How activity regulates connectivity:
The self-organized growth of synfire patterns

René Doursat

Brain Computation Laboratory
Department of Computer Science
University of Nevada, Reno

Elie Bienenstock

Dept. of Neuroscience &
Division of Applied Math.
Brown University

References

René Doursat (1991) *A contribution to the study of representations in the nervous system and in artificial neural networks*. Ph.D. dissertation, Université Paris VI.

Elie Bienenstock (1995) A model of neocortex. *Network*, **6**:179-224.

Doursat, R. & Bienenstock, E. (2006b) Neocortical self-structuration as a basis for learning. *5th International Conference on Development and Learning (ICDL 2006)*, May 31-June 3, 2006, Indiana Univ., Bloomington, IN.

An Epigenetic Development Model of the CNS

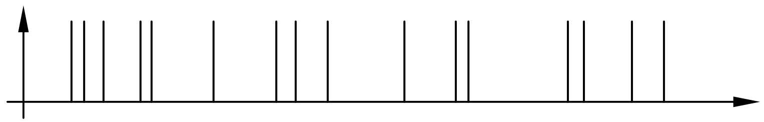
- The neural code
- Neural representations
- The compositionality of cognition
- A model of synaptic development
- Numerical simulations
- Synfire extras

An Epigenetic Development Model of the CNS

- The neural code
  - Rate vs. temporal coding
  - Interest for temporal coding
- Neural representations
- The compositionality of cognition
- A model of synaptic development
- Numerical simulations
- Synfire extras

Rate vs. temporal coding

$x_i(t)$



- Rate coding: average firing rate (mean activity)

$$\langle\, x_i(t)\, \rangle_T \;=\; \frac{1}{T} \int_0^T x_i(t)\, dt$$

- Temporal coding: correlations, possibly delayed

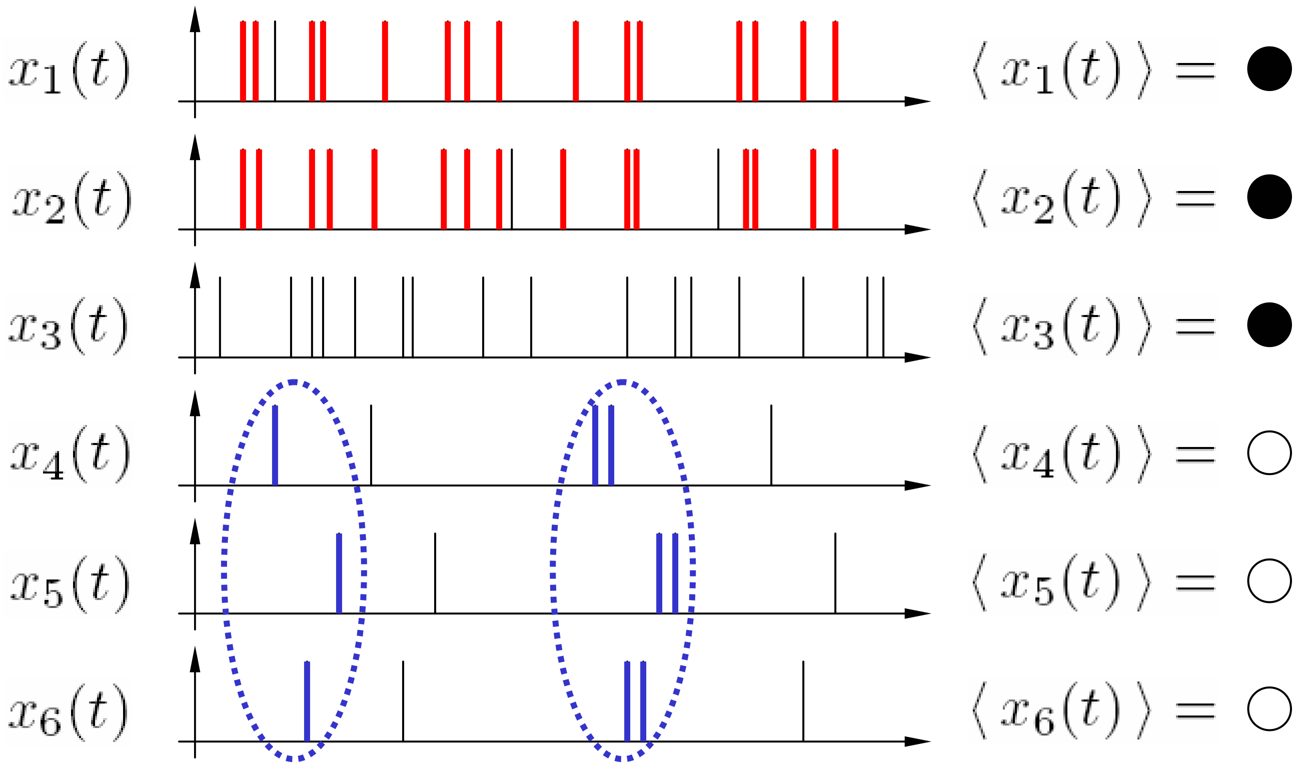
$$\langle\, x_i(t)\, x_j(t)\, \rangle$$

$$\langle\, x_i(t)\, x_j(t - \tau_{ij})\, \rangle$$

$$\langle\, x_1(t)\, x_2(t - \tau_{1,2})\; \ldots\; x_n(t - \tau_{1,n})\, \rangle$$

Christoph von der Malsburg (1981) *The correlation theory of brain function.*

Rate vs. temporal coding



$$\langle x_1(t)\, x_2(t) \rangle \gg \langle x_1(t)\, x_3(t) \rangle$$

$$\langle x_4(t)\, x_5(t-\tau_{4,5})\, x_6(t-\tau_{4,6}) \rangle$$

Interest for temporal coding

- Historical motivation for rate coding
  - Adrian (1926): the firing rate of mechanoreceptor neurons in frog leg is proportional to the stretch applied
  - Hubel & Wiesel (1959): selective response of visual cells; e.g., the firing rate is a function of edge orientation

→ rate coding is confirmed in sensory system and primary cortical areas, but increasingly considered insufficient for integrating the information

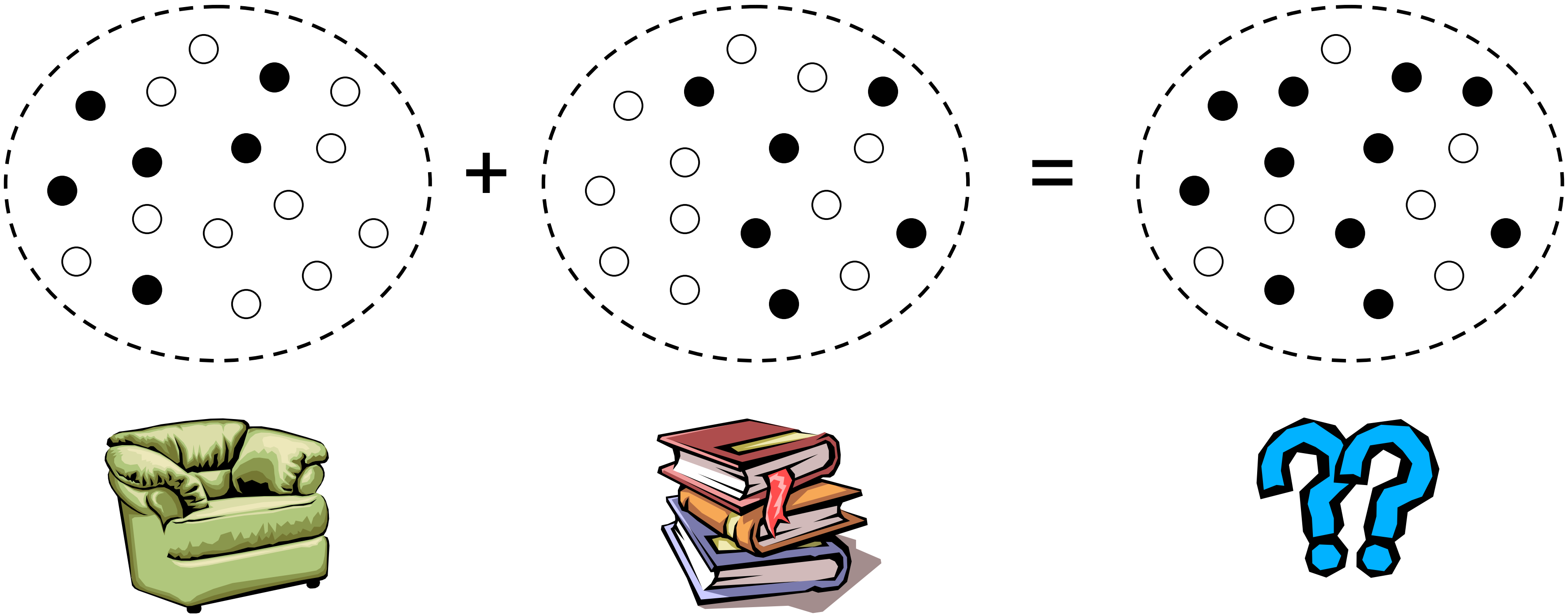
- Recent "temporal boom": a few milestones
  - Abeles (1982, 1991): precise, reproducible spatiotemporal spike rhythms, named "synfire chains"
  - Gray & Singer (1989): stimulus-dependent synchronization of oscillations in monkey visual cortex
  - O'Keefe & Recce (1993): phase coding in rat hippocampus supporting spatial location information
  - Bialek & Rieke (1996, 1997): in H1 neuron of fly, spike timing conveys information about time-dependent input
  - etc., etc.

