Cooperation and Competition in VLSI Networks of Spiking Neurons

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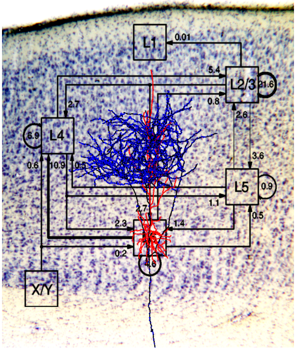
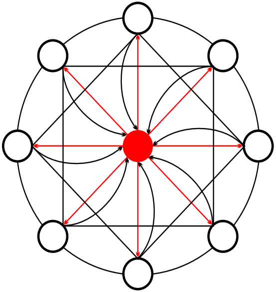
Institute of Neuroinformatics
University | ETH Zurich

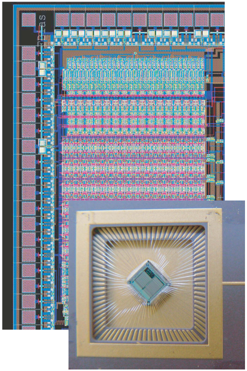
Neuromorphic Engineering Workshop
Telluride, 7 July 2007

Neural computation → neurotechnologies



Binzegger et al. 2004

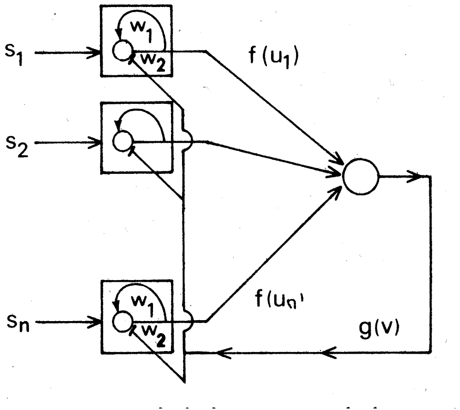




Cooperative-Competitive Networks (CCNs)

1977 **Arbib and Amari**

Competition and Cooperation in Neural Nets



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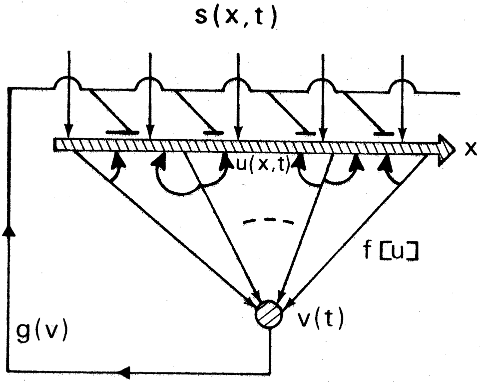

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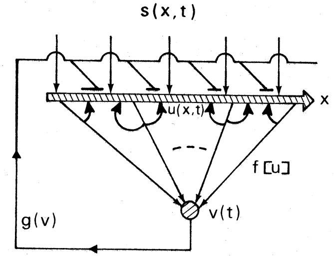
Dynamic Neural Fields:
The neural network is described as a continuous medium rather than a set of discrete neurons. A differential equation describes the activation of the *neural tissue* at different positions in the continuous network.



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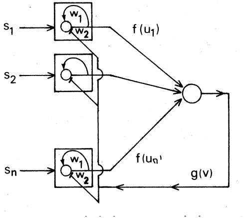
- Excitatory units compete through the activation of the inhibitory unit.



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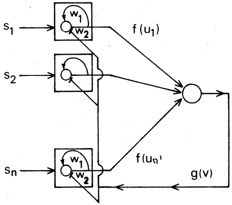
- Excitatory units compete through the activation of the inhibitory unit.
- Eventually the unit which receives the maximum input stimulus win and remain in the excited state, while all other units stay in the quiescent state: WINNER-TAKE-ALL (WTA).



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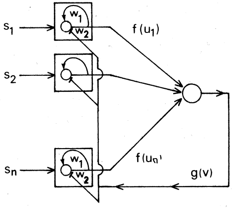
- Eventually the unit which receives the maximum input stimulus win and remain in the excited state, while all other units stay in the quiescent state: WINNER-TAKE-ALL (WTA).
- Self-excitation maintains the winning unit in the excited state even if another input stimulus becomes bigger than one to the winning unit (unless the difference is very large): HYSTERESIS.

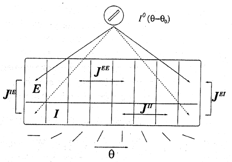


Cooperative-Competitive Networks (CCNs)

1998 **Hansel and Sompolinsky**

Modeling Feature Selectivity in Local Cortical Circuits

- Each neuron is described by a single continuous variable which represent its activity level over a short period of time: RATE MODEL.



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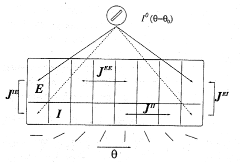

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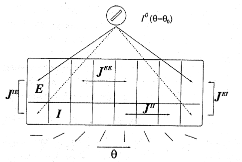
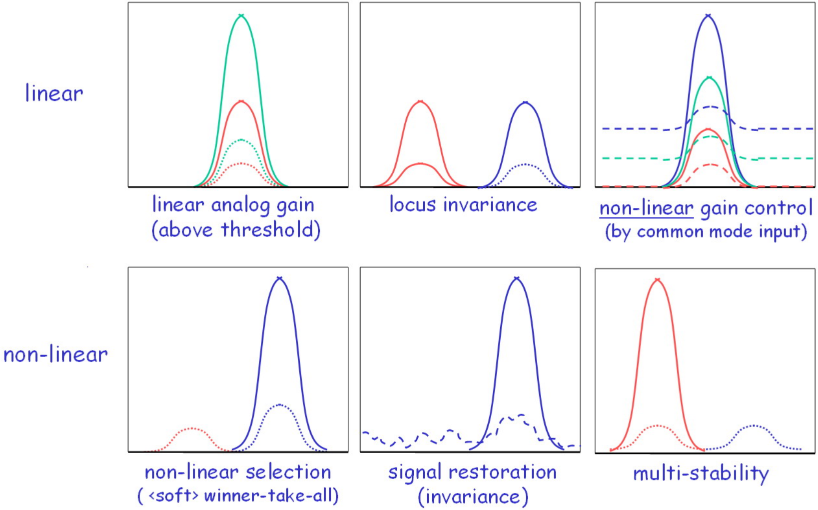
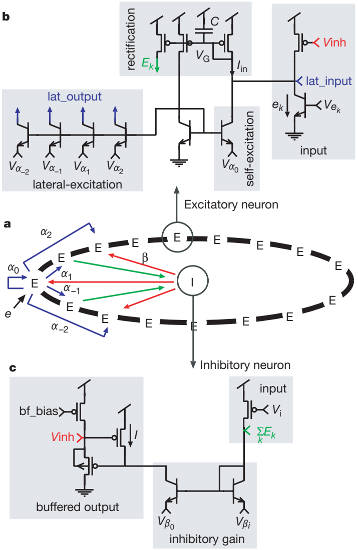


