CS 790R Seminar
Modeling & Simulation

Synchronization in Spiking Neural Networks

~ Lecture 8 ~

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Synchronization in Spiking Neural Networks

1. Temporal Coding
2. Coupled Oscillators
3. Synfire Chains

Synchronization in Spiking Neural Networks

1. **Temporal Coding**
   - Neural networks
   - The neural code
   - Questions of representation
2. **Coupled Oscillators**
3. **Synfire Chains**

Synchronization in Spiking Neural Networks

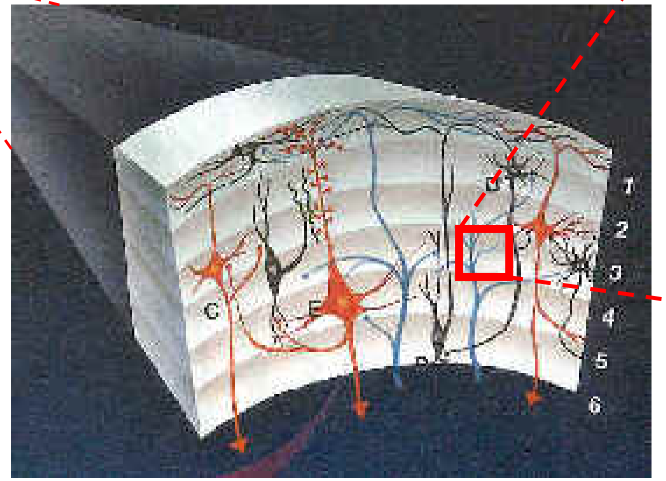
1. **Temporal Coding**
   - Neural networks
     - Structure of neural networks
     - Structure of a neuron
     - Propagation of a “spike”
     - Model of neural network
   - The neural code
   - Questions of representation
2. **Coupled Oscillators**
3. **Synfire Chains**

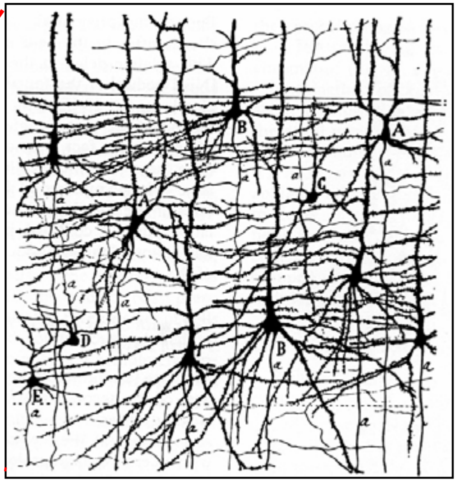
Neural networks

Structure of neural networks

Medial surface of the brain
(Virtual Hospital, University of Iowa)

Cortical layers





Pyramidal neurons and interneurons
(Ramón y Cajal 1900)

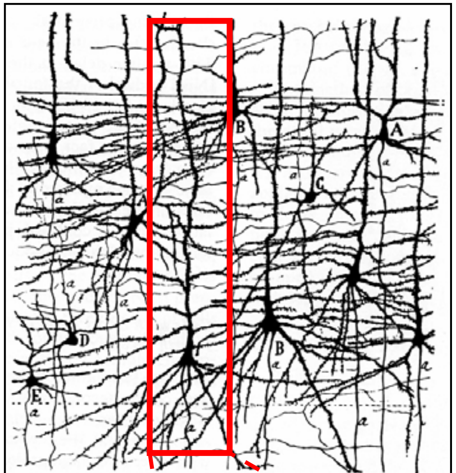
Phenomenon

- neurons together form... the brain! (and peripheral nervous system)
  - perception, cognition, action
  - emotions, consciousness
  - behavior, learning
  - autonomic regulation: organs, glands

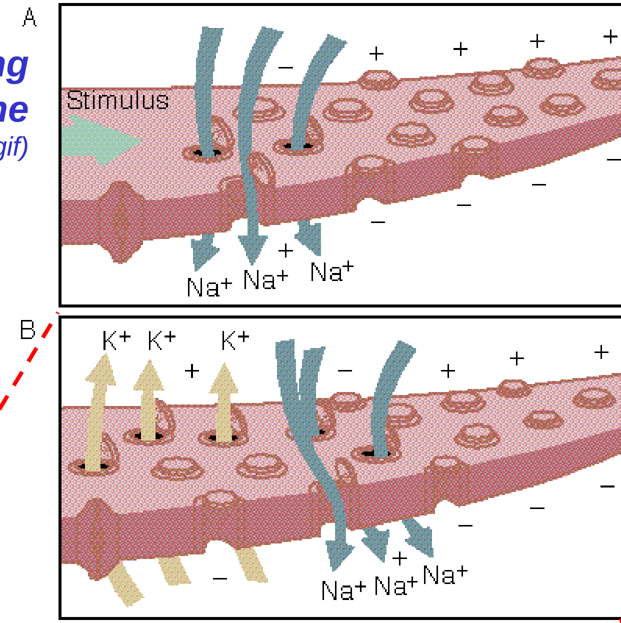
- ~10^{11} neurons in humans
- communicate with each other through (mostly) electrical potentials
- neural activity exhibits specific patterns of *spatial and temporal synchronization* (“temporal code”)

Neural networks

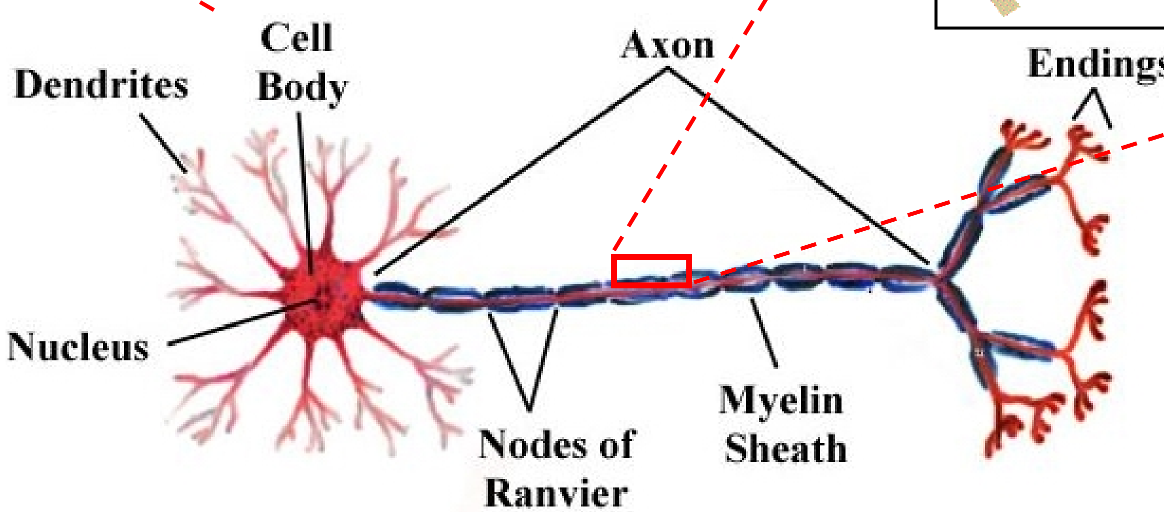
Structure of a neuron



Ionic channels opening and closing
→ depolarization of the membrane
(http://www.awa.com/norton/figures/fig0209.gif)



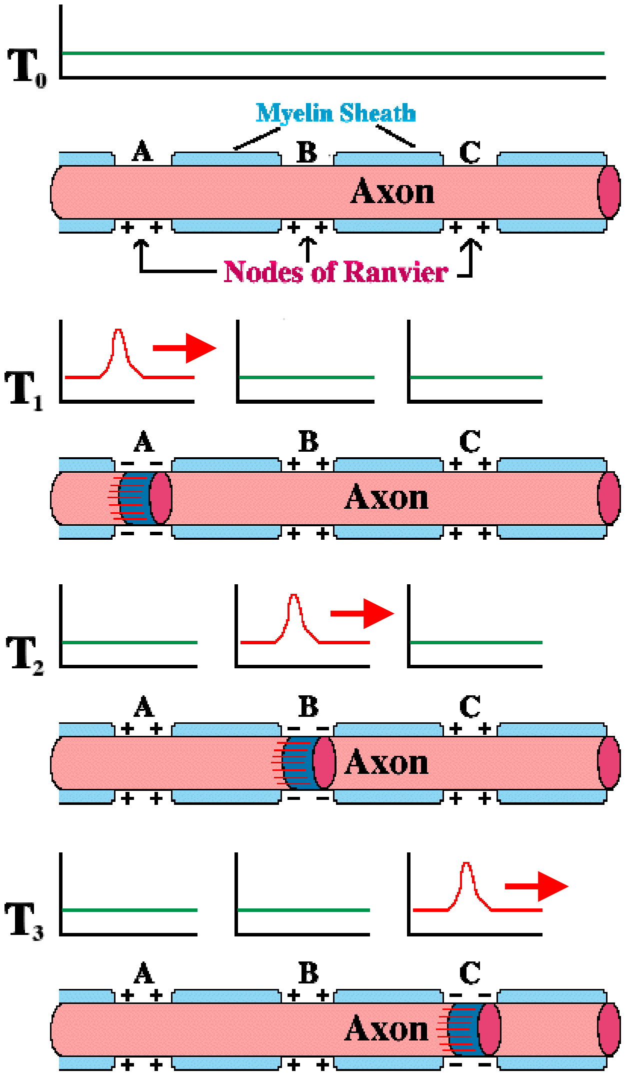
Pyramidal neurons and interneurons
(Ramón y Cajal 1900)

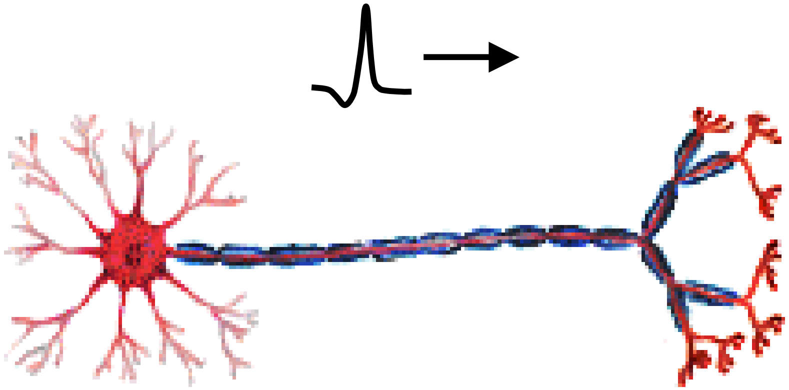


A typical neuron
(http://www.bio.brandeis.edu/biomath/mike/AP.html)