An Epigenetic Development Model of the CNS

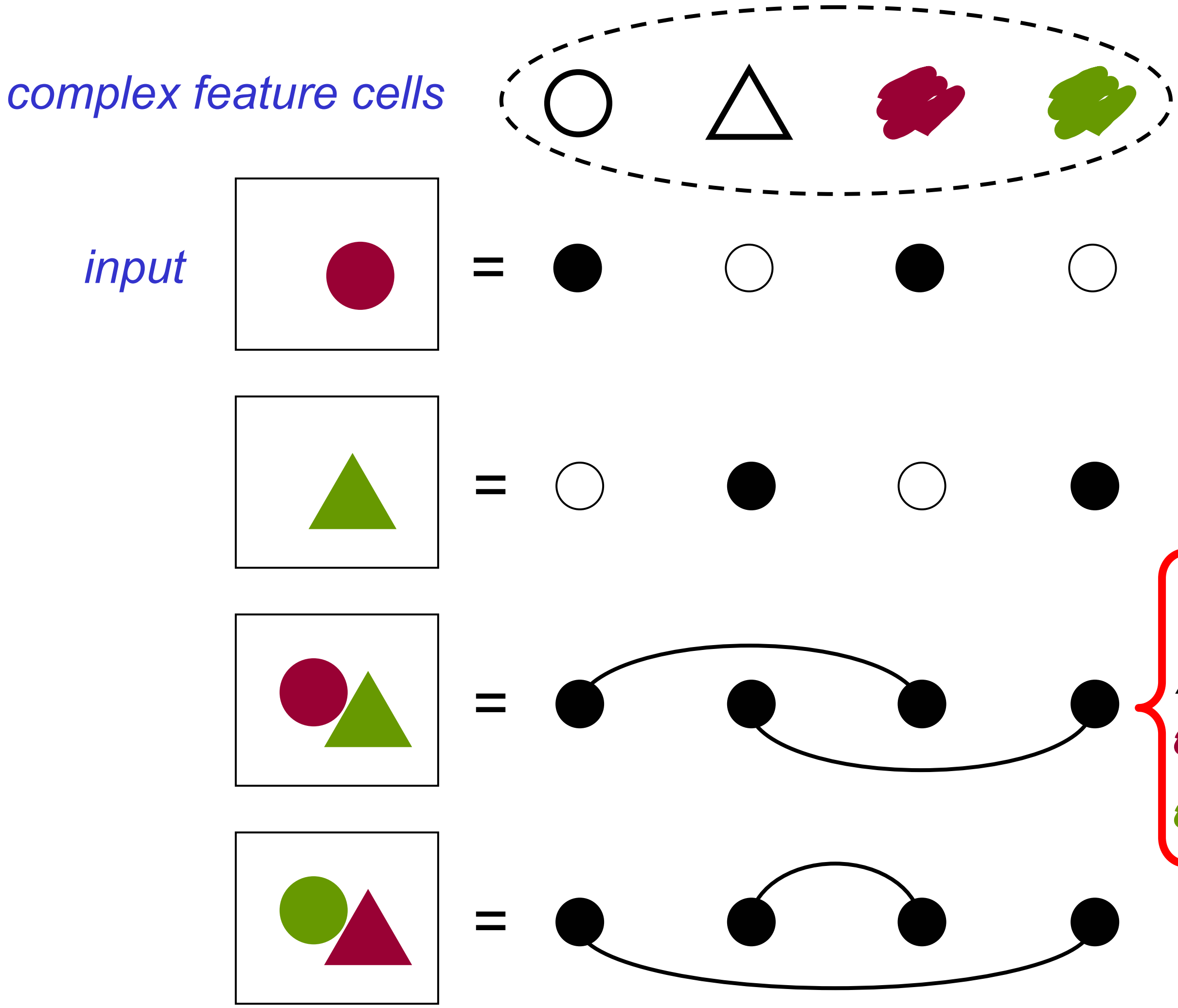
- The neural code
- Neural representations
  - Cell assemblies
  - The binding problem
  - “Grandmother” cells
  - Relational graph format
  - A molecular metaphor
- The compositionality of cognition
- A model of synaptic development
- Numerical simulations
- Synfire extras

Cell assemblies

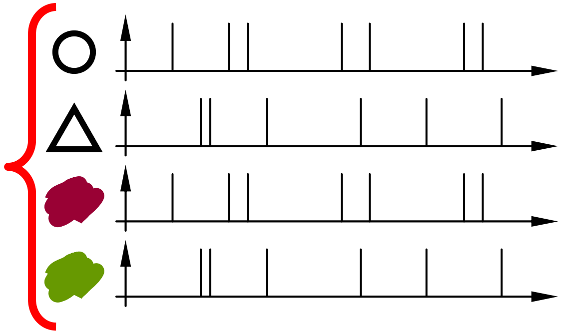
→ unstructured lists of features lead to the “superposition catastrophe”



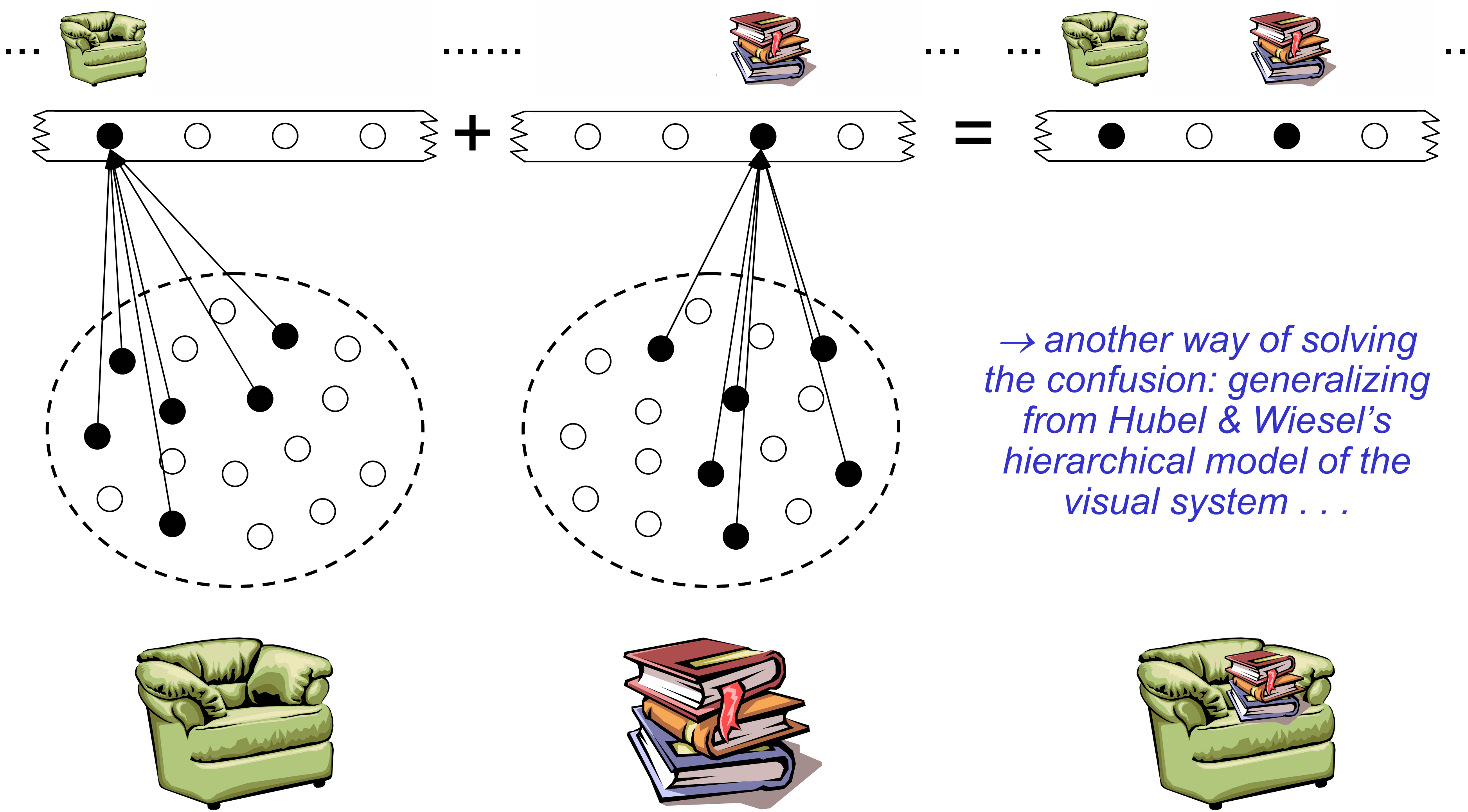
The binding problem



→ *solving the confusion by introducing relational information*

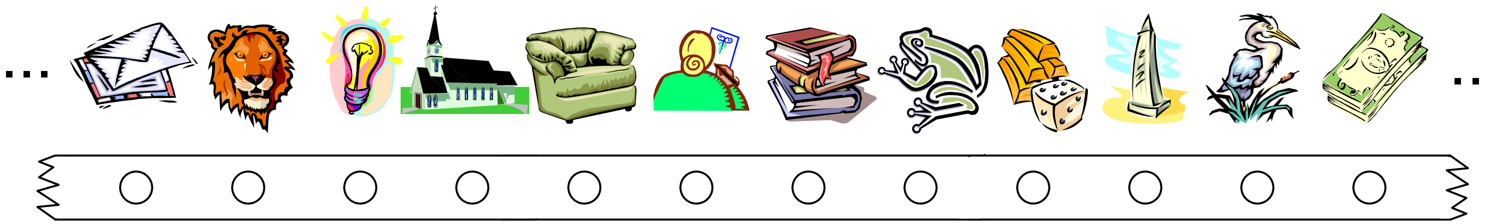


"Grandmother" cells



→ *another way of solving the confusion: generalizing from Hubel & Wiesel's hierarchical model of the visual system . . .*