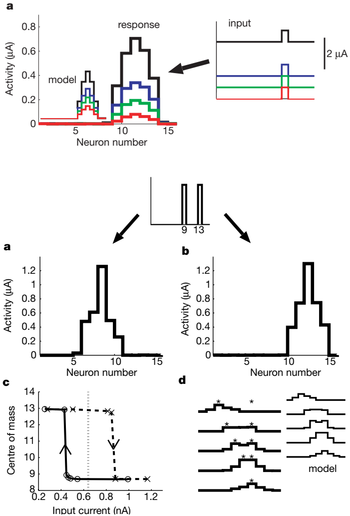
- Each neuron is described by a single continuous variable which represent its activity level over a short period of time: RATE MODEL.
- Each neuron is selective to a particular range of orientations and it fires maximally when a particular value of orientation is present in the input stimulus (preferred orientation).
- Cooperative interactions are strongest in magnitude for neurons that have identical preferred orientation and get weaker as the difference between preferred orientation increases.

Rich linear and non-linear set of behaviors



Linear–Threshold–Unit WTA Circuit





Hahnloser et al. *Digital selection and analogue amplification coexist in a cortex-inspired silicon circuit*, Nature, 2000

VLSI *Spiking* Cooperative-Competitive Networks

- DeYong et al. 1992 *The Design, Fabrication, and Test of a New VLSI Hybrid Analog-Digital Neural Processing Element*
  - all-to-all inhibitory connections
  - 4 neurons
- Hylander et al. 1993 *VLSI implementation of Pulse Coded Winner Take All Networks*
  - global inhibition
  - 3 neurons
- Indiveri et al. 2001 *A Competitive Network of Spiking VLSI Neurons*
  - global inhibition and first neighbors lateral excitation
  - 32 neurons

VLSI *Spiking* Cooperative-Competitive Networks

- Oster and Liu 2004 *A Winner-take-all Spiking Network with Spiking Inputs*
  - all-to-all inhibitory connections and self excitation
  - 64 neurons
- Chicca et al. 2004 *An Event Based VLSI Network of Integrate-and-Fire Neurons*
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- Abrahamsen et al. 2004 *A Time Domain Winner-Take-All Network of Integrate-and-Fire Neurons*
  - global reset
  - 3 WTA: 2×48 neurons + 1×4 neurons

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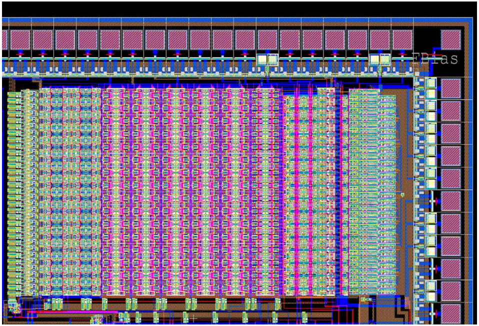
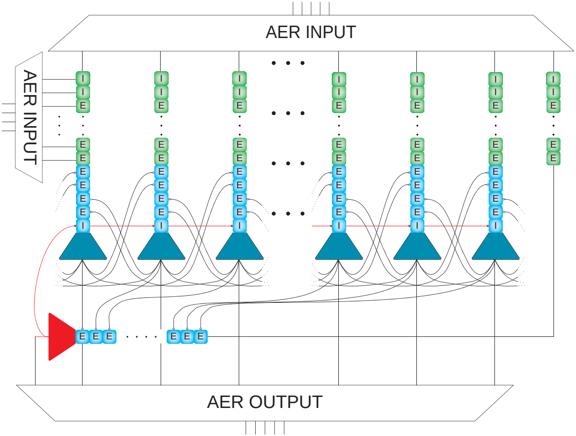
The IFRON Chip

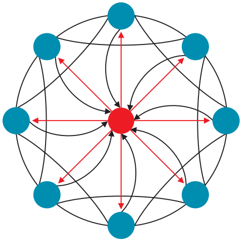


Technology:	AMS 0.8μm
Size:	$1.1 \times 1.9mm^2$
Neurons:	32
AER Synapses:	16×32
Local Synapses:	6×31

E. Chicca, G. Indiveri, and R. J. Douglas, "An event based VLSI network of integrate-and-fire neurons," in *Proceedings of IEEE International Symposium on Circuits and Systems*. IEEE, 2004, pp. V–357–V–360.

The IFRON Chip – Network architecture





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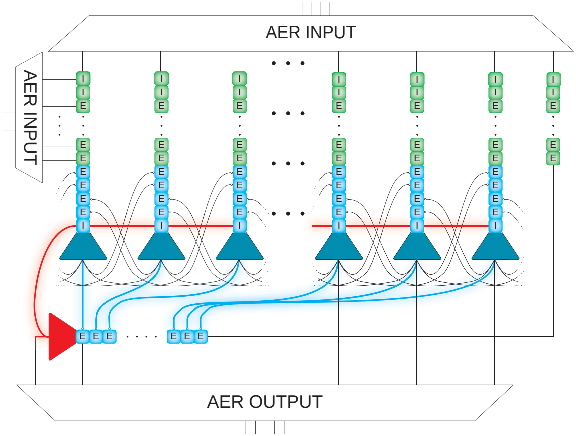