Neural networks

Propagation of a "spike"



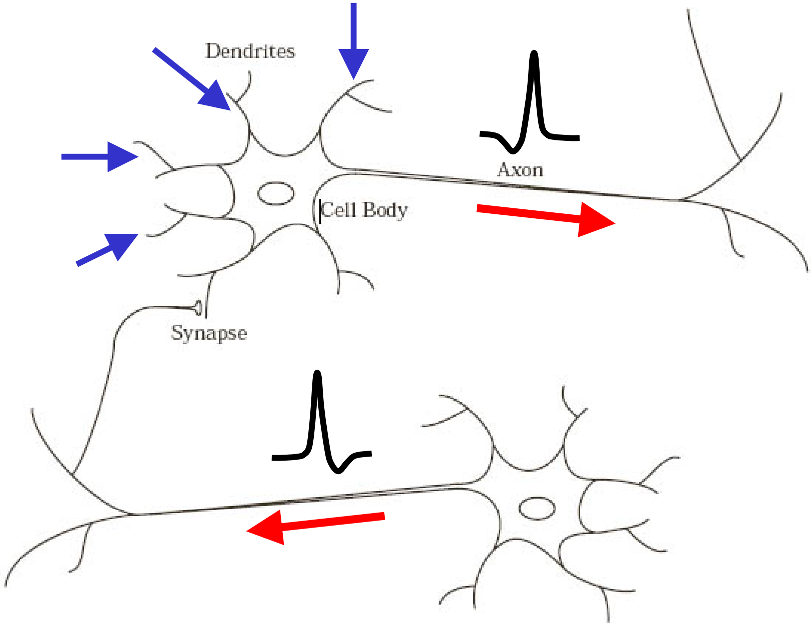


(http://www.bio.brandeis.edu/biomath/mike/AP.html)

Propagation of the depolarization along the axon
→ called "action potential", or "spike"
(http://hypatia.ss.uci.edu/psych9a/lectures/lec4fig/n-action-potential.gif)

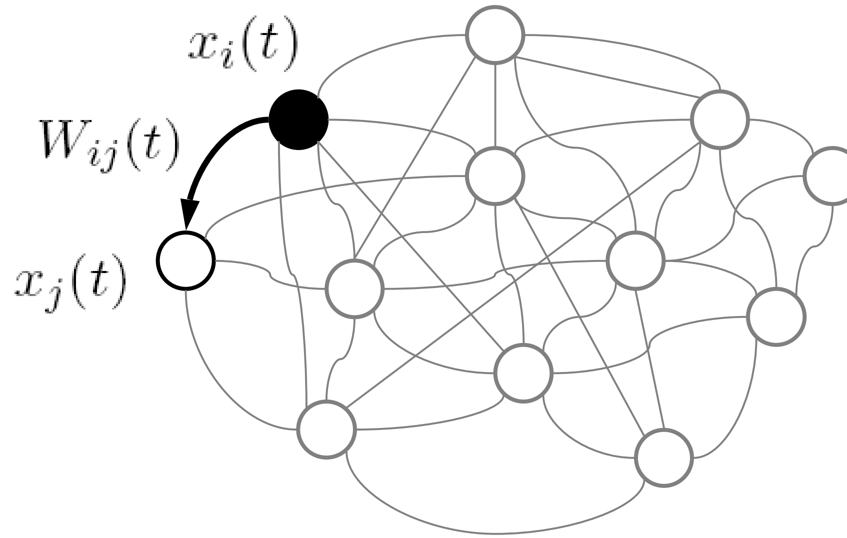
Neural networks

Model of neural network



Schematic neurons

(adapted from CS 791S "Neural Networks", Dr. George Bebis, UNR)



A binary neural network

Mechanism

- each neuron receives signals from many other neurons through its *dendrites*
- the signals converge to the *soma* (cell body) and are integrated
- if the integration exceeds a threshold, the neuron fires a <u>spike</u> on its *axon*

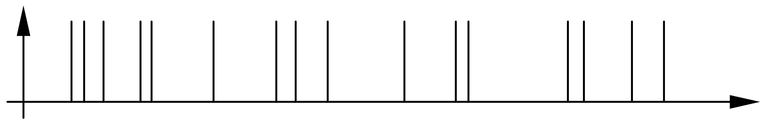
Synchronization in Spiking Neural Networks

1. **Temporal Coding**
   - Neural networks
   - The neural code
     - Rate vs. temporal coding
     - Synchronization and correlations
     - Interest for temporal coding
   - Questions of representation
2. **Coupled Oscillators**
3. **Synfire Chains**

The neural code

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

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

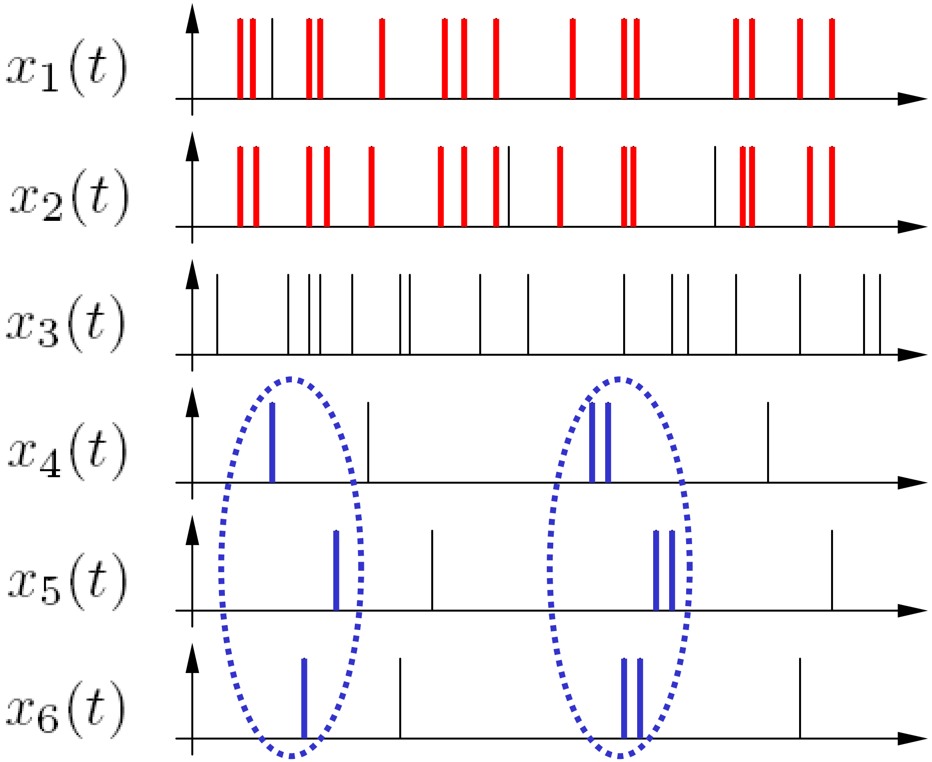
$$\langle\, x_i(t)\, x_j(t-\tau_{ij})\, \rangle$$

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

von der Malsburg, C. (1981) The correlation theory of brain function. Internal Report 81-2, Max Planck Institute for Biophysical Chemistry, Göttingen.

The neural code

Synchronization and correlations



$\langle x_1(t) \rangle =$ ● high activity rate

$\langle x_2(t) \rangle =$ ● high activity rate

$\langle x_3(t) \rangle =$ ● high activity rate

$\langle x_4(t) \rangle =$ ○ low activity rate

$\langle x_5(t) \rangle =$ ○ low activity rate

$\langle x_6(t) \rangle =$ ○ low activity rate

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

- 1 and 2 more in sync than 1 and 3

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

- 4, 5 and 6 correlated through delays

The neural code

Interest for temporal coding

- Historical motivation for <u>rate coding</u>
  - 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, however increasingly considered insufficient for <u>integrating</u> the information*

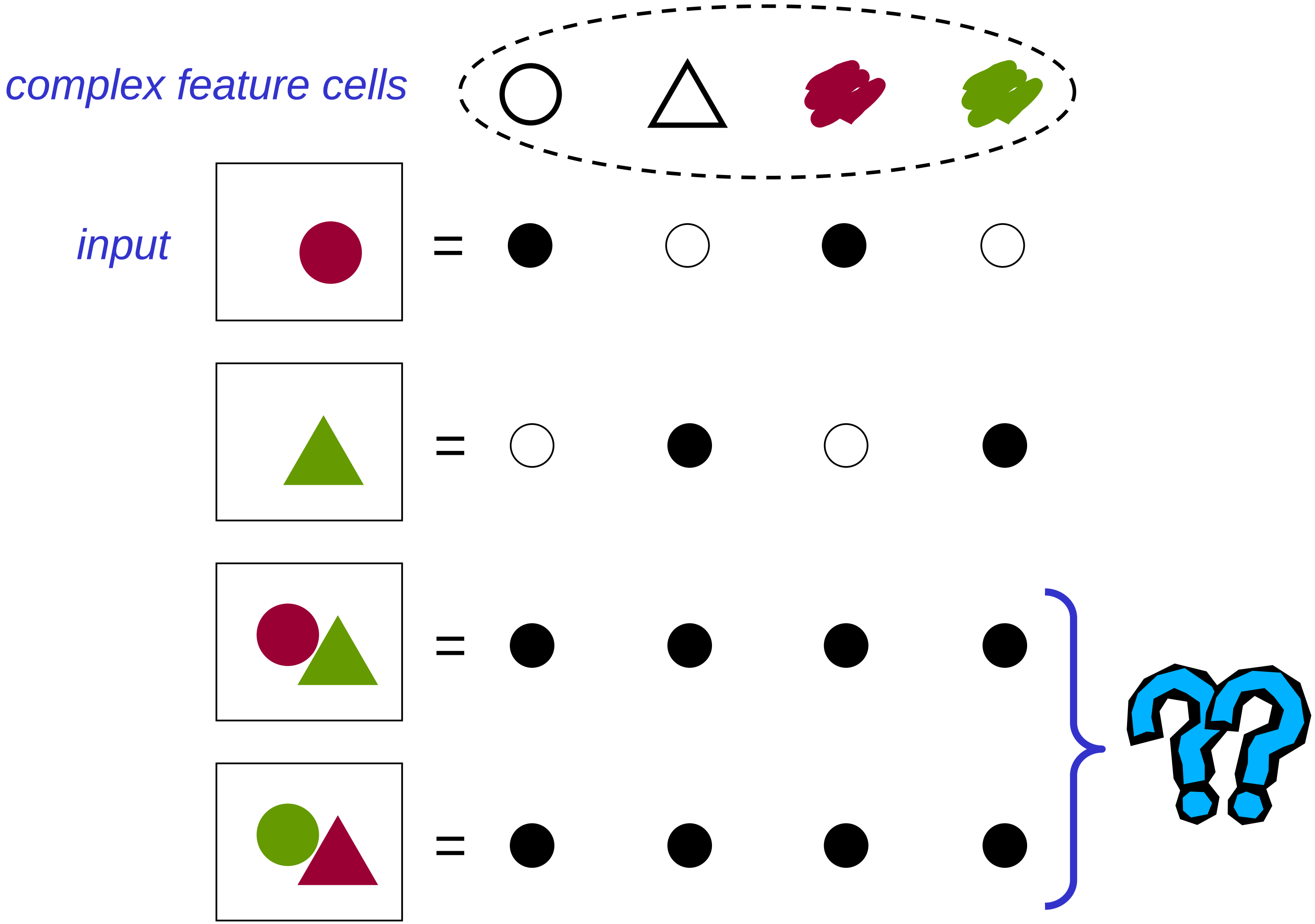
- Recent <u>temporal coding</u> "boom": a few milestones
  - Abeles (1982, 1991): *precise, <u>reproducible spatiotemporal spike rhythms</u>, named "synfire chains"*
  - Gray & Singer (1989): *stimulus-dependent <u>synchronization of oscillations</u> in monkey visual cortex*
  - O'Keefe & Recce (1993):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