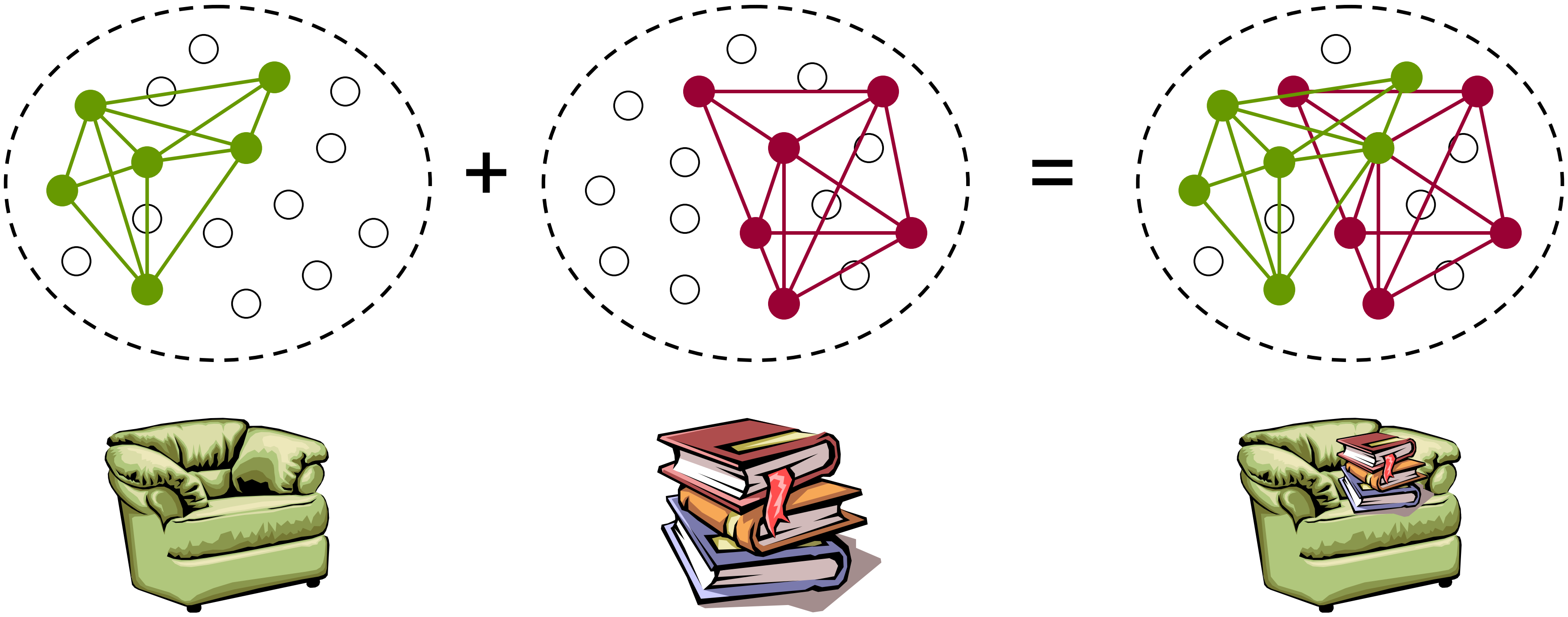
"Grandmother" cells



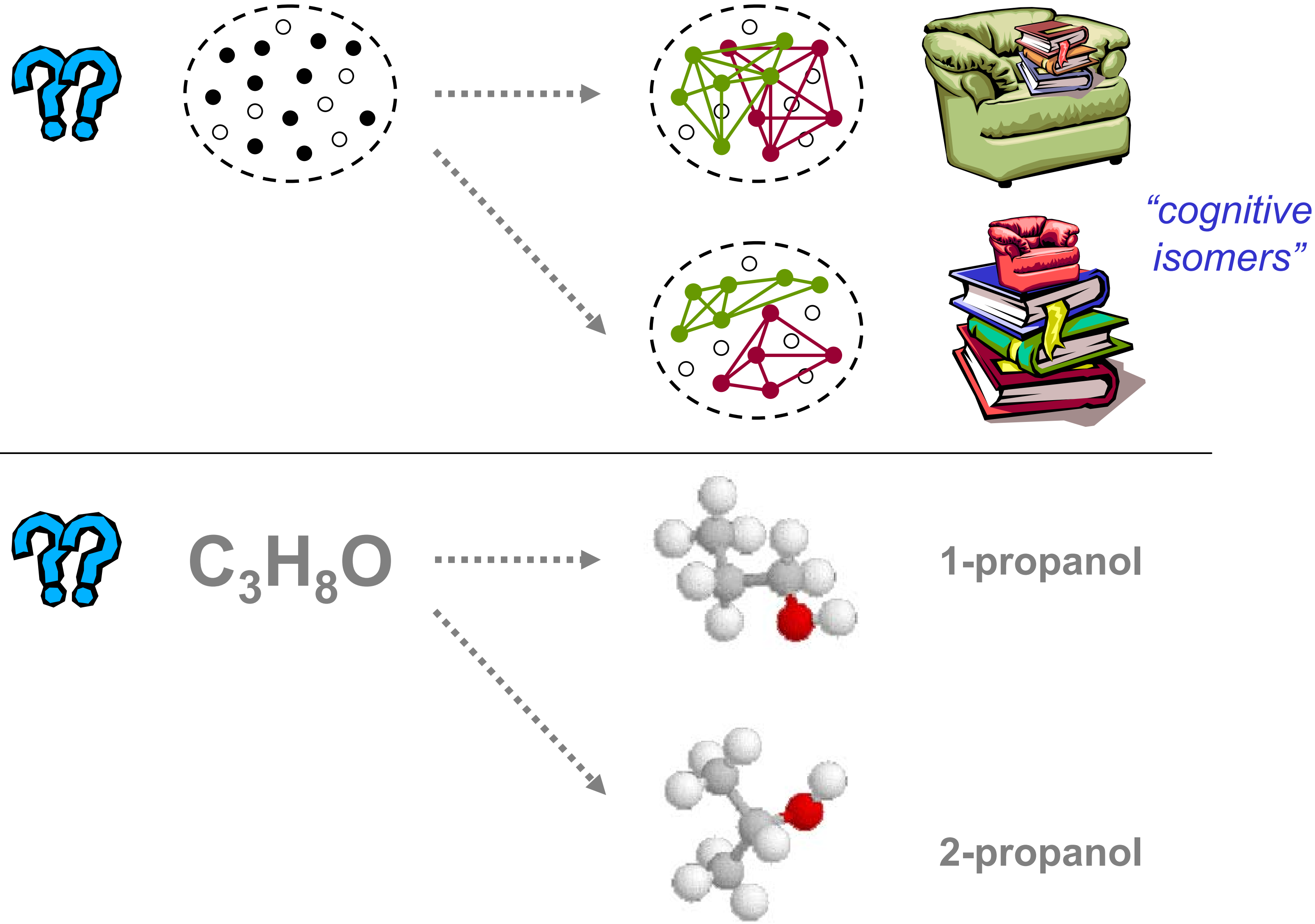
. . . however, this soon leads
to an unacceptable
combinatorial explosion!

Relational graph format

→ back to relational information:
with Christoph von der Malsburg
correlations = dynamical links,
assuming a fast synaptic plasticity on the ms timescale



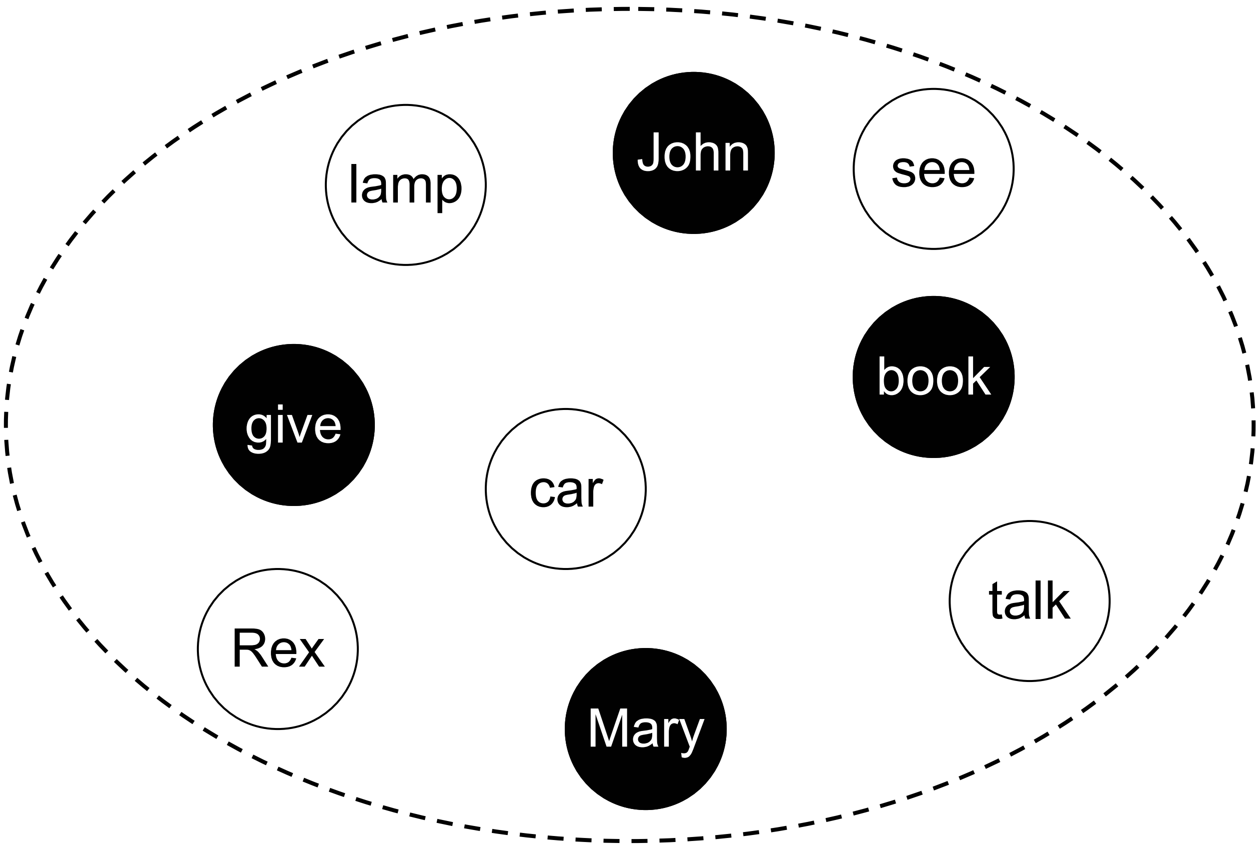
A molecular metaphor



An Epigenetic Development Model of the CNS

- The neural code
- Neural representations
- The compositionality of cognition
  - Compositionality in language
  - Compositionality in vision
  - Structural bonds
- A model of synaptic development
- Numerical simulations
- Synfire extras

