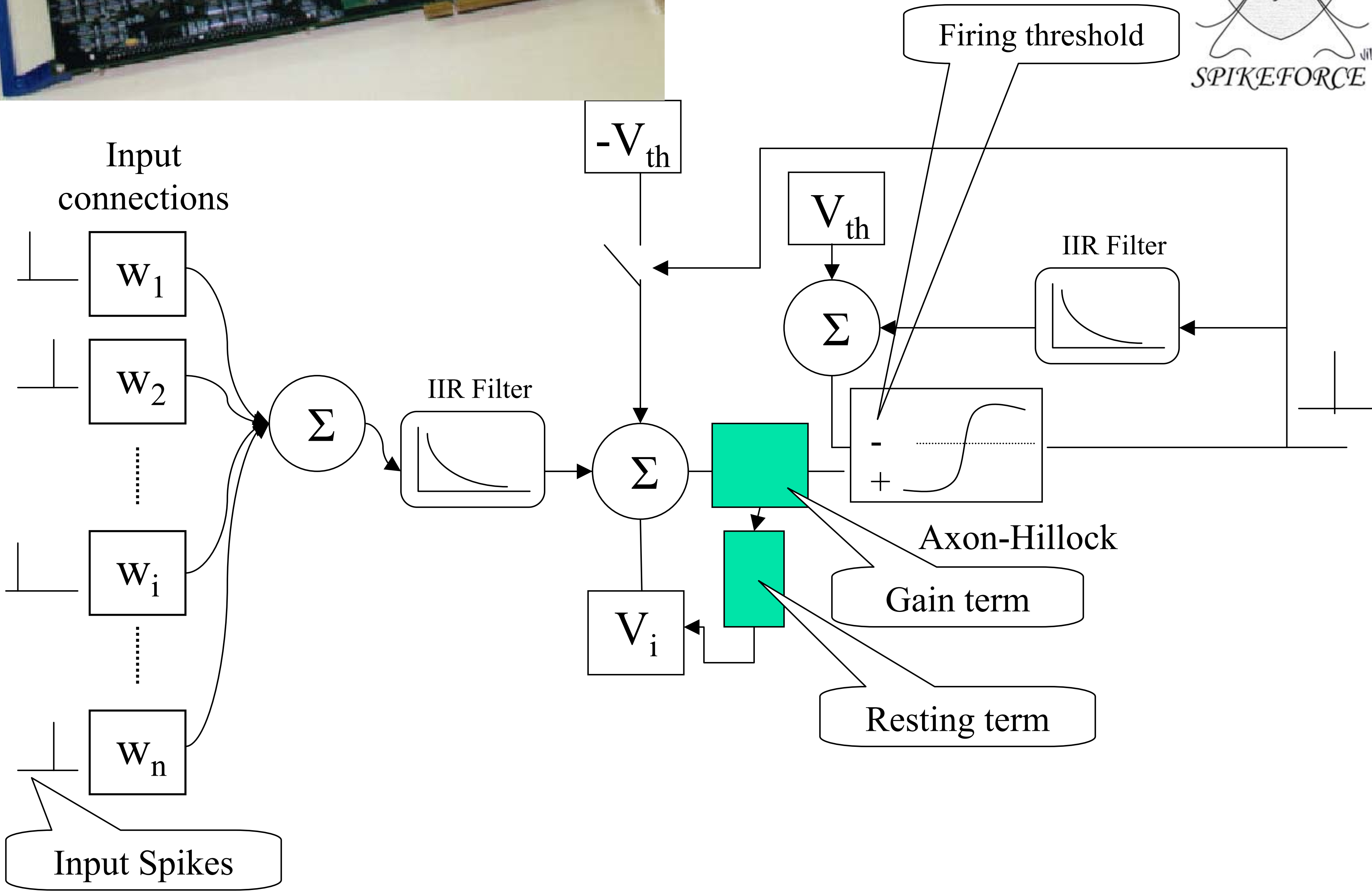
Analitical expression



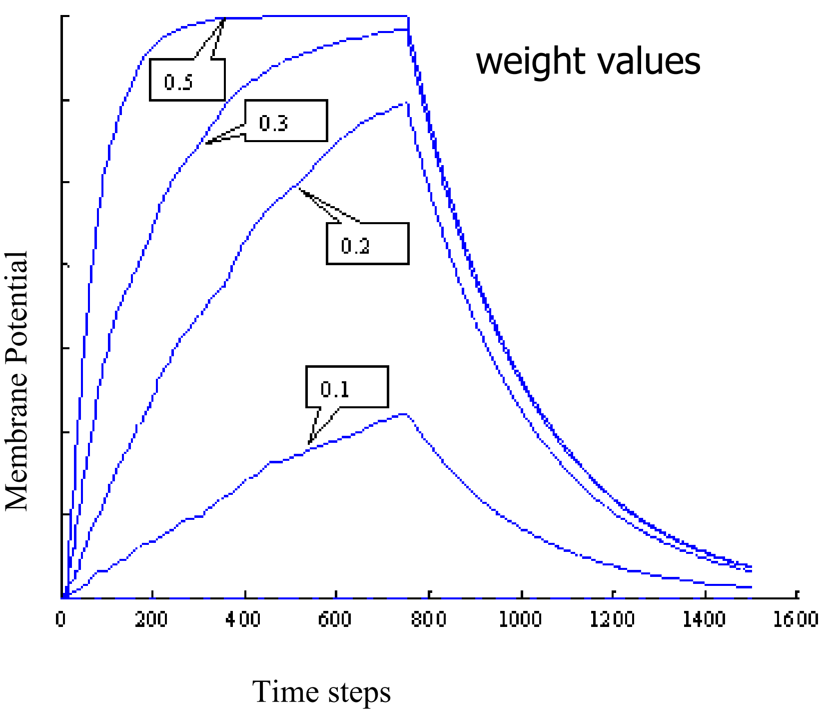
16 values approach

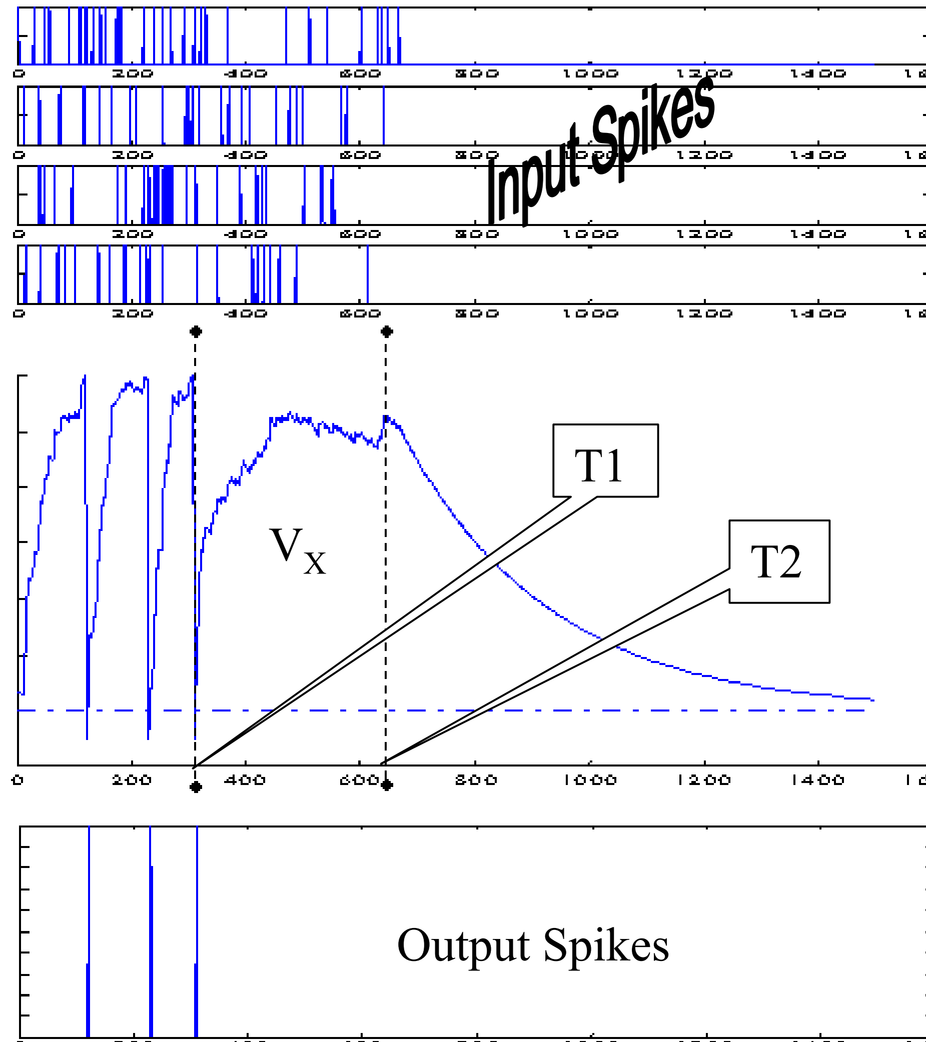


SPIKEFORCE


Firing threshold
-Vth
Vth
Input
connections
IIR Filter
IIR Filter
W1
W2
Wi
Wn
Σ
Σ
Σ
-
+
Axon-Hillock
Gain term
Vi
Resting term
Input Spikes

Experimental Results





Preliminary Implementation (NRH approach)