Synchronization in Spiking Neural Networks

1. **Temporal Coding**
   - Neural networks
   - The neural code
   - Questions of representation
     - The “binding problem”
     - Feature binding in cell assemblies
     - “Grandmother” cells
     - Relational graph format
     - Solving the binding problem with temporal coding
     - A molecular metaphor
2. **Coupled Oscillators**
3. **Synfire Chains**

Questions of representation

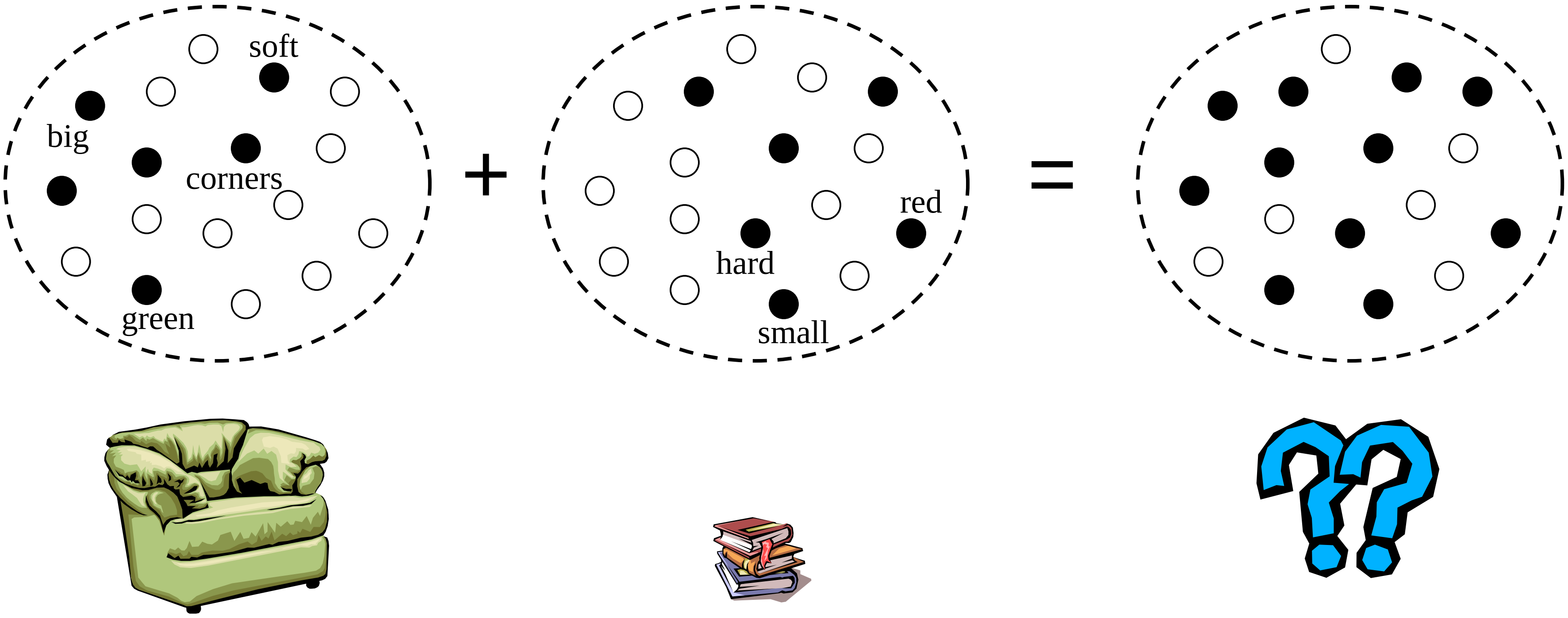
The “binding problem”



Questions of representation

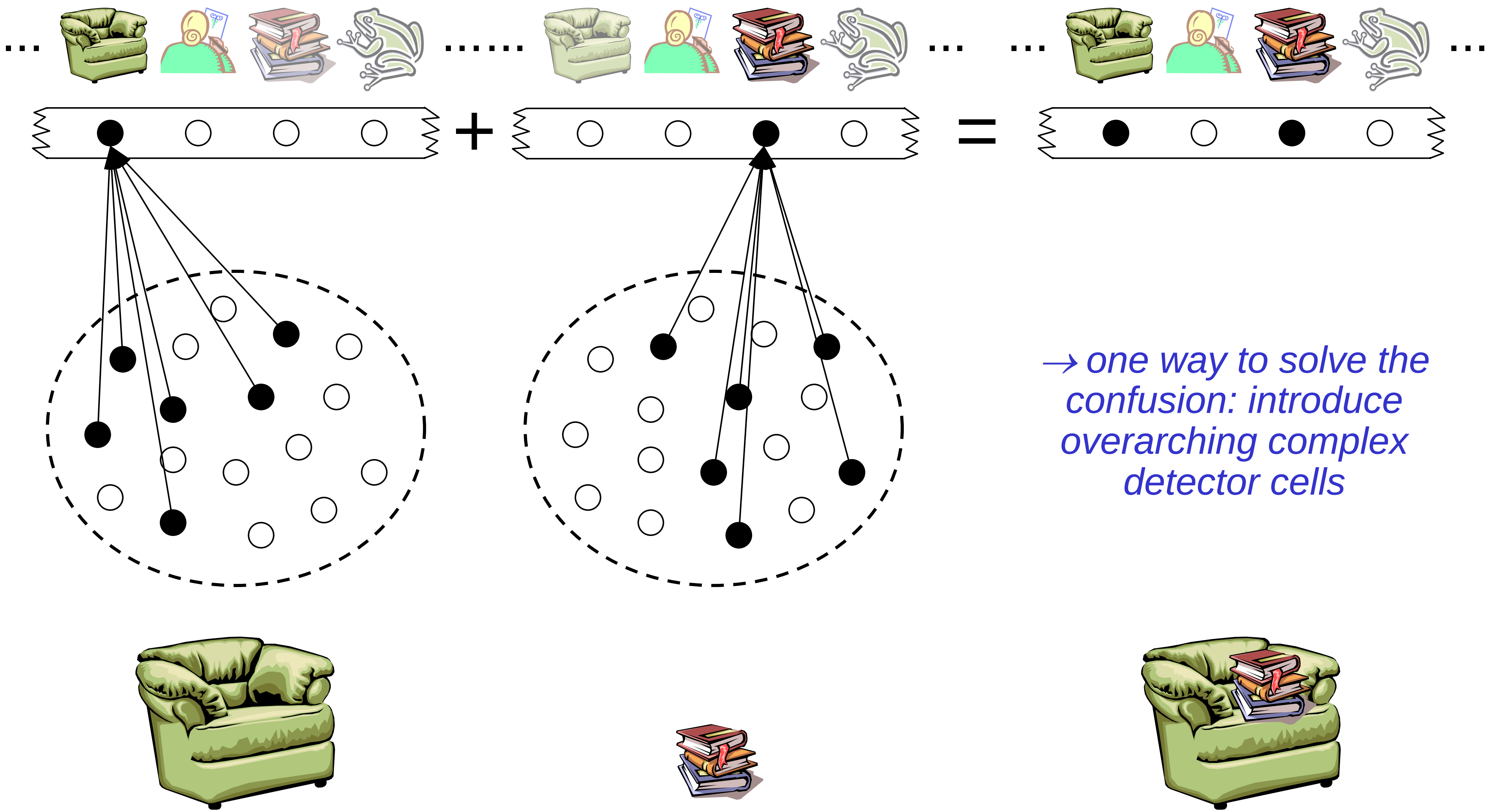
Feature binding in cell assemblies

→ unstructured lists of features lead to the "superposition catastrophe"