Compositionality in language

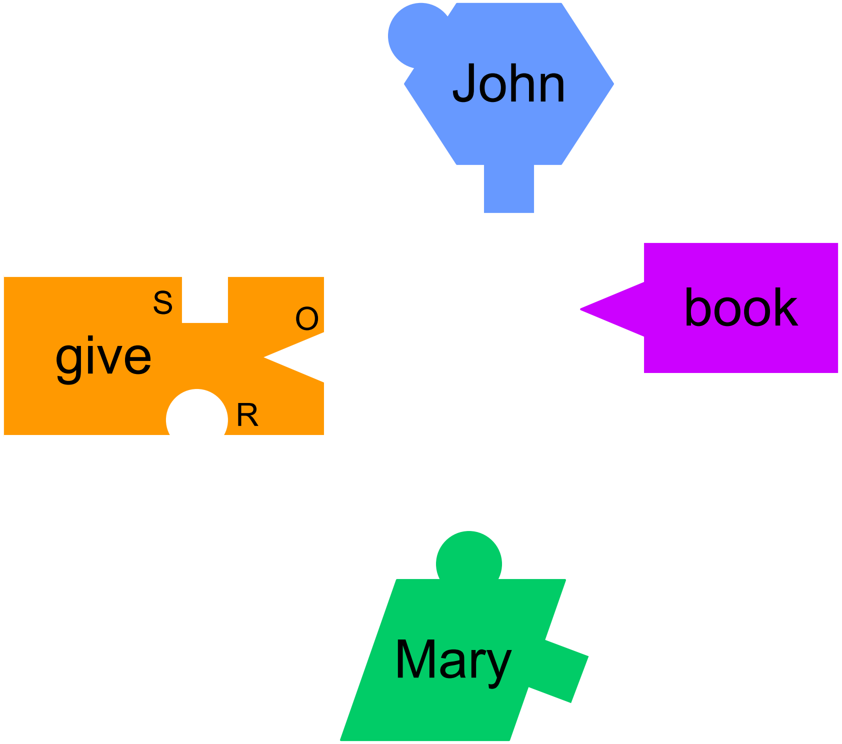


(a) John gives a book to Mary.

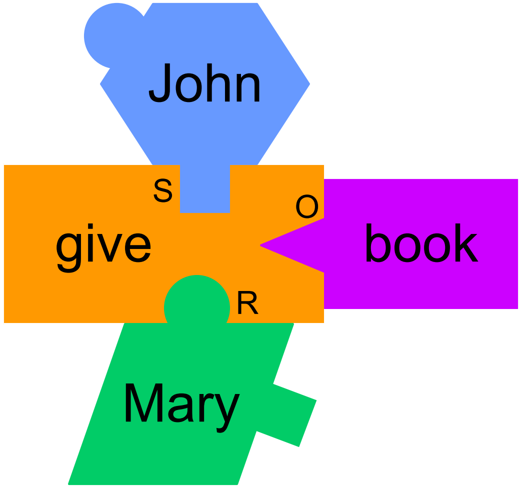
(b) Mary gives a book to John.

(c)* Book john mary give.