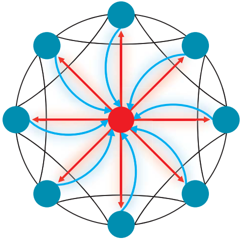

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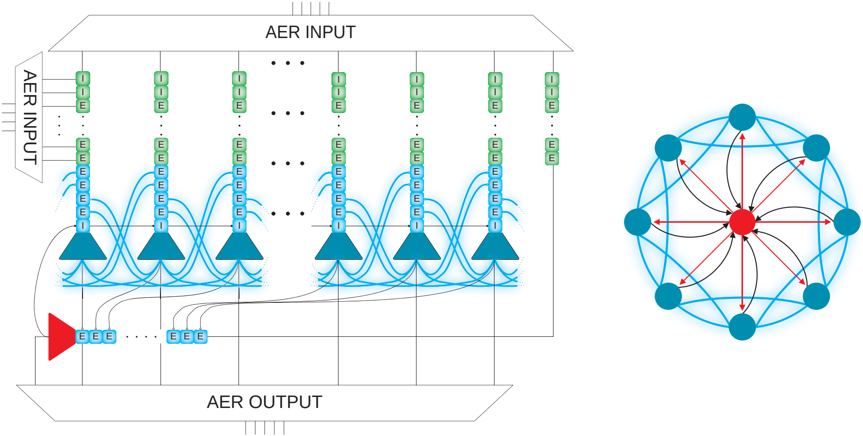

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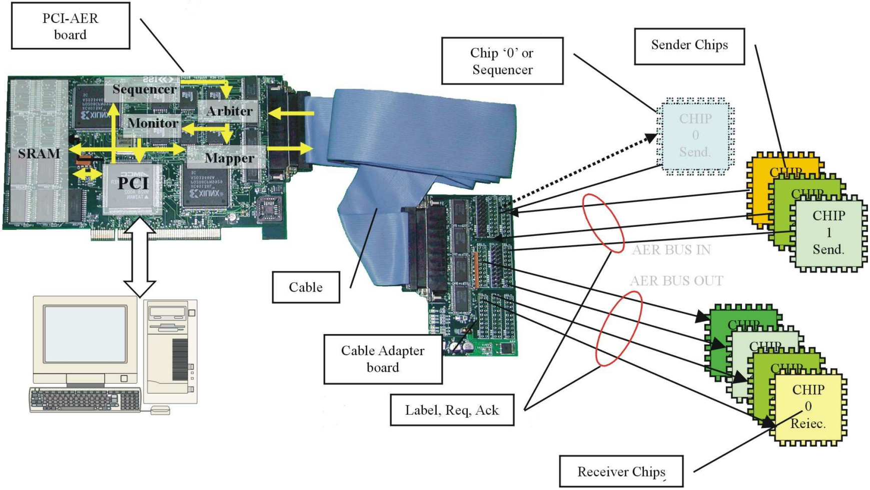
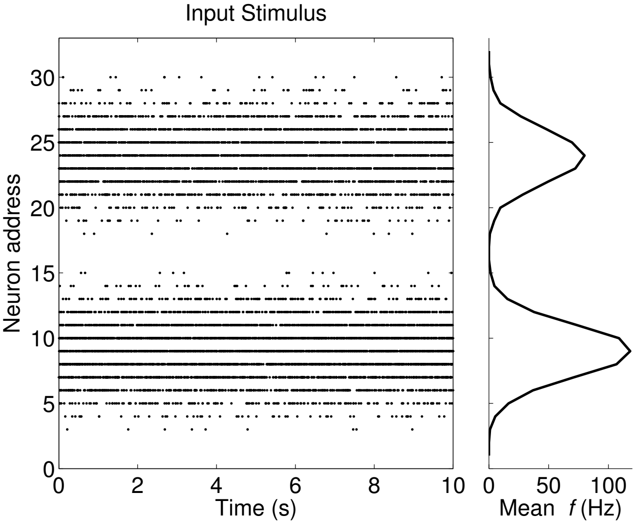
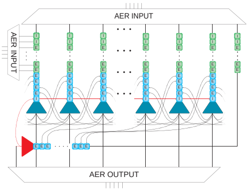
A Spike–Based neuromorphic VLSI System



E. Chicca, V. Dante, A. M. Whatley, P. Lichtsteiner, T. Delbruck, G. Indiveri, P. Del Giudice and R. J. Douglas, "Multi–chip Pulse Based Neuromorphic Systems: A Communication Infrastructure and an Application Example" submitted to *IEEE Circuits and Systems I*, 2006.

Experimental Results





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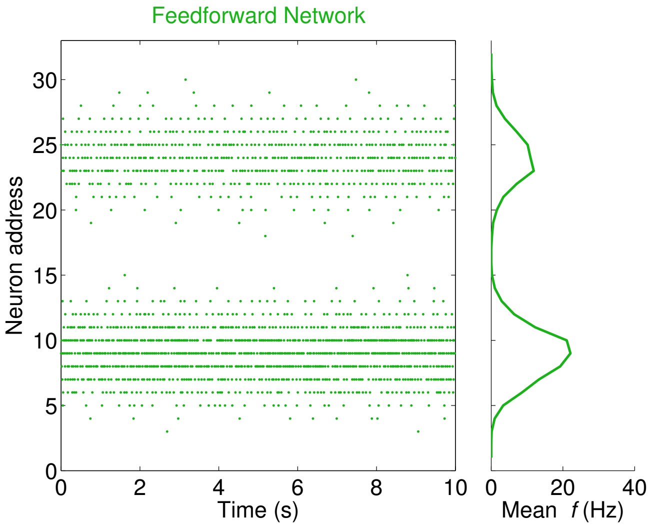