Questions of representation

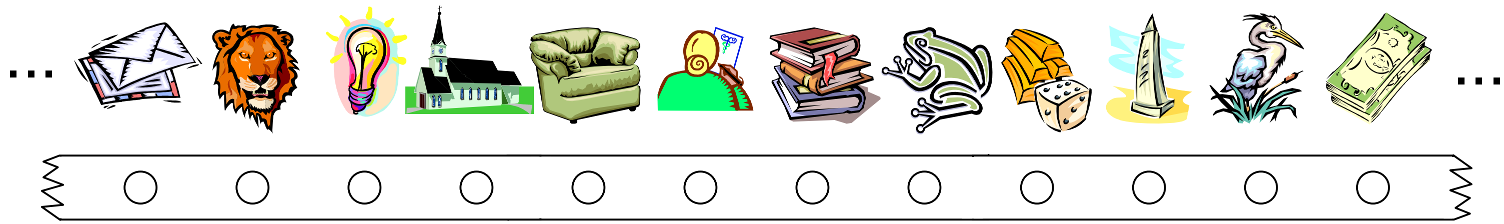
"Grandmother" cells



→ one way to solve the confusion: introduce overarching complex detector cells

Questions of representation

"Grandmother" cells

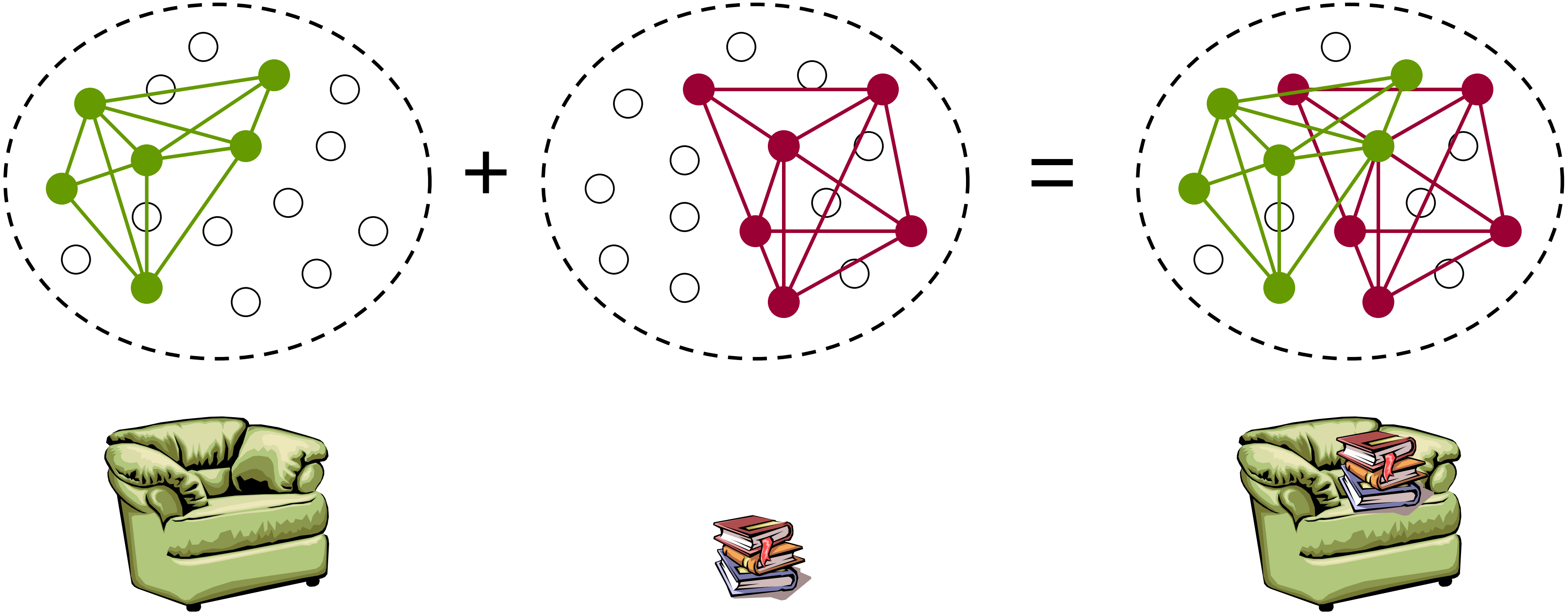


. . . however, this soon leads
to an unacceptable
combinatorial explosion!

Questions of representation

Relational graph format

→ another way to solve the confusion: represent relational information



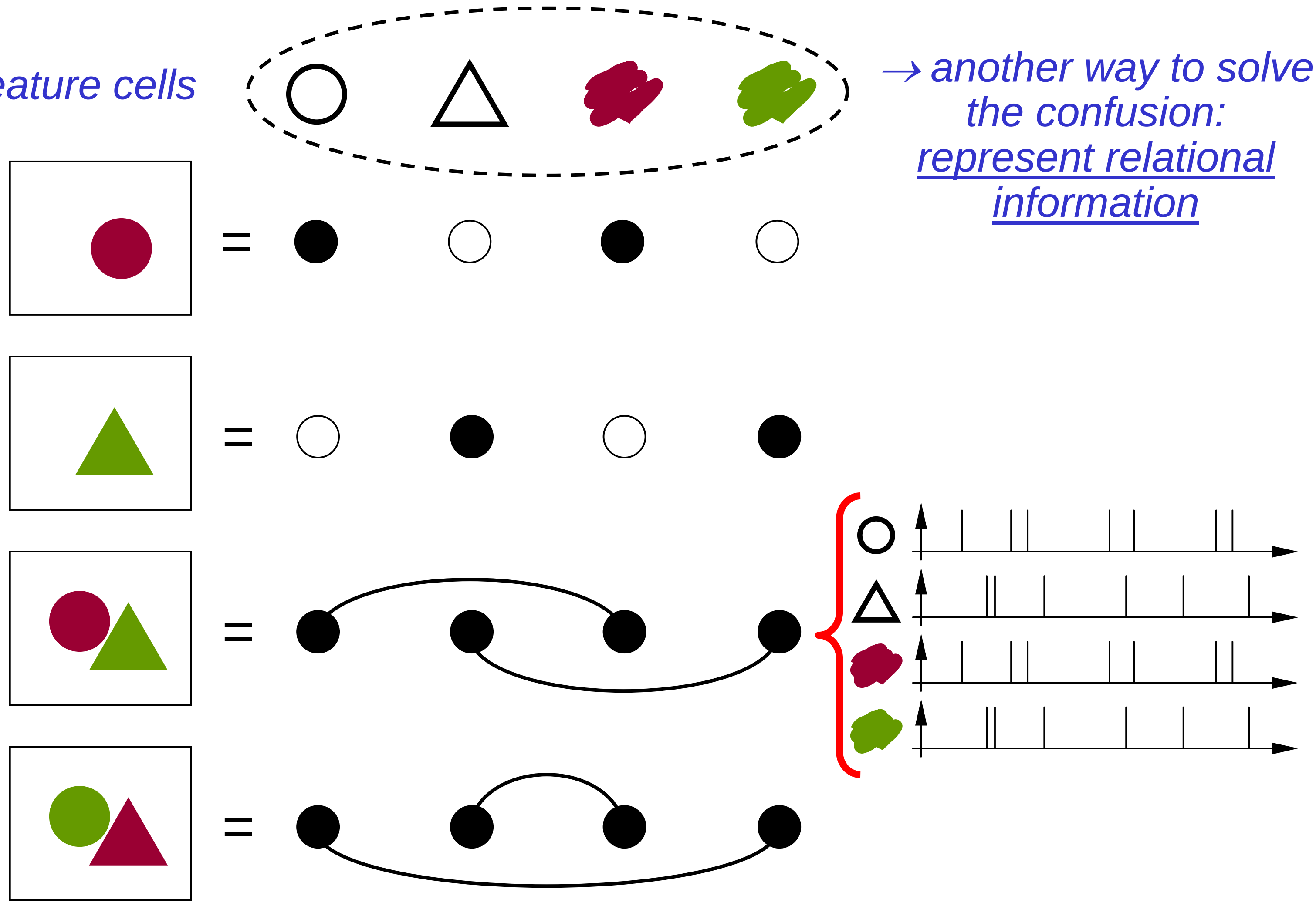
Questions of representation

Solving the binding problem with temporal coding

complex feature cells

→ another way to solve the confusion: represent relational information

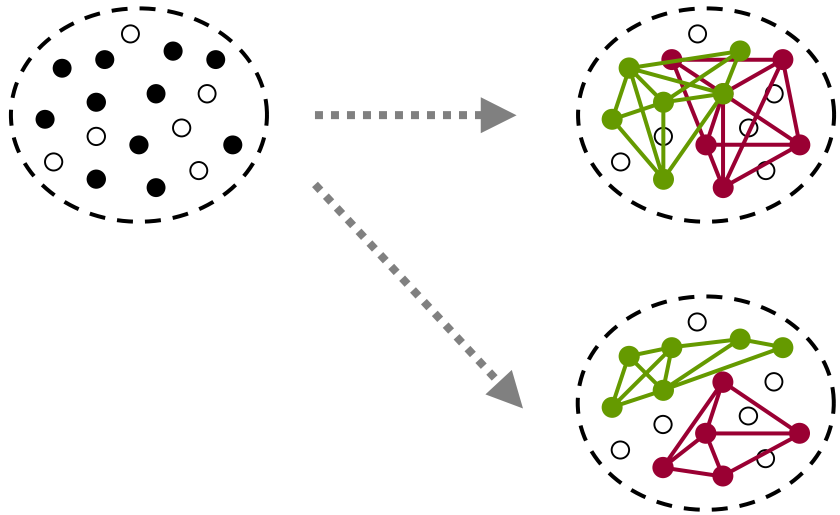
input



von der Malsburg, C. (1981) The correlation theory of brain function.

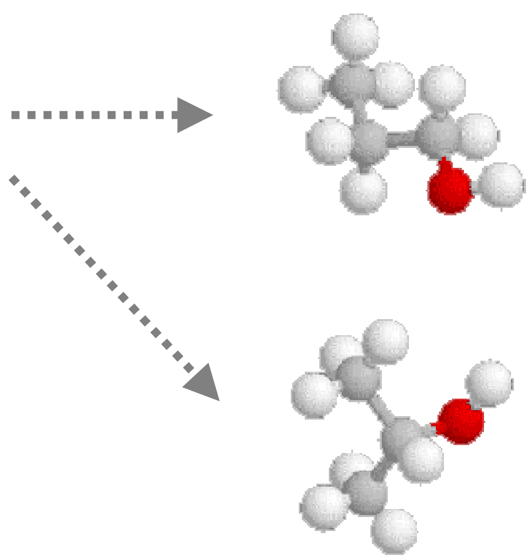
Questions of representation

A molecular metaphor



“cognitive isomers” made of the same atomic features

C_3H_8O



1-propanol

2-propanol

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Synchronization in Spiking Neural Networks