Compositionality in language

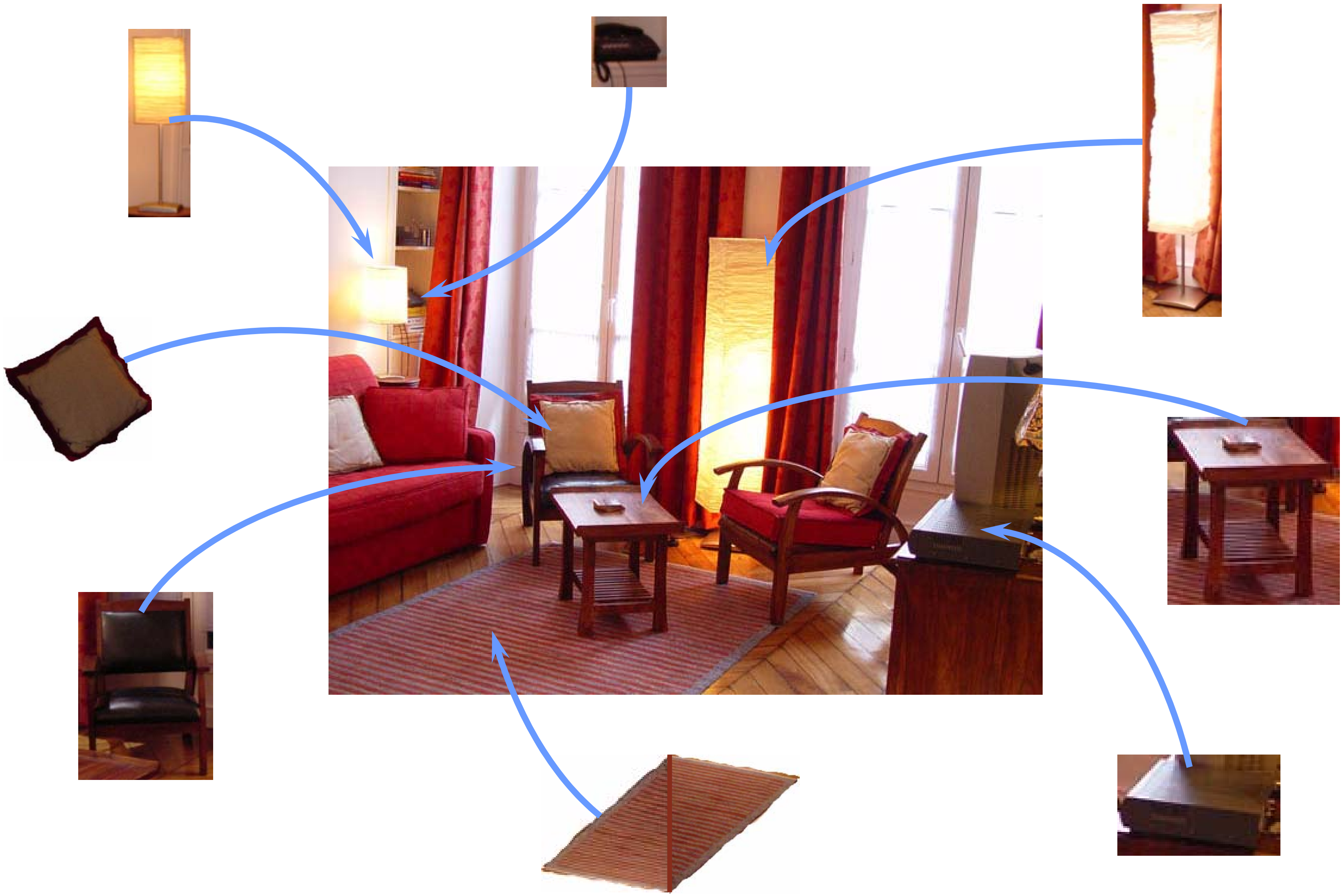


Compositionality in language



→ language is a “building blocks” construction game

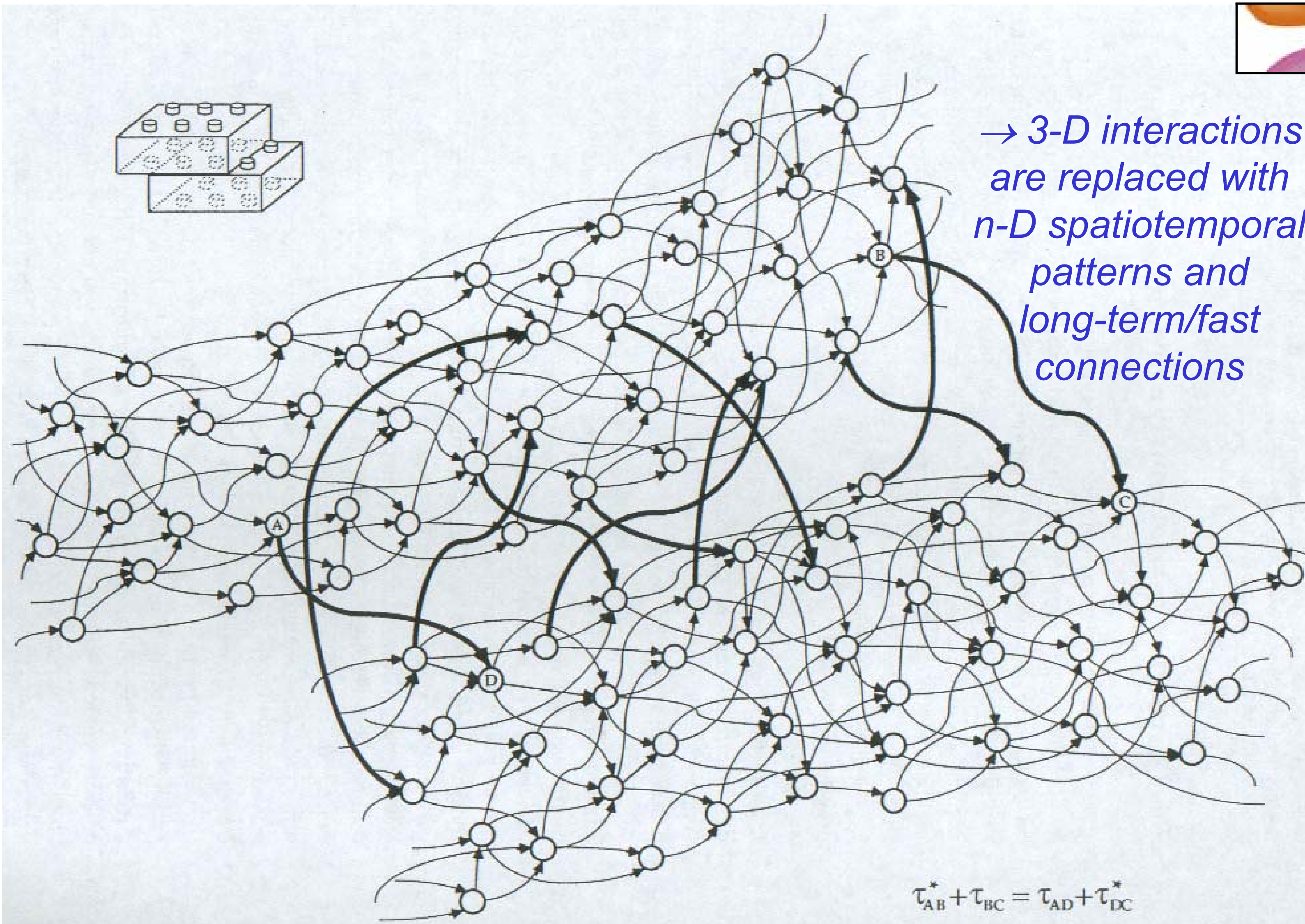
Compositionality in vision



Structural bonds

*→ protein structures
provide a metaphor
for the "mental objects"
or "building blocks"
of cognition*

Structural bonds

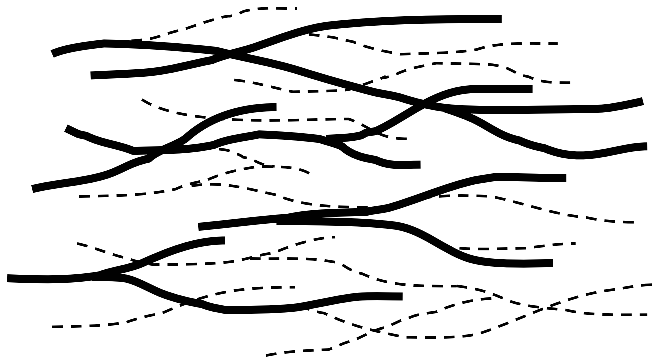


→ 3-D interactions are replaced with n-D spatiotemporal patterns and long-term/fast connections

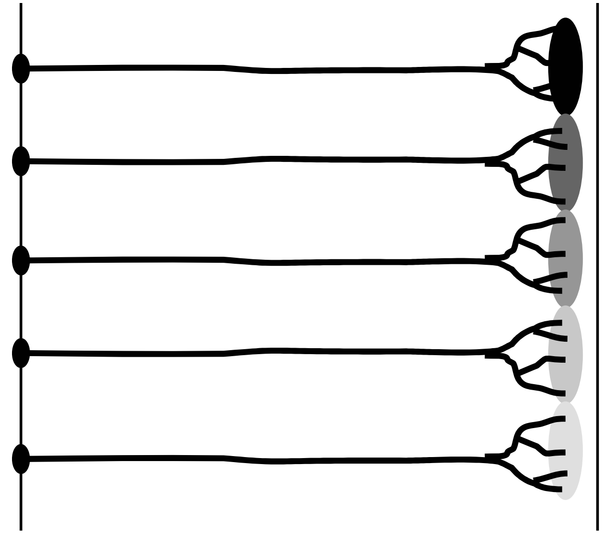
An Epigenetic Development Model of the CNS

- The neural code
- Neural representations
- The compositionality of cognition
- A model of synaptic development
  - Focusing of the innervation
  - A simple binary model
  - The growth of a synfire chain
  - Crystallization from seed neurons
  - Dynamic composition of two chains
- Numerical simulations
- Synfire extras

Focusing of the innervation

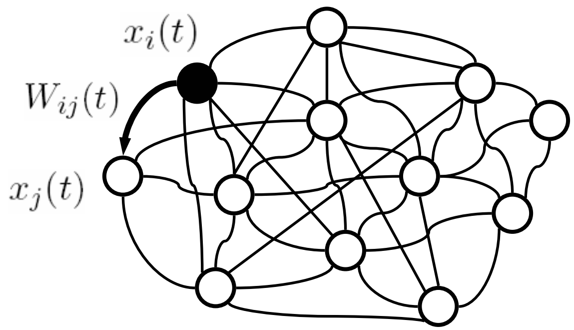


"selective stabilization" (Changeux & Danchin, 1976)



retinotopic projection (Willshaw & von der Malsburg, 1976)

A simple binary model

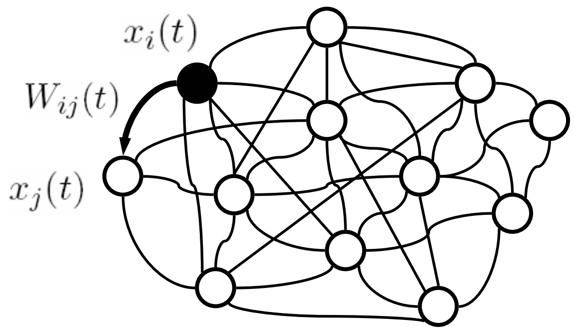


- Neuronal dynamics: fast McCulloch & Pitts

$$P[x_j(t) = 1] = \frac{1}{1 + e^{-(V_j(t) - \theta_j)/T}}$$

$$V_j(t) = \sum_i W_{ij}(t)\, x_i(t - \tau_{ij})$$

A simple binary model

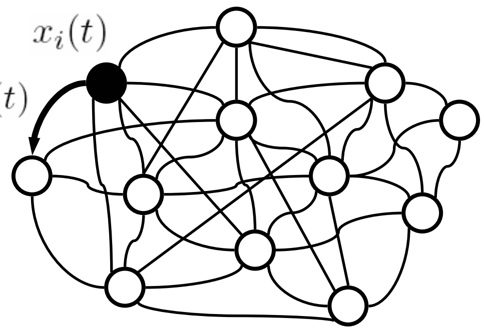


- Synaptic dynamics: fast Hebbian cooperation

$$W_{ij}(t) = W_{ij}(t-1) + \underbrace{A_{ij}(t)} + B_{ij}(t)$$

$$\begin{aligned}
x_i(t-\tau_{ij}) = 1,\ x_j(t) = 1 \quad &\Rightarrow \quad A_{ij}(t) = +\alpha \\
x_i(t-\tau_{ij}) = 1,\ x_j(t) = 0 \quad &\Rightarrow \quad A_{ij}(t) = -\beta \\
x_i(t-\tau_{ij}) = 0,\ x_j(t) = 1 \quad &\Rightarrow \quad A_{ij}(t) = -\beta \\
x_i(t-\tau_{ij}) = 0,\ x_j(t) = 0 \quad &\Rightarrow \quad A_{ij}(t) = 0
\end{aligned}$$