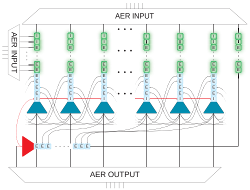

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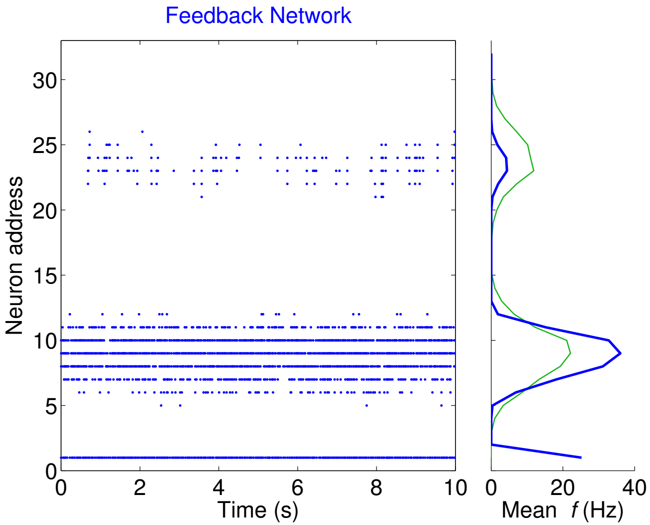

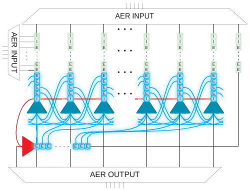

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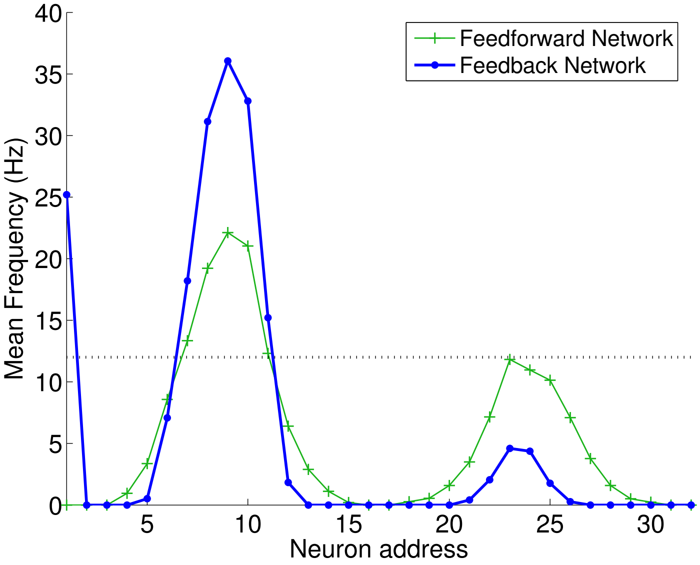

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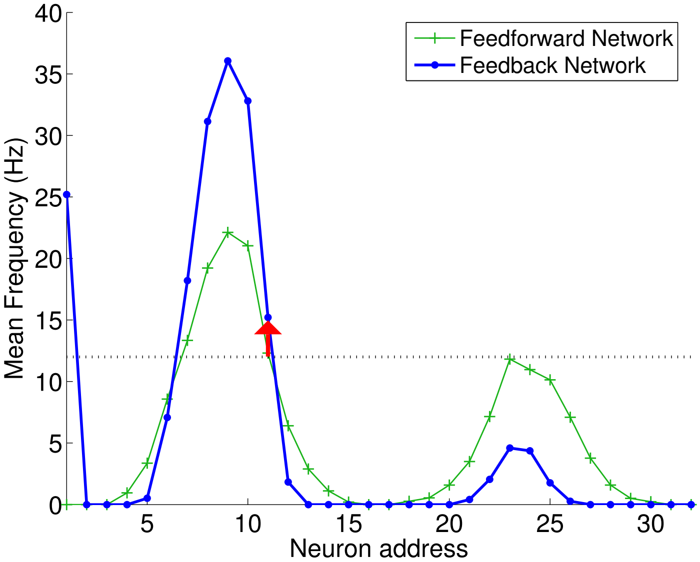

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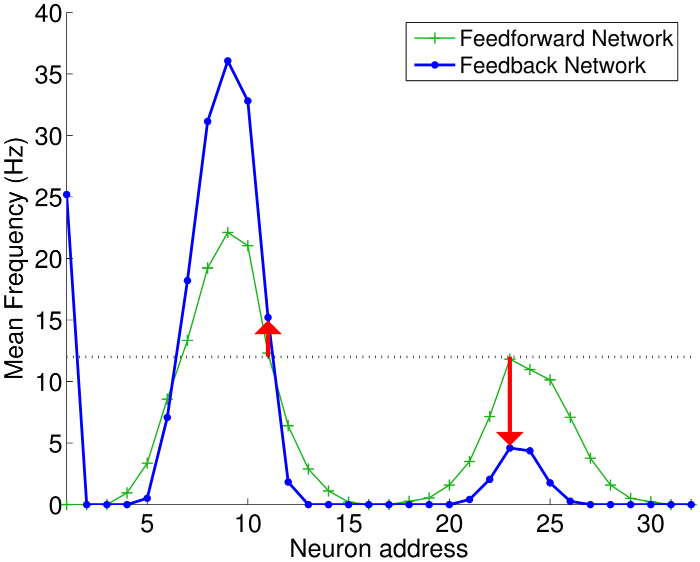
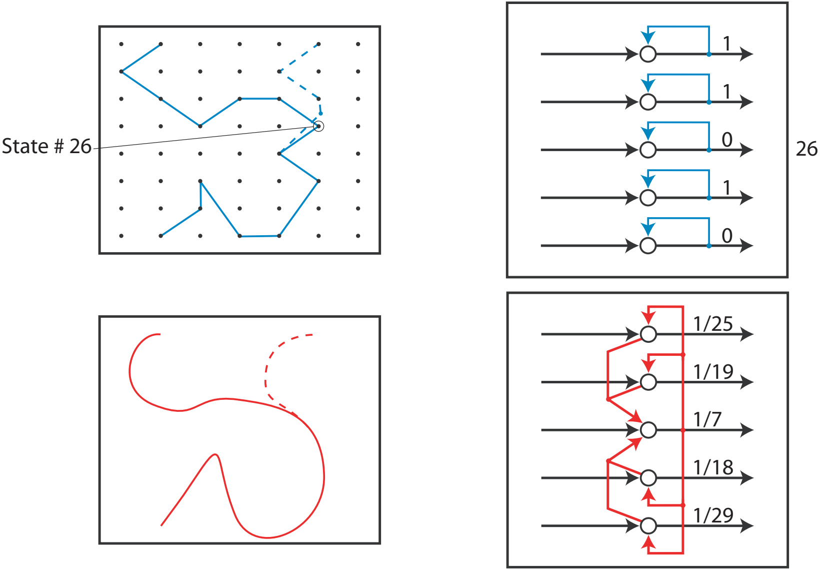
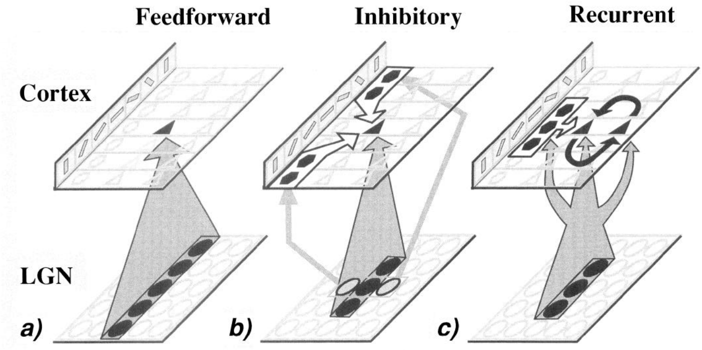