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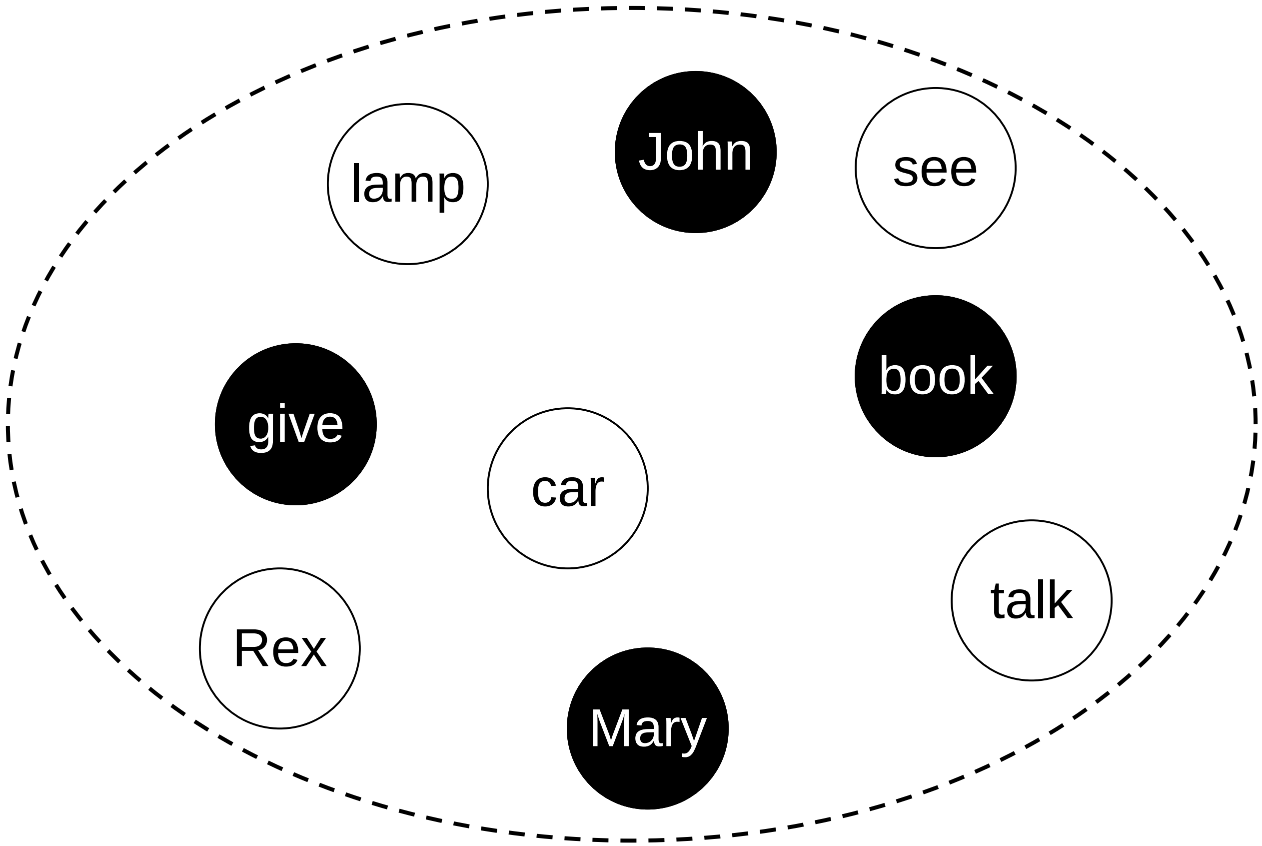
2. **Coupled Oscillators**
   - Temporal tagging
   - Group synchronization
   - Traveling waves
3. **Synfire Chains**

Synchronization in Spiking Neural Networks

1. Temporal Coding
2. **Coupled Oscillators**
   - Temporal tagging
     - The binding problem in language
     - A model of semantic binding: SHRUTI
     - Using correlations to implement binding
   - Group synchronization
   - Traveling waves
3. **Synfire Chains**

Temporal tagging

The binding problem in language



(a) John gives a book to Mary.

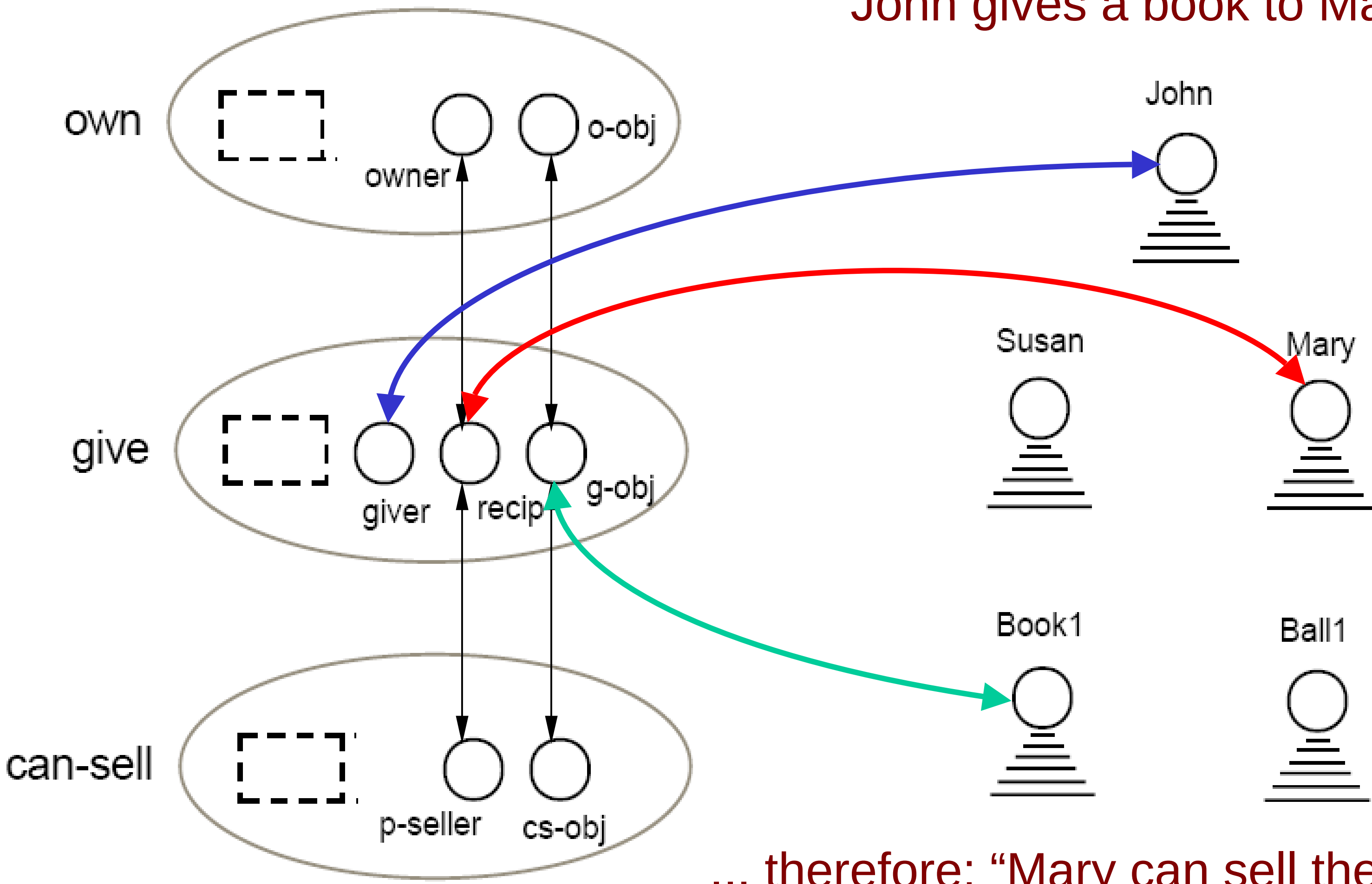
(b) Mary gives a book to John.

(c)* Book John Mary give.

Temporal tagging

A model of semantic binding: SHRUTI

"John gives a book to Mary."

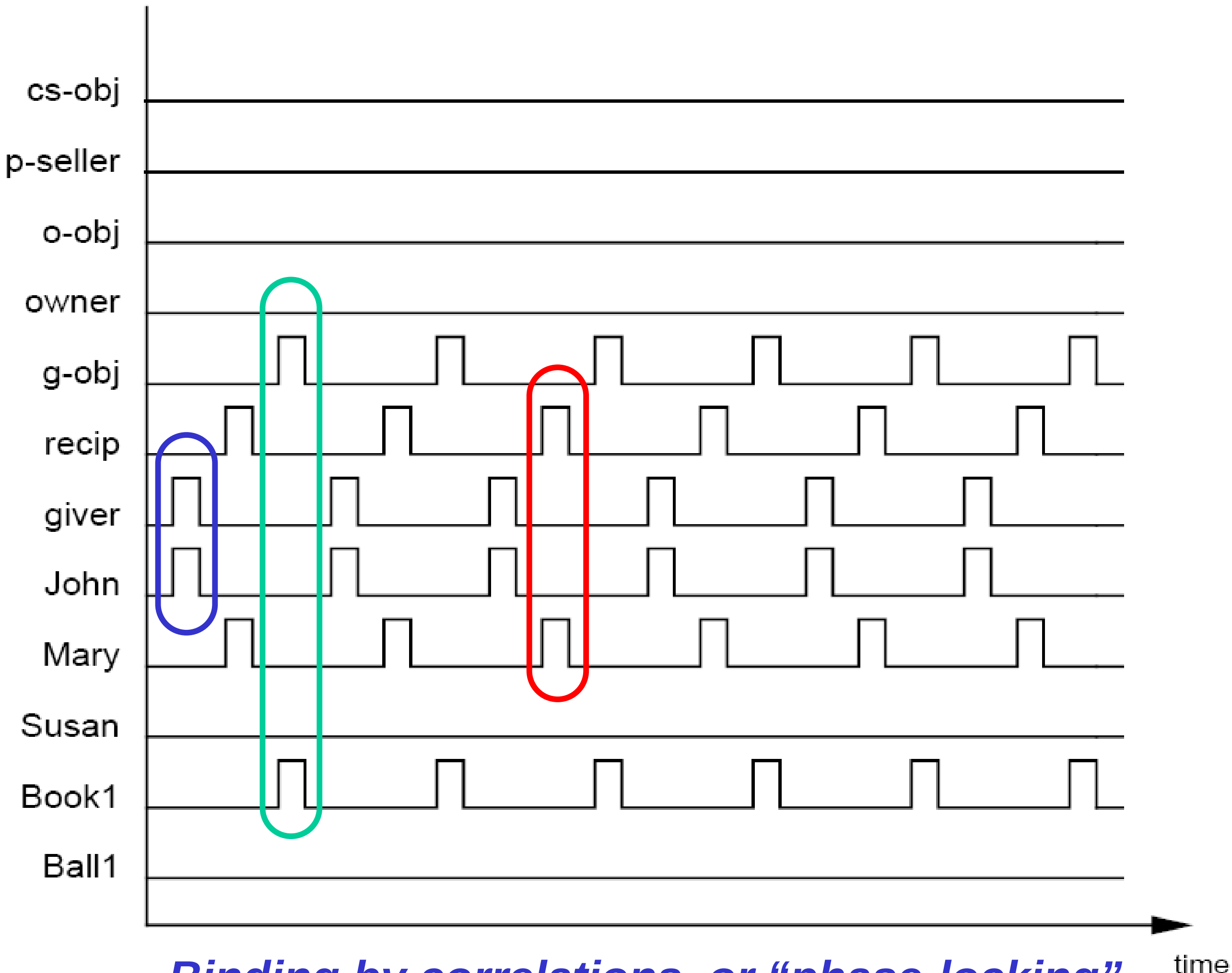


... therefore: "Mary can sell the book."