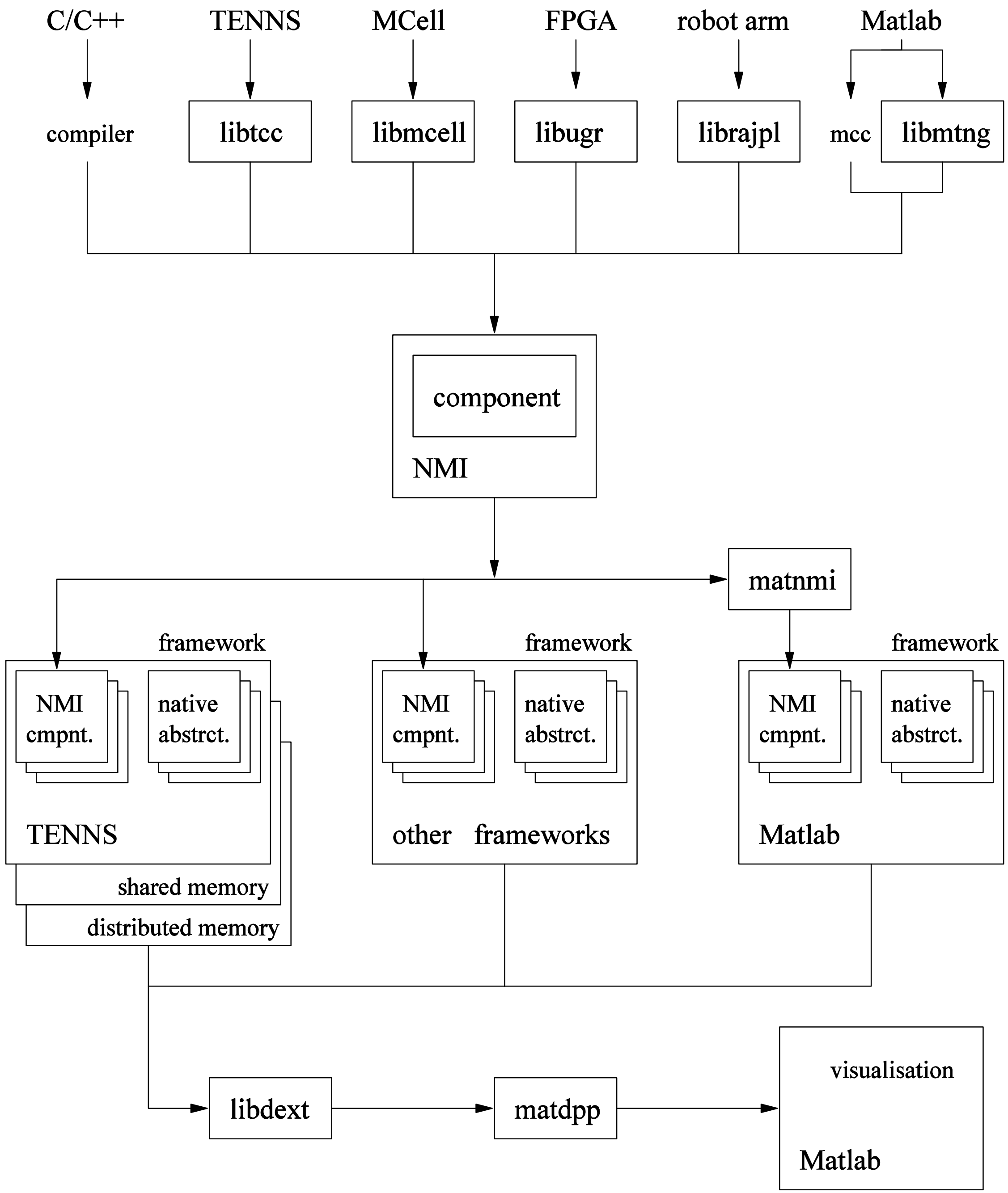
Table 1. Implementation cost and computing time of different neural configurations.

Inputs per Neuron	Functional Units	Total Num. of Neu.	Number of Slices	Max. Clock freq. (Mhz)	Computing time (ms)	Embedded Memory Blocks (EMB)
2	2	4	1832 (9%)	23.3	0.0055	24 (15%)
2	2	1024	1966 (10%)	20.2	1.4	65 (60%)
8	4	8	5476 (28%)	20.9	0.0011	36 (22%)
8	4	1760	5595 (29%)	20.5	2.9	160 (100%)
8	8	16	12011 (62%)	18.7	0.0018	36 (22%)
8	8	1760	12010 (62%)	18.7	4.5	160 (100%)

Supporting Focus Group Software Framework

Outline:

- **Network Model Interface (NMI)**


C/C++
TENNS
MCell
FPGA
robot arm
Matlab
compiler
libtcc
libmcell
libugr
librajpl
mcc
libmtng
component
NMI
matnmi
framework
NMI cmpnt.
native abstrct.
TENNS
shared memory
distributed memory
framework
NMI cmpnt.
native abstrct.
other frameworks
framework
NMI cmpnt.
native abstrct.
Matlab
libdext
matdpp
visualisation
Matlab

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