Digital versus neural systems



CCNs Applied to Orientation Selectivity

1995 **Somers et al.**
An Emergent Model of Orientation Selectivity in Cat Visual Cortical Simple Cells



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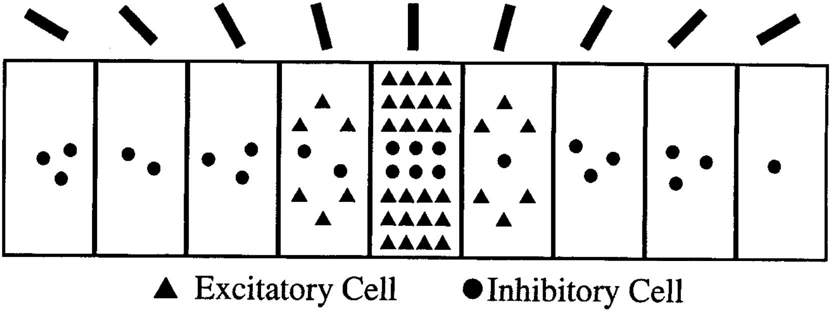

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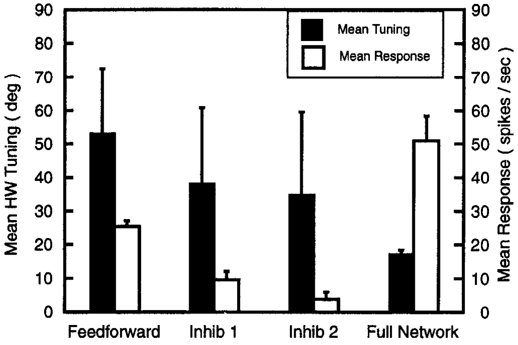
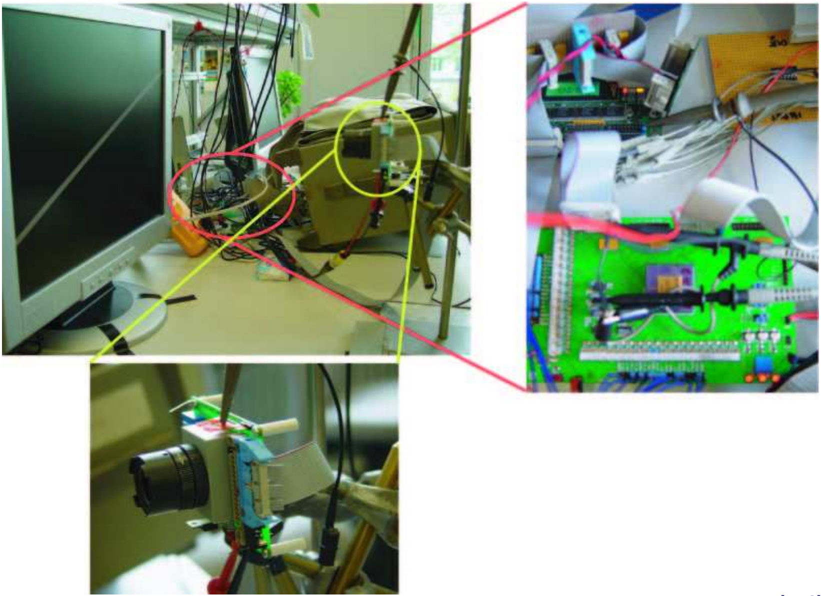


Orientation Selectivity Experiment



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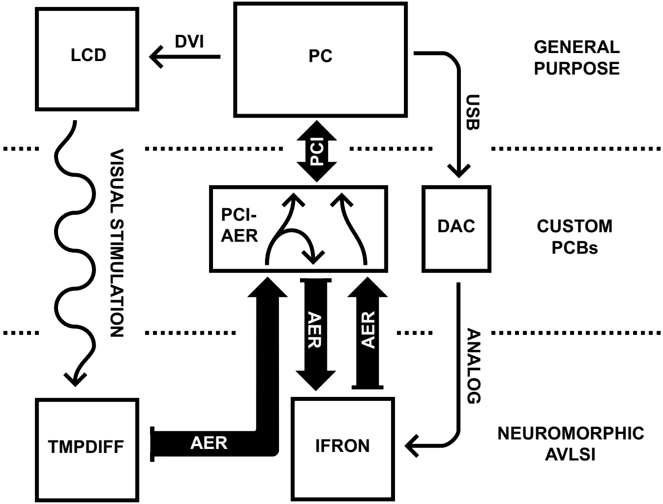