Shastri, L. & Ajjanagadde, V. (1993) From simple associations to systematic reasoning. *Behavioral and Brain Sciences*, 16(3): 417-451.

Temporal tagging

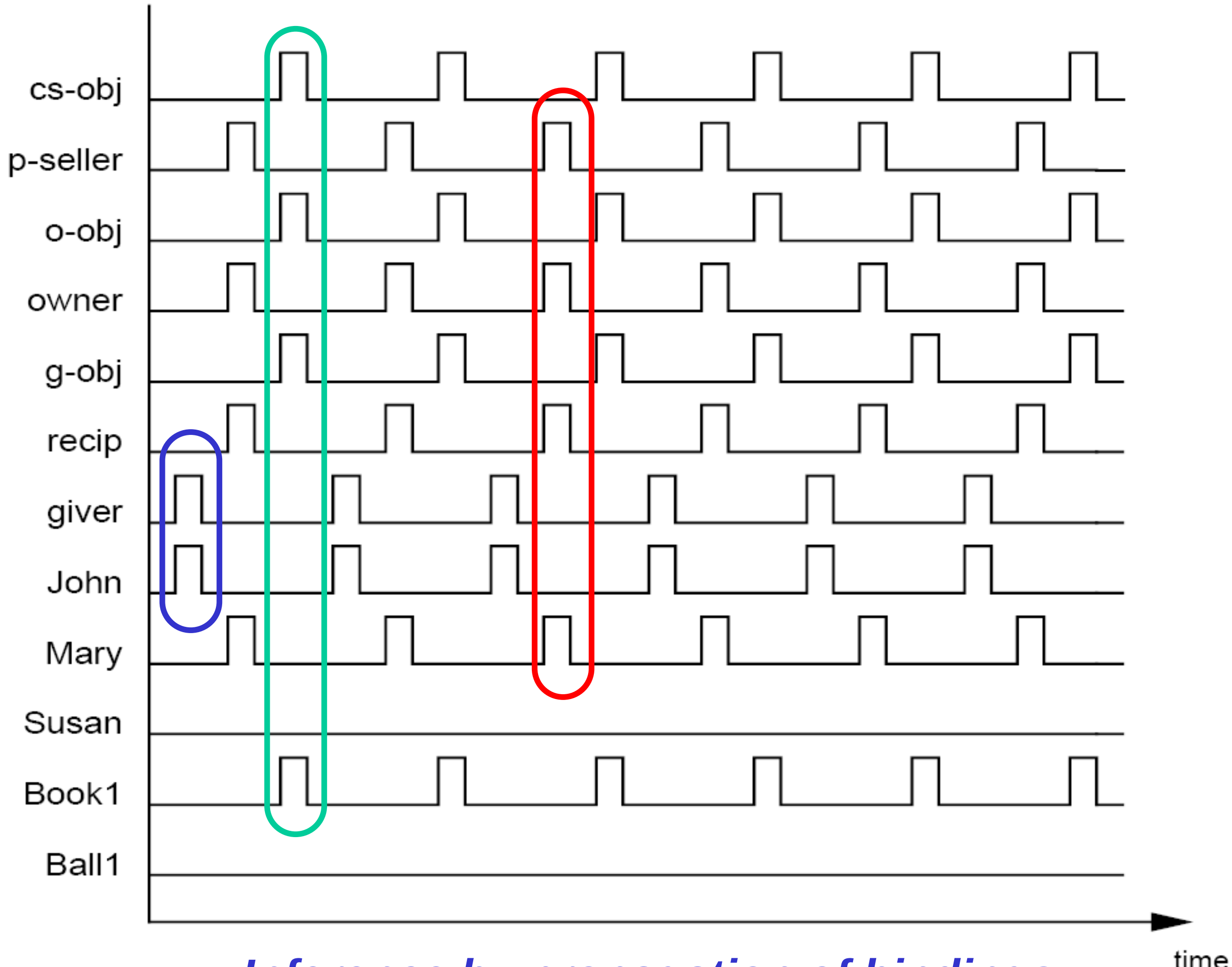
Using correlations to implement binding



Binding by correlations, or "phase-locking"

Temporal tagging

Using correlations to implement binding



Inference by propagation of bindings

Synchronization in Spiking Neural Networks

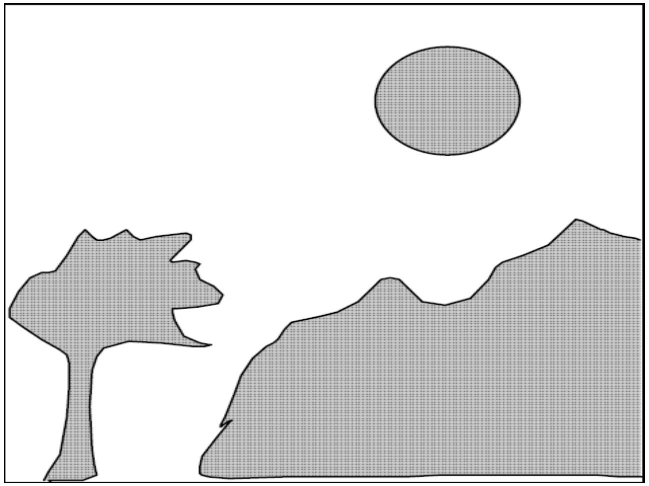
1. **Temporal Coding**
2. **Coupled Oscillators**
   - Temporal tagging
   - Group synchronization
     - The scene segmentation problem
     - Excitatory-inhibitory relaxation oscillator
     - Van der Pol relaxation oscillator
     - Networks of coupled oscillators
     - A model of segmentation by sync: LEGION
   - Traveling waves
3. **Synfire Chains**

Group synchronization

The scene segmentation problem

Real scene

Doursat, Rene (http://www.cse.unr.edu/~doursat)



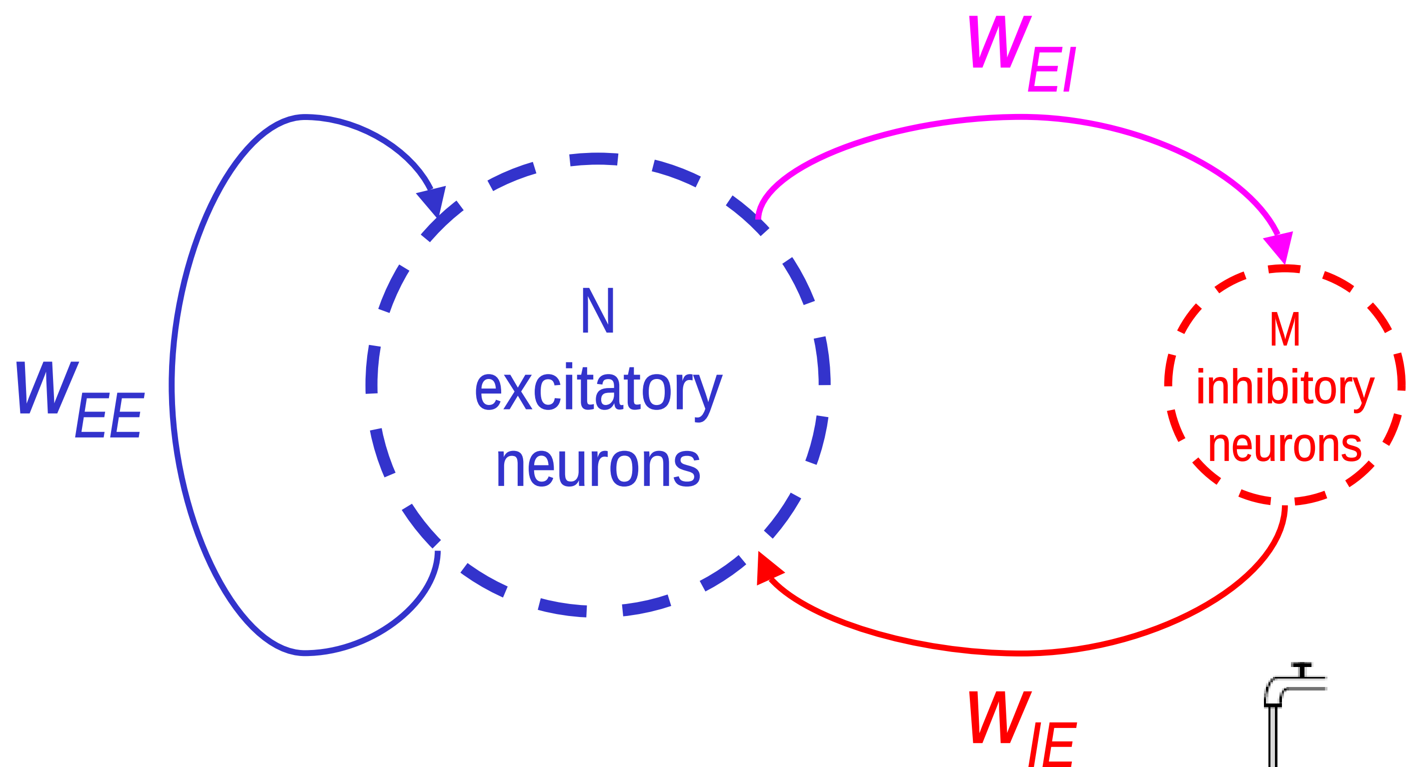
Schematic scene

Wang, DeLiang (http://www.cse.ohio-state.edu/~dwang/)

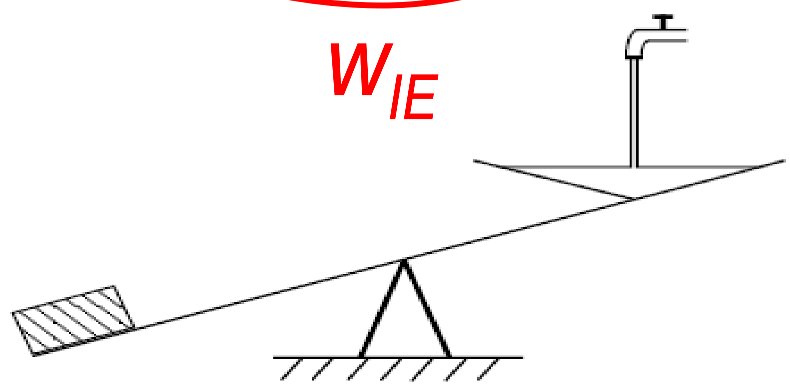
- scene analysis and segmentation is a fundamental aspect of perception
- ability to group elements of a perceived scene or sensory field into coherent clusters or objects
- can be addressed with temporal correlations, especially:
- dynamics of large networks of coupled neural oscillators
- how does it work? . . .