A simple binary model



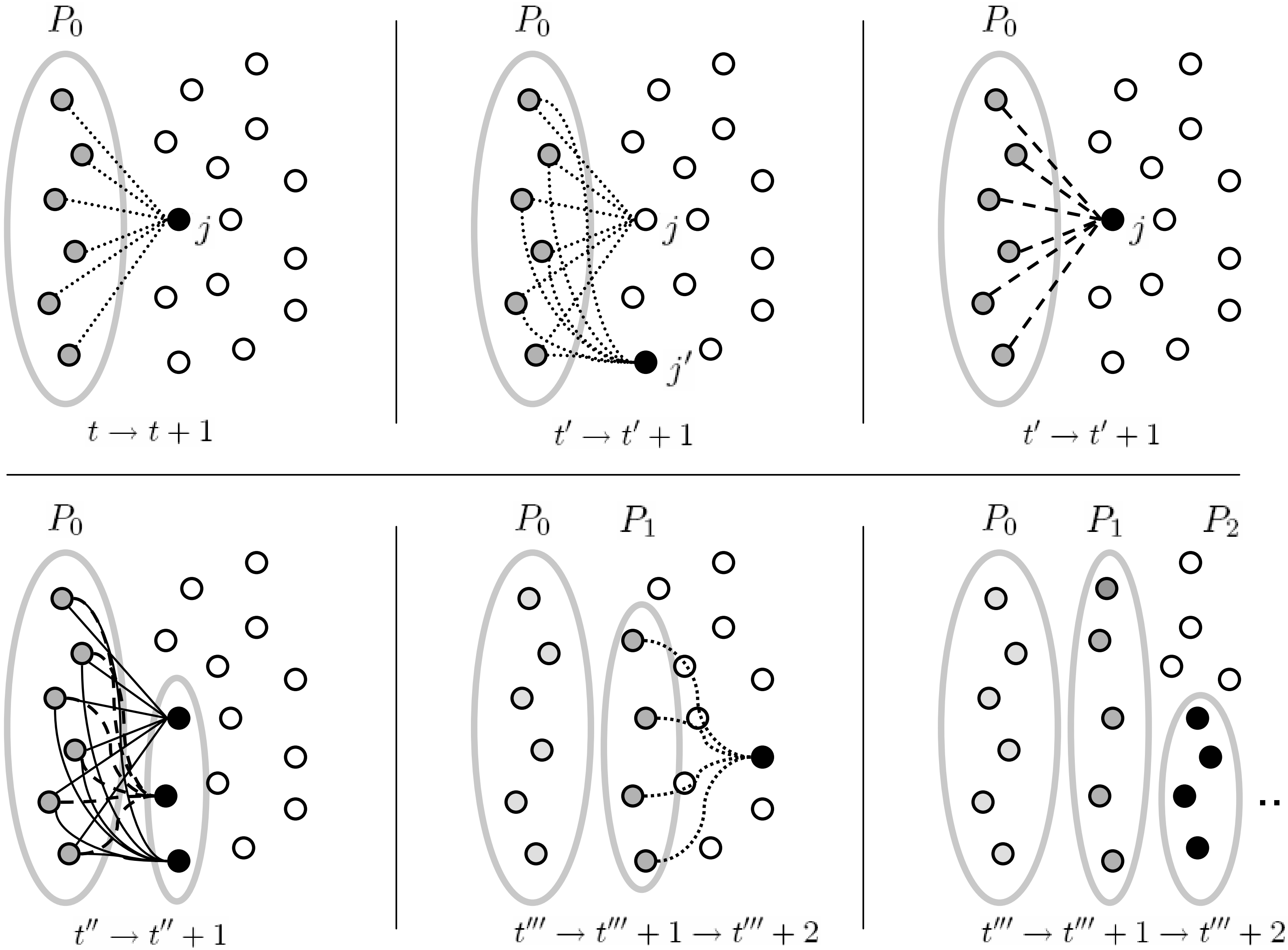
- Synaptic dynamics: competition

$$W_{ij}(t) = W_{ij}(t-1) + A_{ij}(t) + \underbrace{B_{ij}(t)}$$

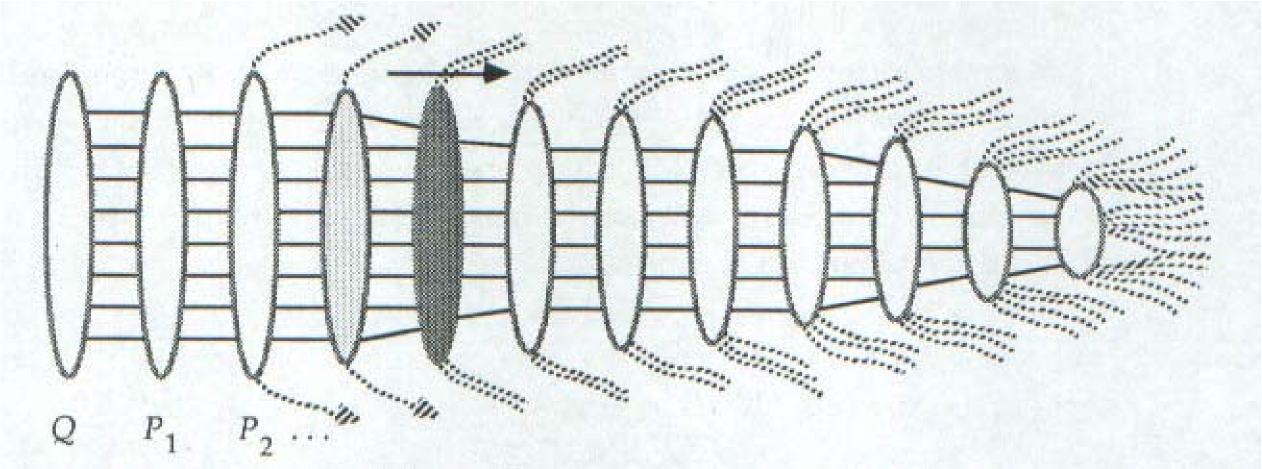
$$B_{ij}(t) = -\left(\frac{\partial H}{\partial W_{ij}}\right)_{\mathbf{W}(t-1)+\mathbf{A}(t)}$$

$$H(\mathbf{W}) = \gamma \sum_i \left(\sum_j W_{ij} - s_0\right)^2 + \gamma' \sum_j \left(\sum_i W_{ij} - s'_0\right)^2$$

The growth of a synfire chain

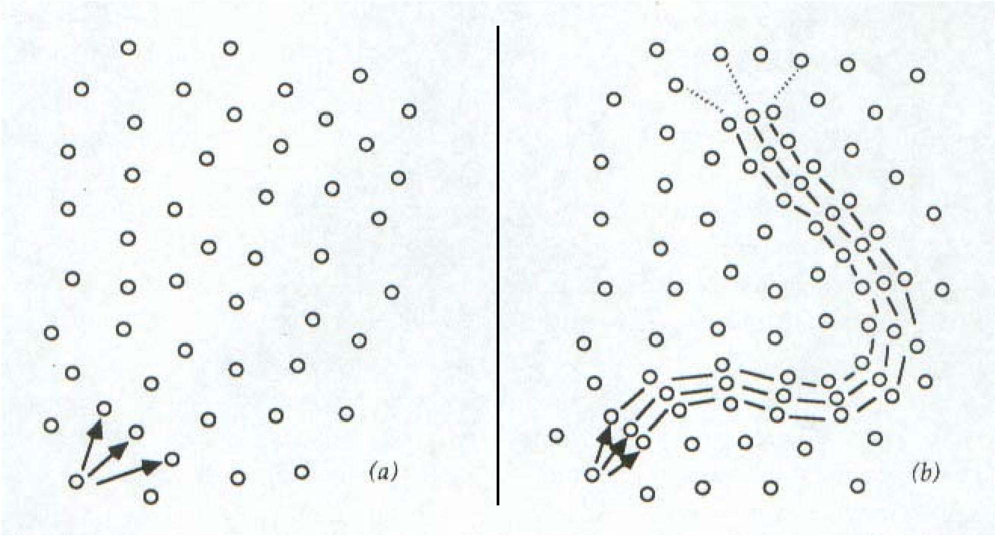


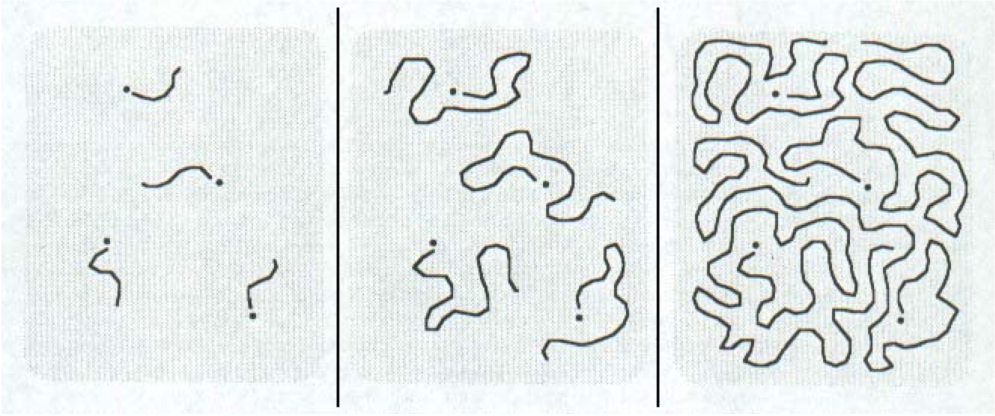
The growth of a synfire chain



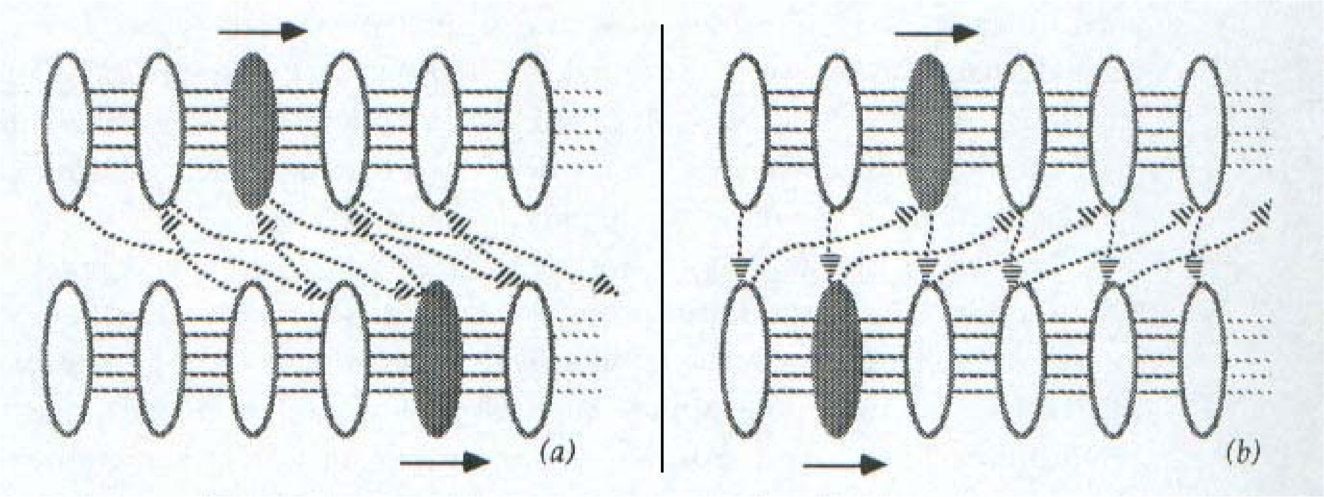
→ synchronous pools start creating new pools ahead of them before reaching maturity, making a "beveled head" (along propagation axis)