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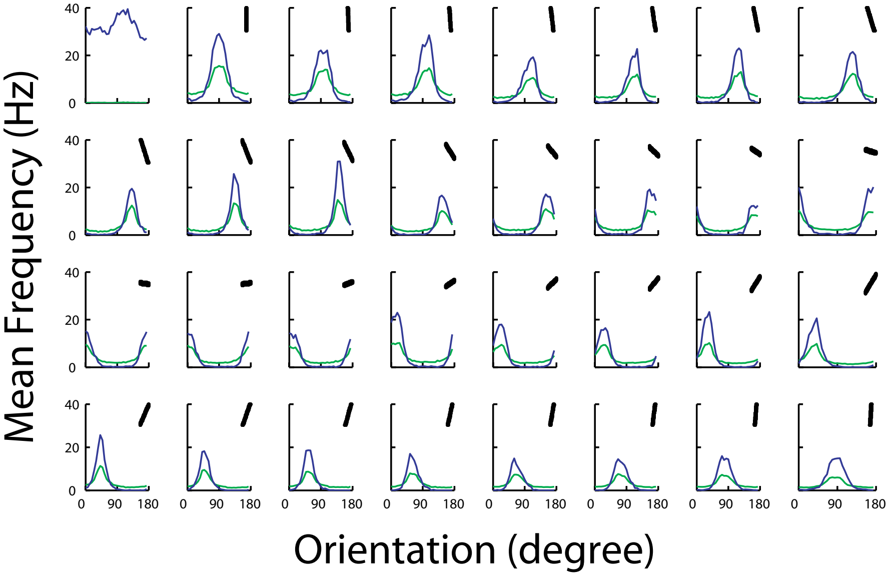
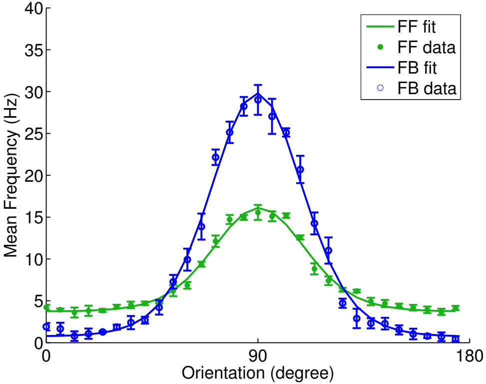


Least–squares Fit of the Tuning Curves



	FF	FB
A (*Hz*)	16	30
HWHH (°)	30	23
R–square (%)	98.7	99.3

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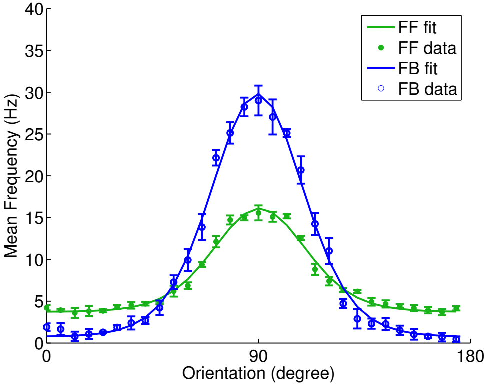

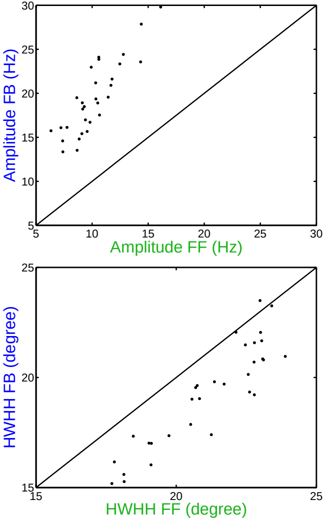

CCN Summary

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- VLSI spiking CCNs are robust to noise and perform computation in real-time.
- Possibility to use the time domain as additional dimension to perform computation.
- General computational module that can be used for sensory input filtering, learning enhancement, relational networks.

Constrains Satisfaction and Relational Networks using CCNs

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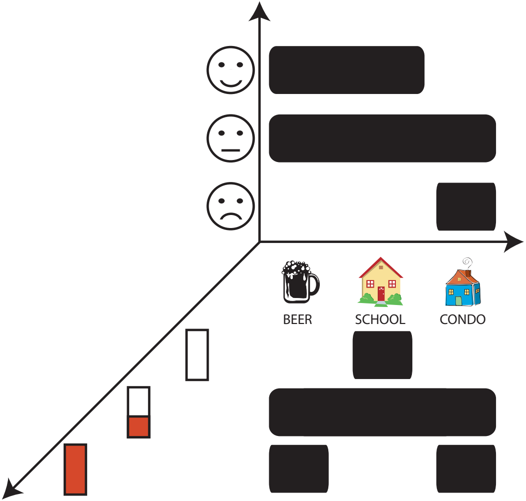
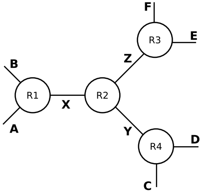
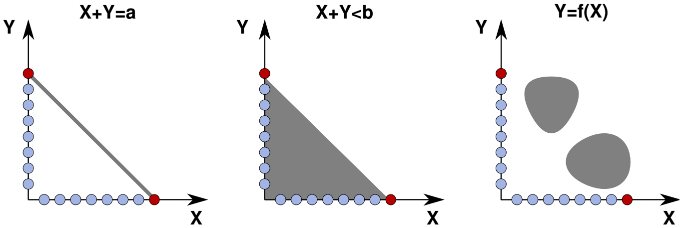


Simple relations for computation





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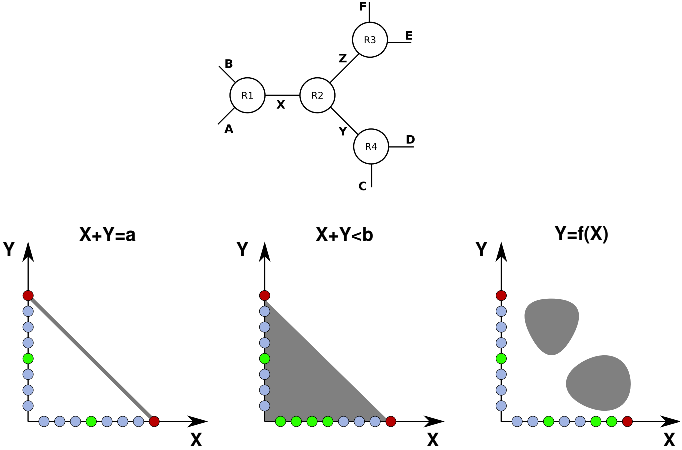