Group synchronization

Excitatory-inhibitory relaxation oscillator



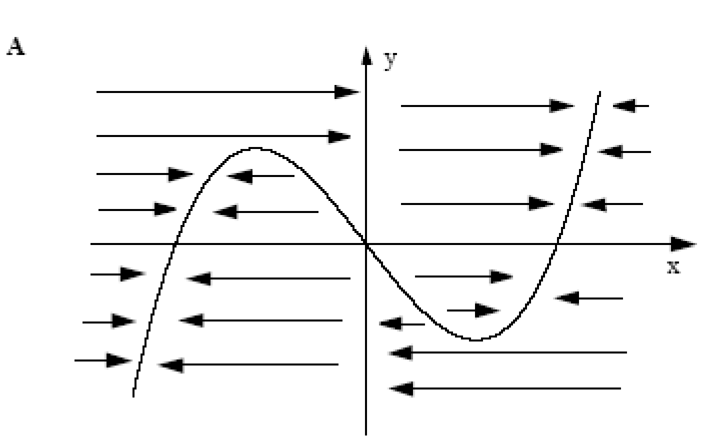
- relaxation oscillators exhibit discontinuous jumps
- different from sinusoidal or harmonic oscillations

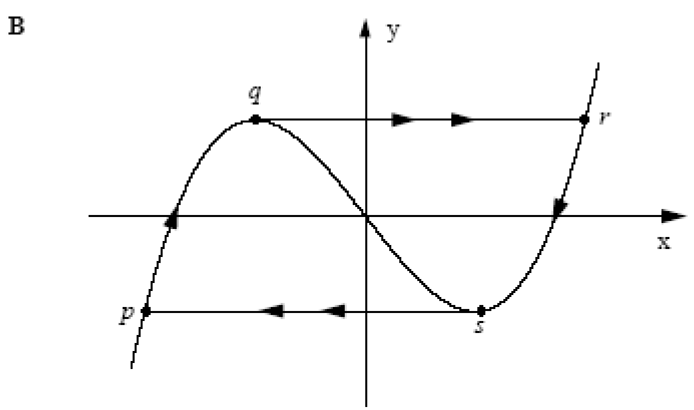


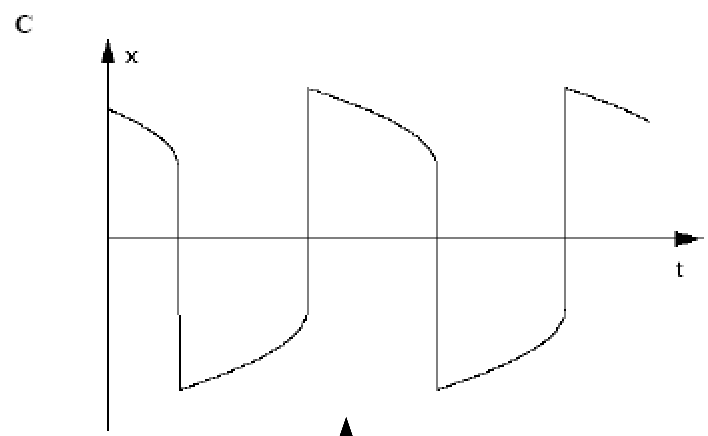
Wang, DeLiang (http://www.cse.ohio-state.edu/~dwang/)

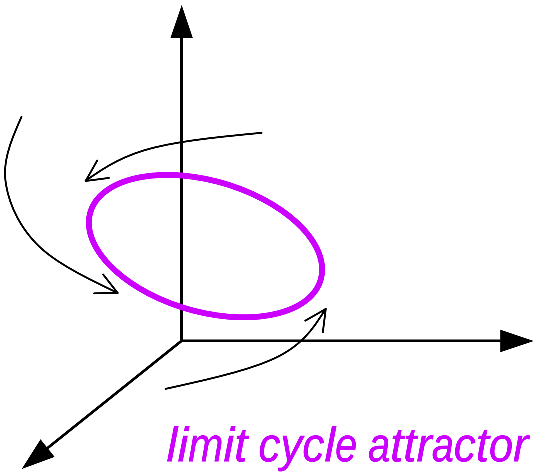
Group synchronization

Van der Pol relaxation oscillator









limit cycle attractor

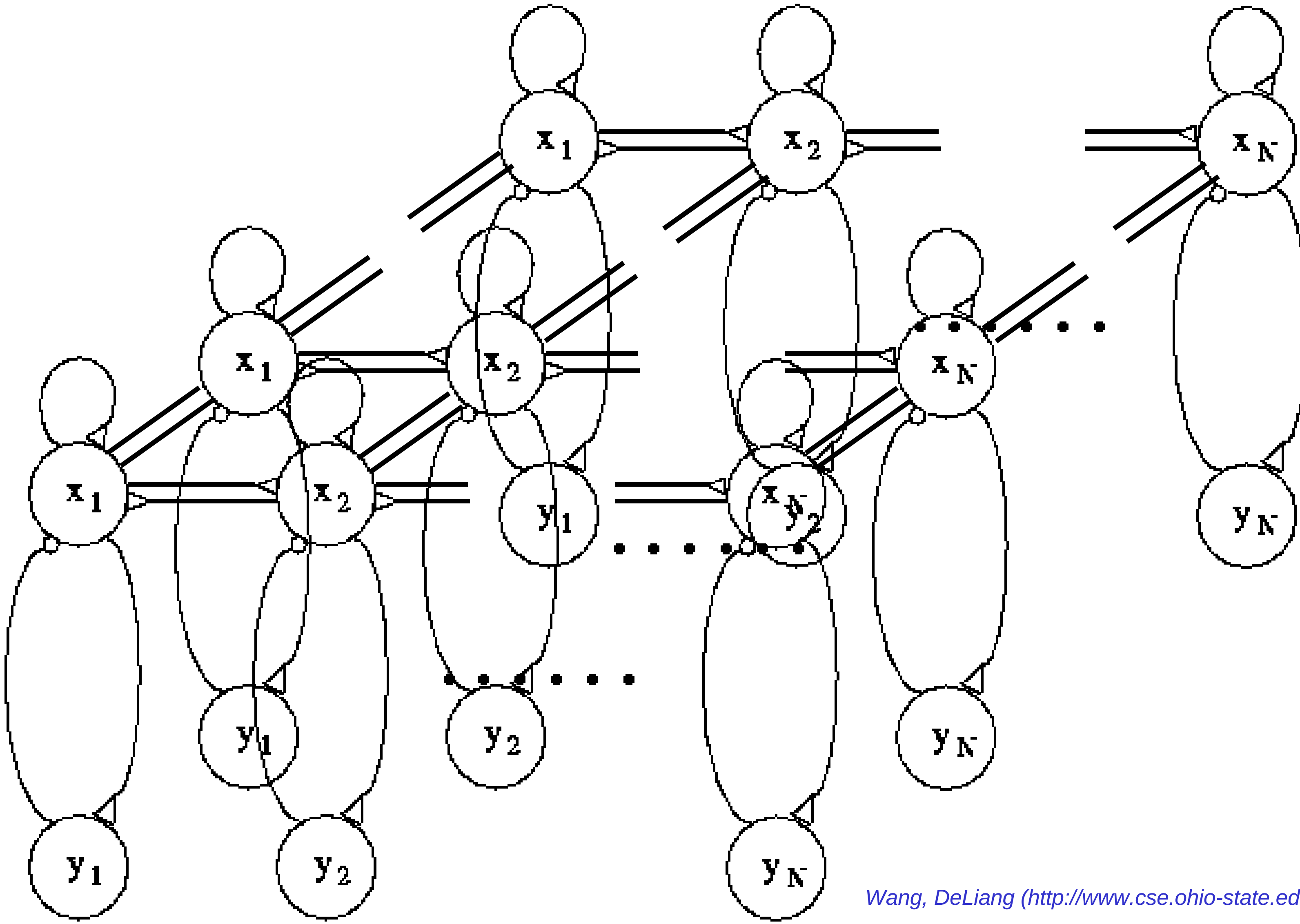
Van der Pol relaxation oscillator

Wang, DeLiang (http://www.cse.ohio-state.edu/~dwang/)

$$\ddot{x} + x = c(1 - x^2)\dot{x} \quad \Leftrightarrow \quad \begin{cases} \dot{x} = c(y - f(x)) \\ \dot{y} = -x / c \end{cases}$$

Group synchronization

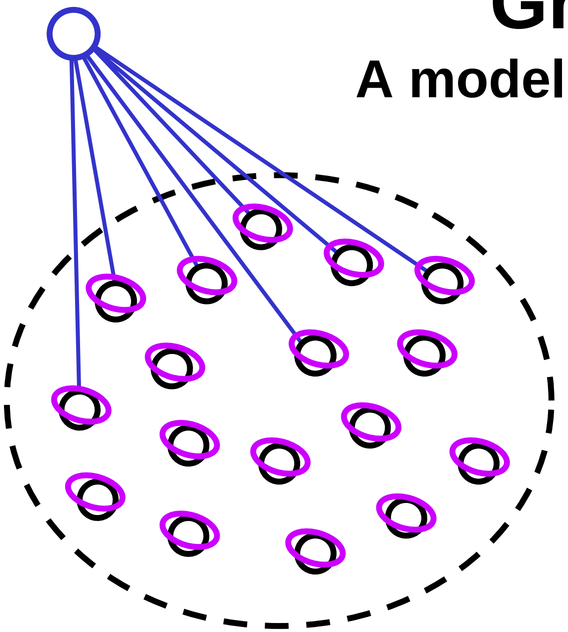
Networks of coupled oscillators



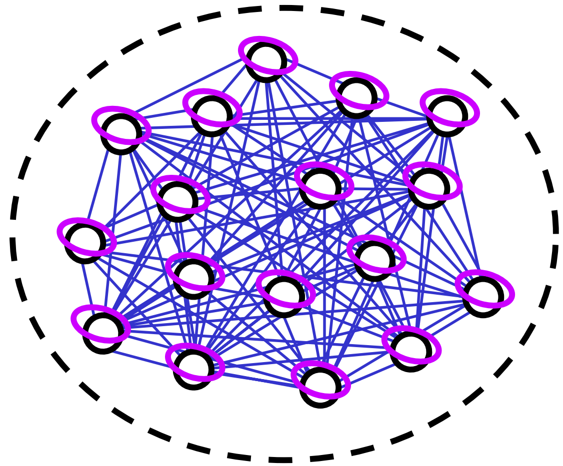
Wang, DeLiang (http://www.cse.ohio-state.edu/~dwang/)