Crystallization from seed neurons





Dynamic composition of two chains



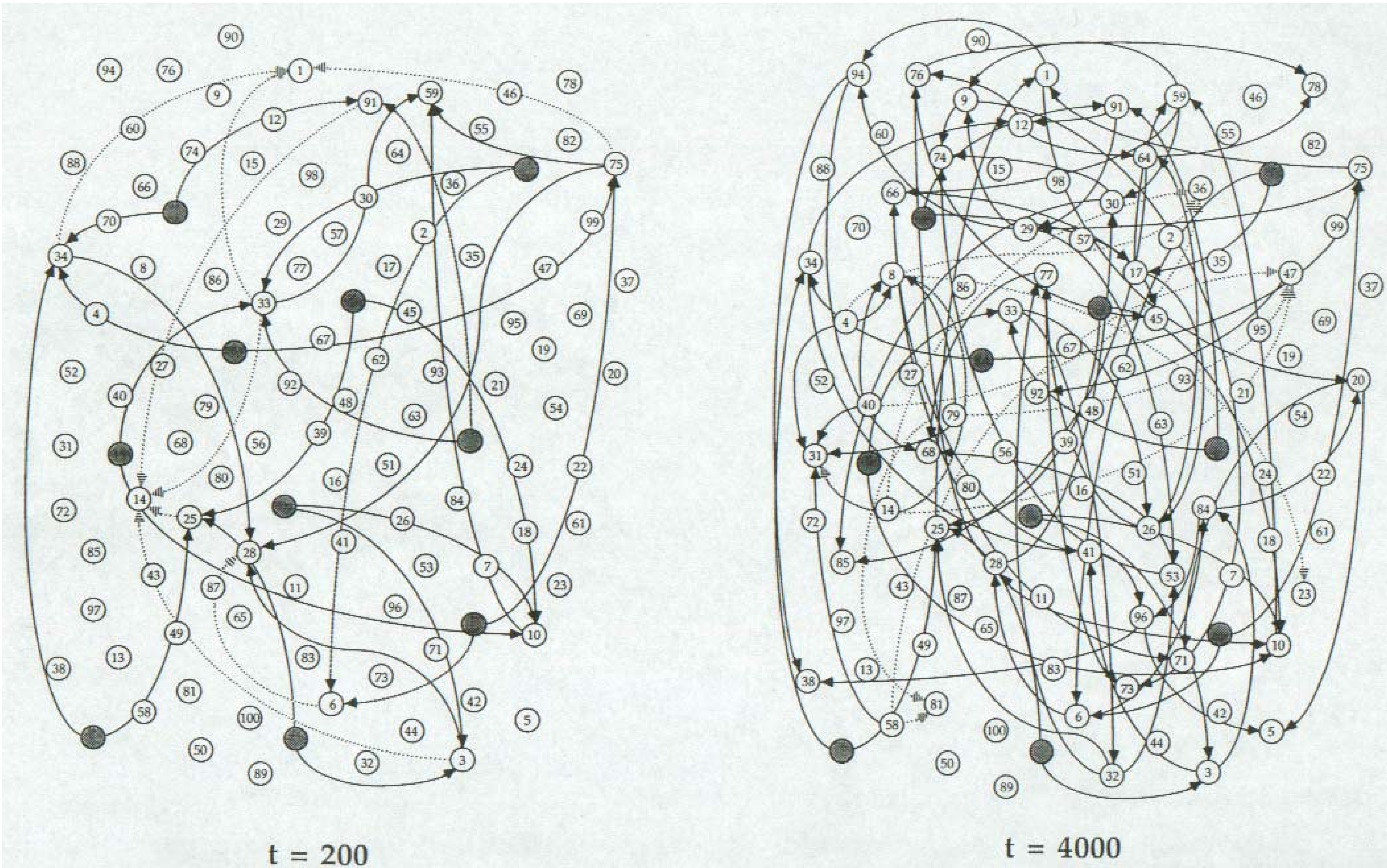
→ *"zipper-matching"*

An Epigenetic Development Model of the CNS

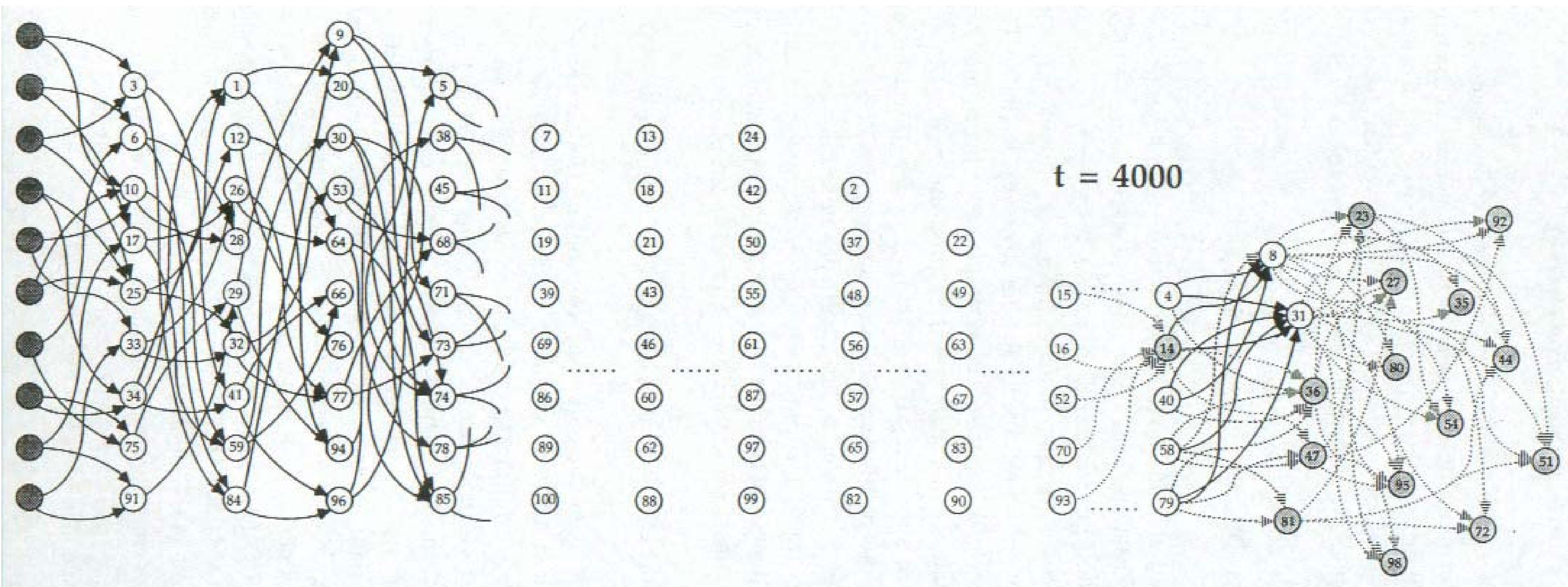
- The neural code
- Neural representations
- The compositionality of cognition
- A model of synaptic development
- Numerical simulations
  - Network activity
  - Network self-organization
  - Cross-correlograms
  - Synaptic evolution
- Synfire extras