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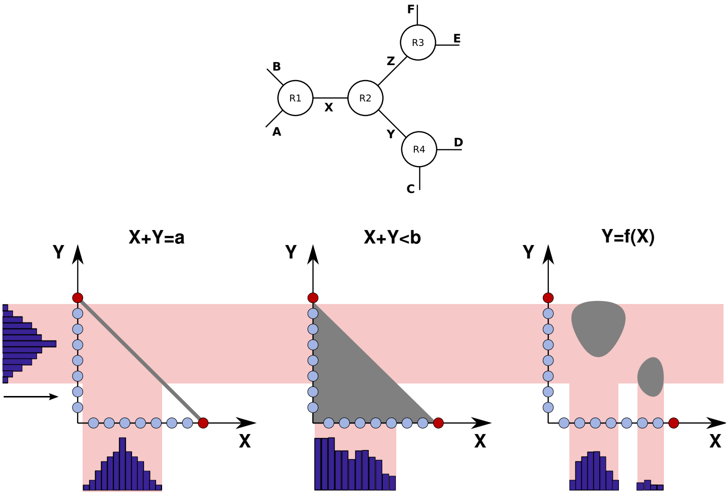
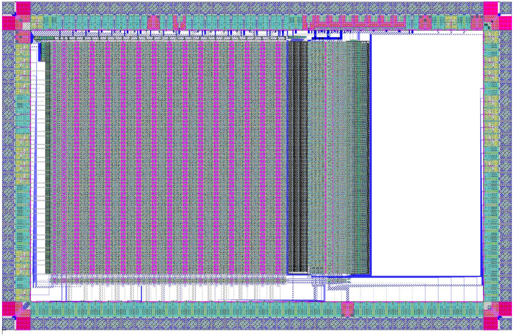
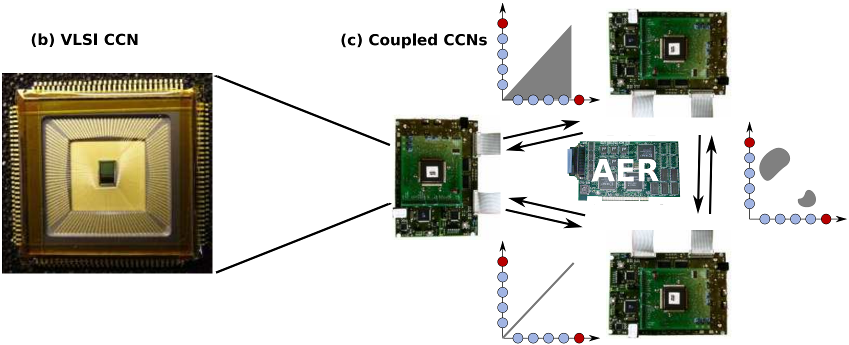


The IFSLWTA chip

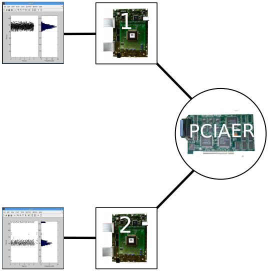


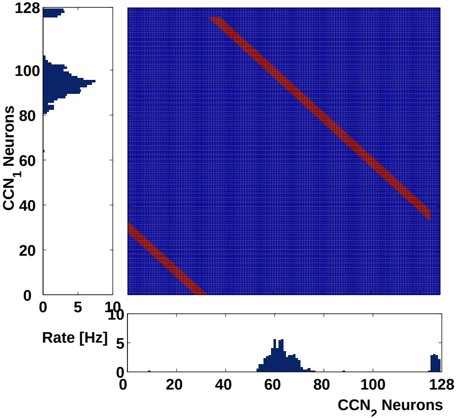
Technology:	AMS 0.35μm
Total area:	$3.94mm \times 2.54mm$
Core area:	$2.6mm \times 1.9mm$
Neurons:	128 (124 exc. + 4 inh.)
Synapses:	32×128
Dendritic tree multiplexer:	32x128 | 64x64 | ... | 2048x2 | 4096x1|

Address Event Representation (AER) used to implement contraints between CCNs

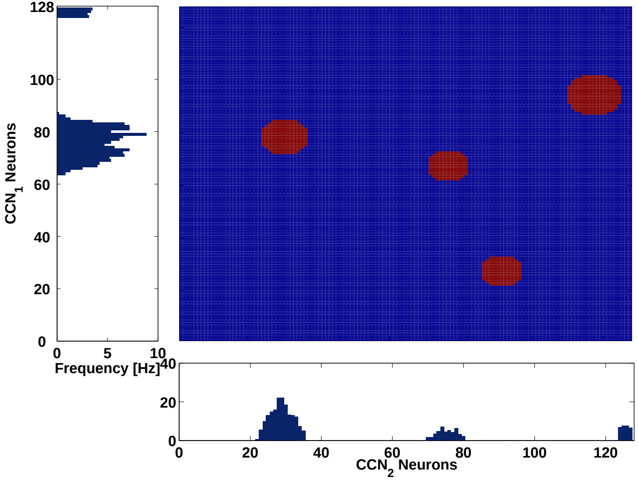


Shifted Inverse Identity Relation $X + Y = a$





Blobby Connectivity Implements Analog Input to Discrete Output Relation



A 2D Spiking Cooperative-Competitive Network - Motivations

- Implement several relations on a single chip.

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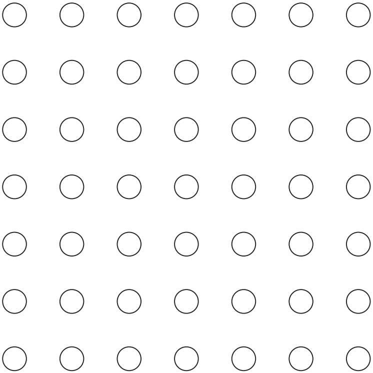
- Implement several relations on a single chip.
- 2D feature selectivity.
- Explore different connectivity patterns between the excitatory and the inhibitory populations.

2D Network - Cooperation



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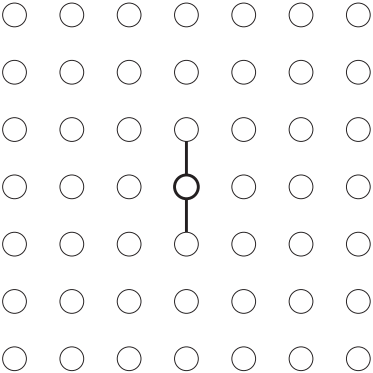
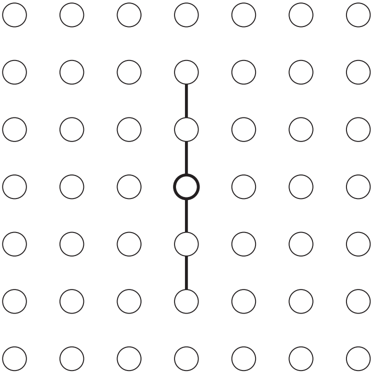
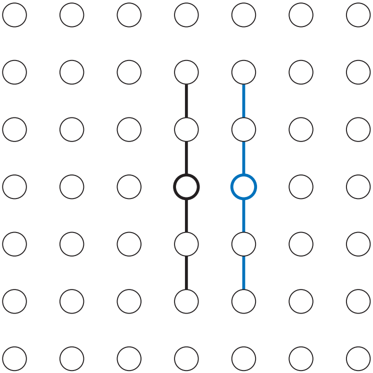


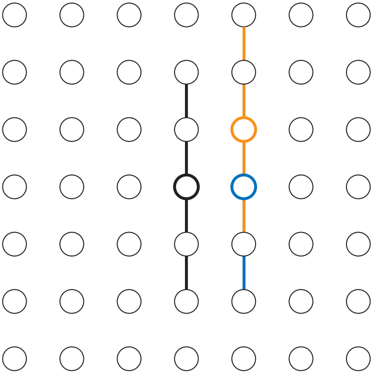
2D Network - Cooperation



2D Network - Cooperation



2D Network - Cooperation



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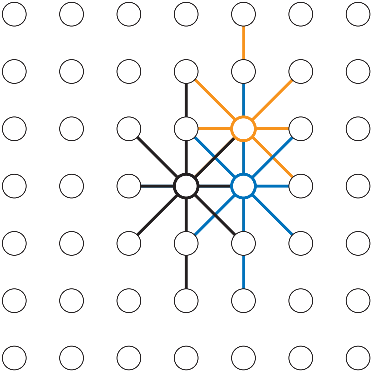
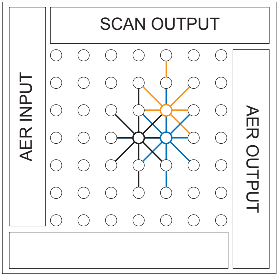


2D Network - Cooperation

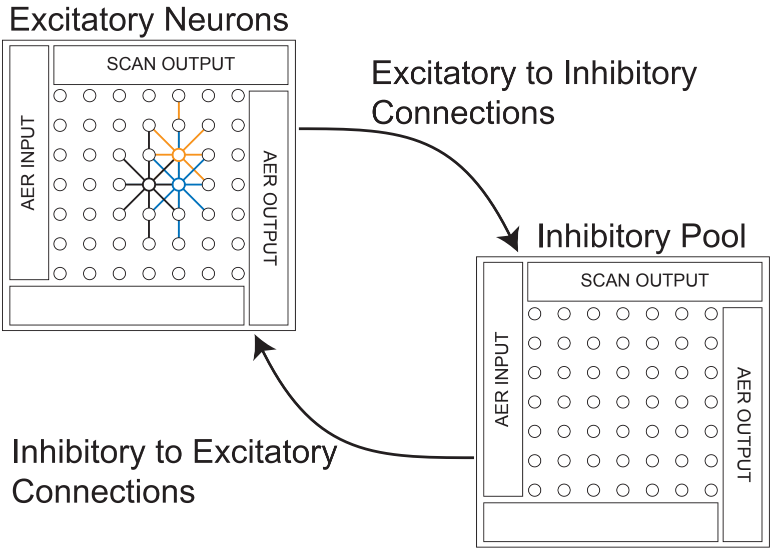


Single cell components

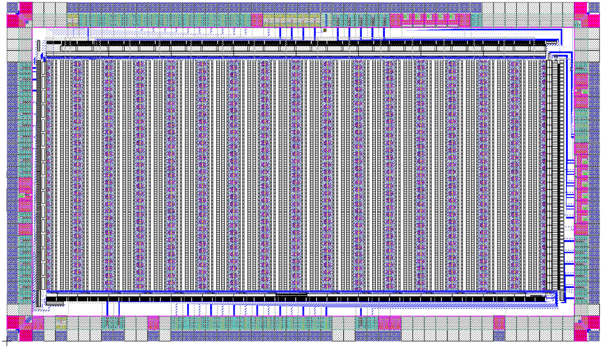
1 I&F neuron
1 self-excitatory synapse
1 local excitatory integrator
10 nMOS for local excitory weights
2 nMOS + 1 pMOS for membrane voltage output

2 AER excitatory synapses
1 AER inhibitory synapse

2D System - Cooperation and Competition



The 2DIFWTA chip



Technology:	AMS 0.35μm
Area:	$5.14mm \times 2.94mm$
Neurons:	2048 (32×64)
AER Synapses:	2048×3
Local Synapses:	2048×11

Conclusions and Outlook

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  - We can implement VLSI spiking CCNs.
  - In the mean rate domain, VLSI spiking CCNs perform as well as models.
  - Time domain can be exploited.

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- **2D VLSI spiking CCN chip**
  - 2D feature selectivity
  - Arbitrary connectivity between excitatory and inhibitory populations
  - Complex relational networks

Acknowledgments

Giacomo Indiveri Rodney J. Douglas

PCI-AER Board (Hardware and Software)
Vittorio Dante Adrian Whatley

Orientation selectivity experiment
Patrick Lichtsteiner
Tobi Delbruck

Relational networks
Emre Neftci
Matthew Cook
Jean-Jacques Slotine

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Thank you ...

... for your attention.

Cooperative-Competitive Networks (CCNs)

1969 **Kilmer, McCulloch and Blum**
Model of the role of the vertebrates' reticular formation of the brainstem in deciding the overall mode of behavior (e.g. sleeping, fighting, fleeing or feeding).

1975 **Dev**
Model of the use of stereopsis to recognize depth in space.

1976 **Didday**
Model of how the frog's tectum decides the snapping position.