Network activity

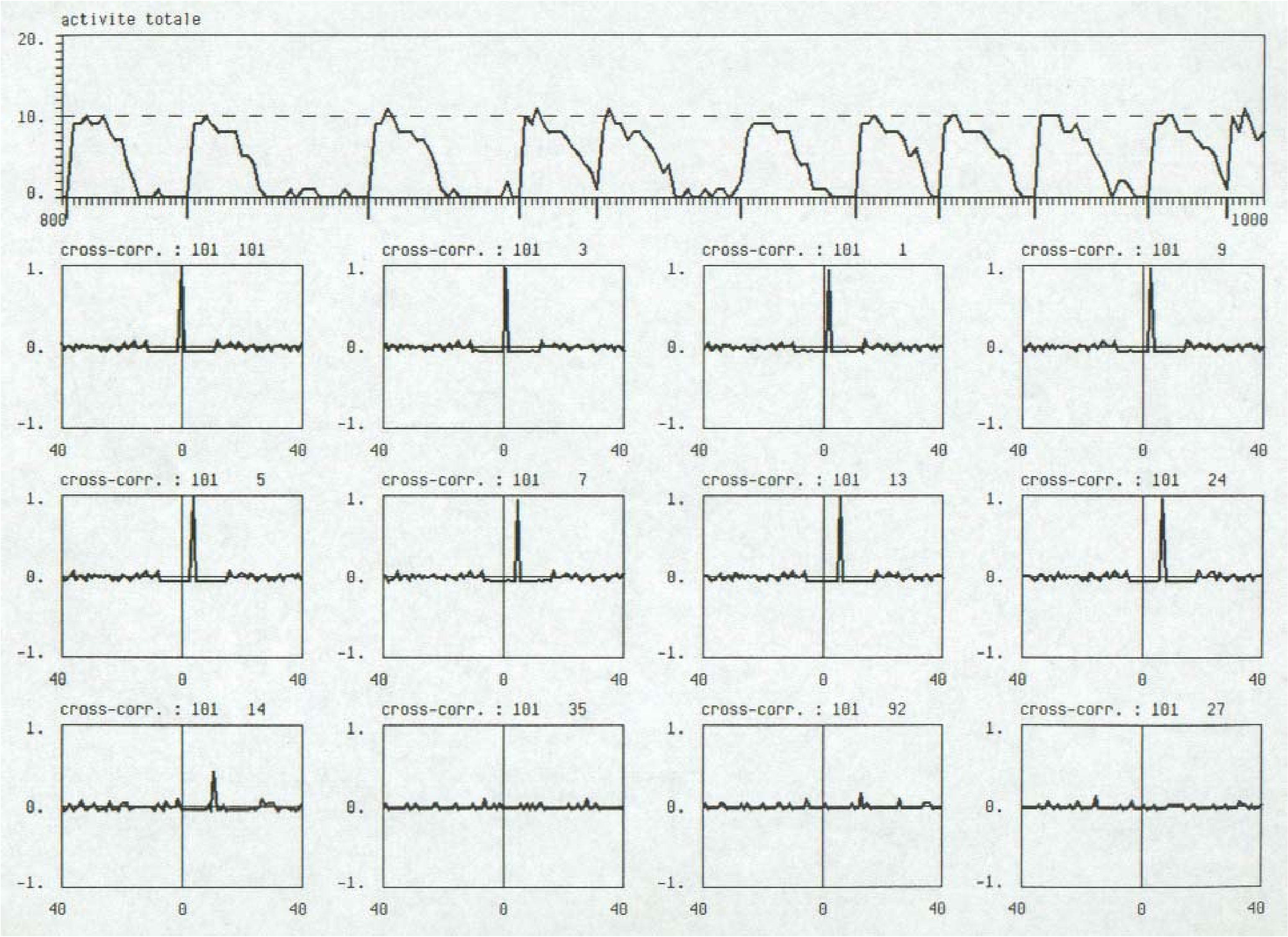
Network self-organization



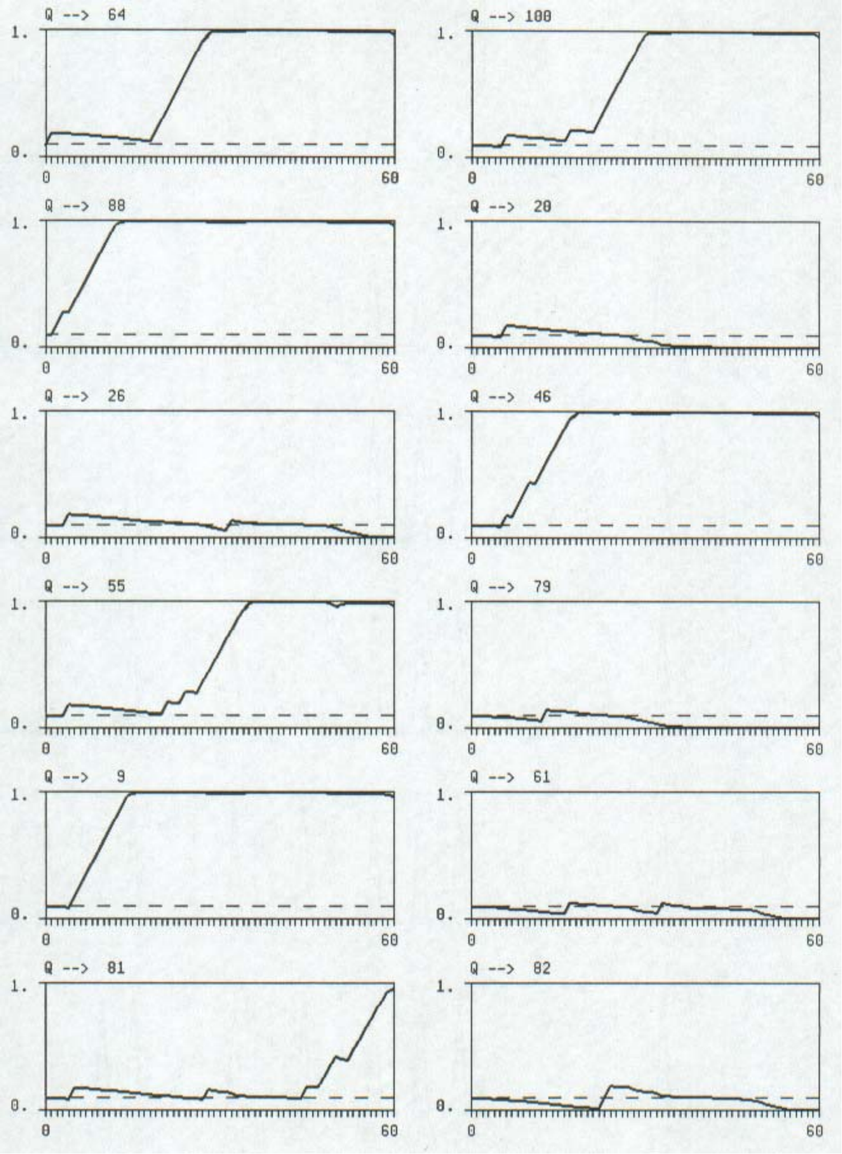
Network self-organization



Cross-correlograms



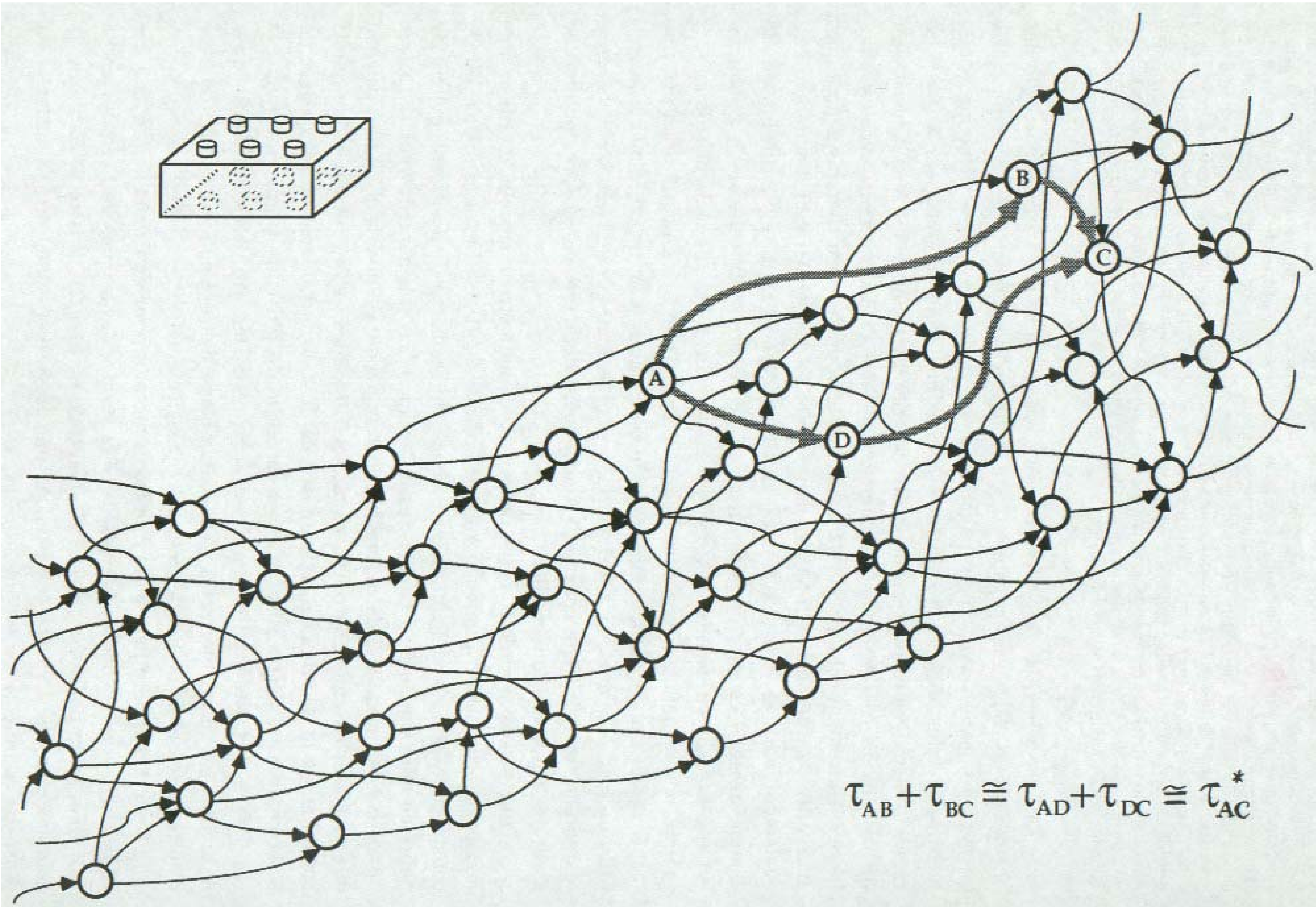
Synaptic evolution



An Epigenetic Development Model of the CNS

- The neural code
- Neural representations
- The compositionality of cognition
- A model of synaptic development
- Numerical simulations
- Synfire extras
  - Synfire braids
  - More recent synfire references

Synfire braids



Other synfire references

- A. Aertsen, Universität Freiburg
  - Diesmann et al. (1999): stable propagation of precisely synchronized APs happens despite noisy dynamics
- C. Koch, Caltech
  - Marsalek et al. (1997): preservation of highly accurate spike timing in cortical networks (macaque MT area), explained by analysis of output/input jitter in I&F model
- R. Yuste, Columbia University
  - Mao et al. (2001): recording of spontaneous activity with statistically significant delayed correlations in slices mouse visual cortex, using calcium imaging
  - Ikegaya et al. (2004): "cortical songs" in vitro and in vivo (mouse and cat visual cortex)
- E. Izhikevich, The Neurosciences Institute
  - Izhikevich, Gally and Edelman (2004): self-organization of spiking neurons in a biologically detailed "small-world" model of the cortex