Group synchronization

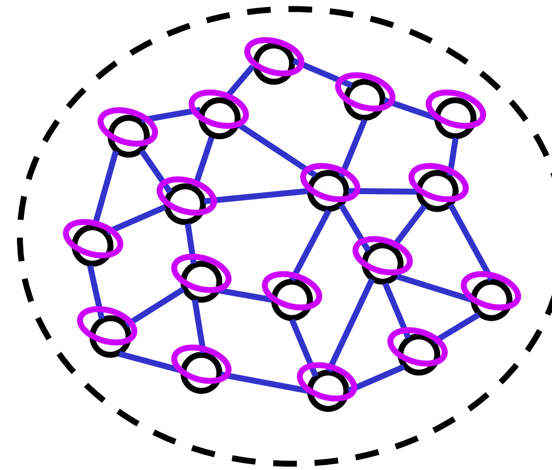
A model of segmentation by sync: LEGION



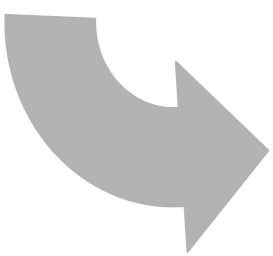
indirectly coupled through central pacemaker

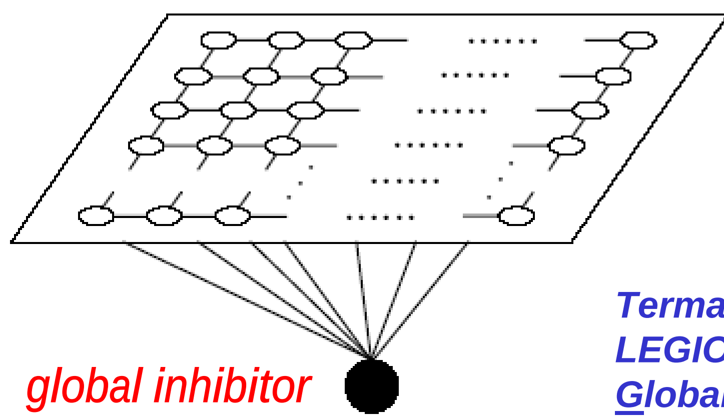


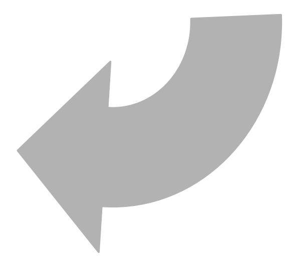
globally coupled



locally coupled





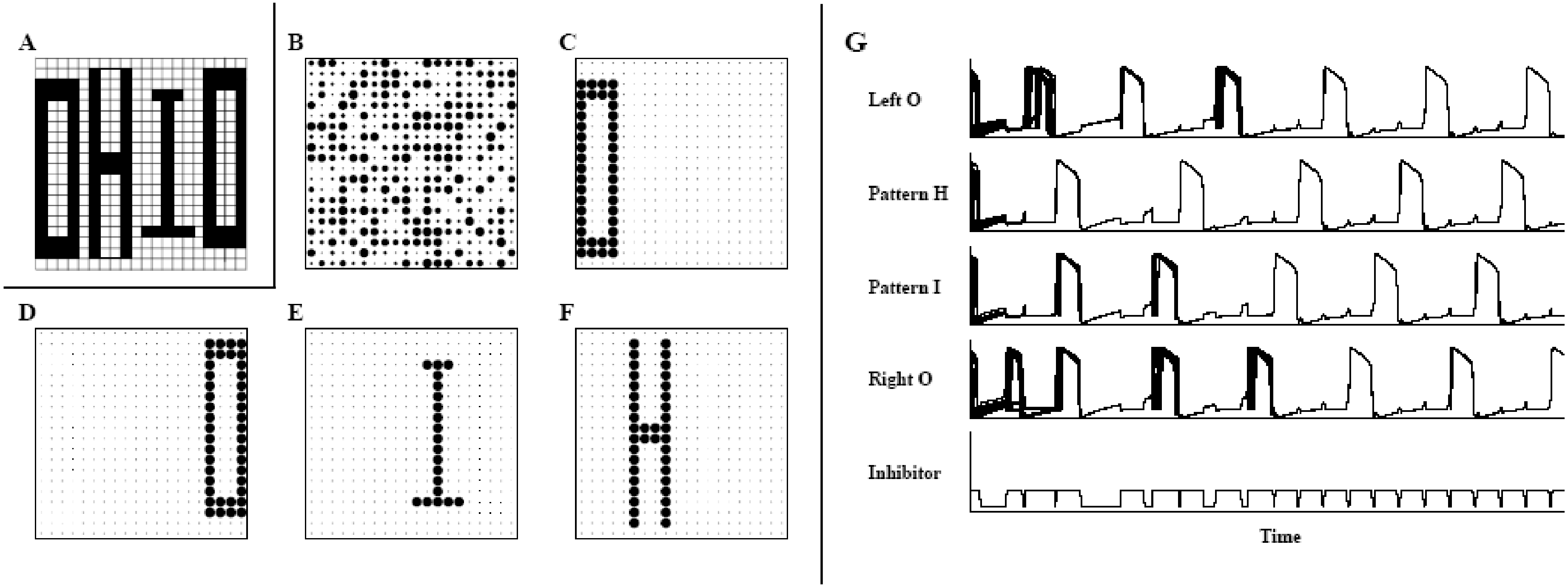


Terman & D.L. Wang's (1995) LEGION network: Locally Excitatory Globally Inhibitory Oscillator Network

(http://www.cse.ohio-state.edu/~dwang/)

Group synchronization

A model of segmentation by sync: LEGION



Wang, D. L. & Terman, D. (1995) Locally excitatory globally inhibitory oscillator networks. *IEEE Trans. Neural Net.*, 6: 283-286.

Group synchronization

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Wang, D. L. & Terman, D. (1997) Image segmentation based on oscillatory correlation. *Neural Computation*, 9: 805-836,1997

Group synchronization

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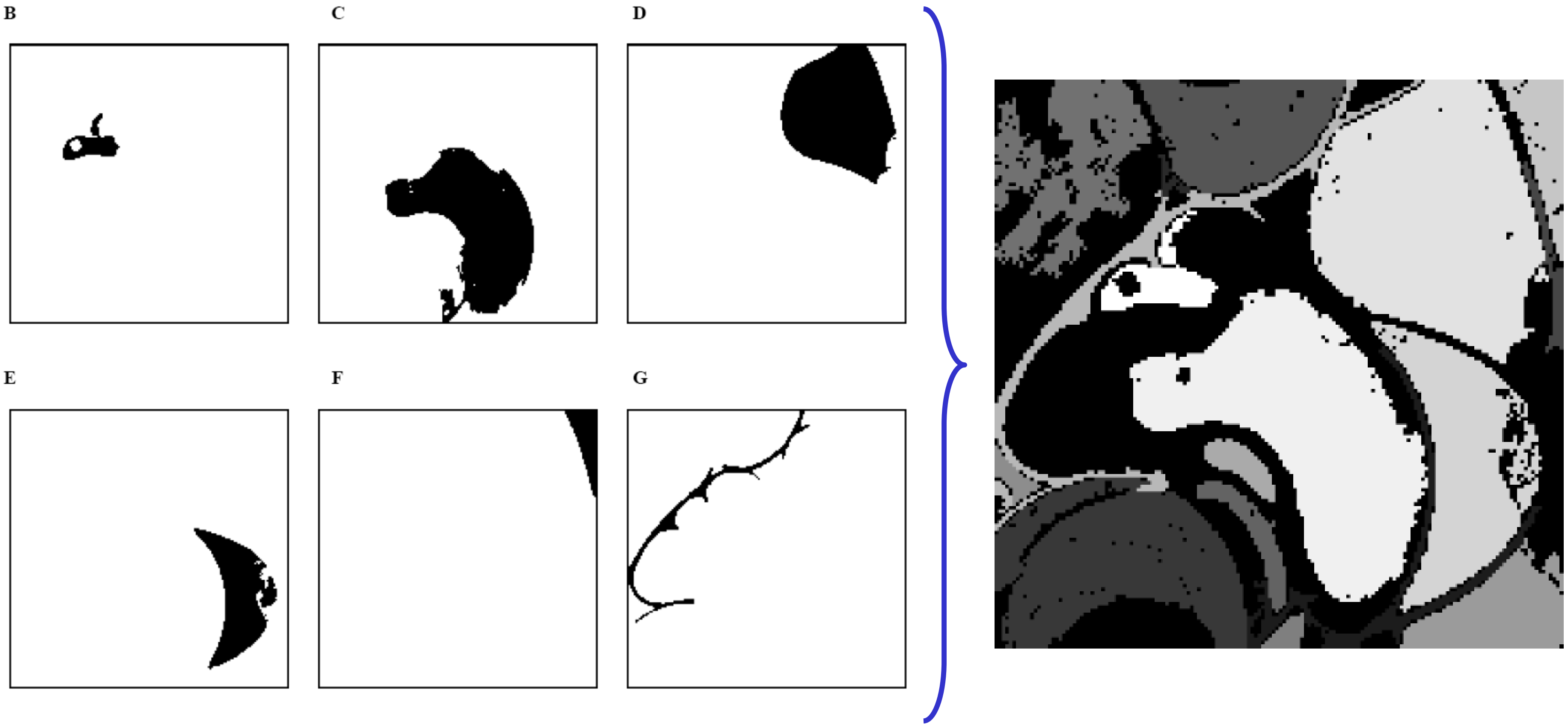

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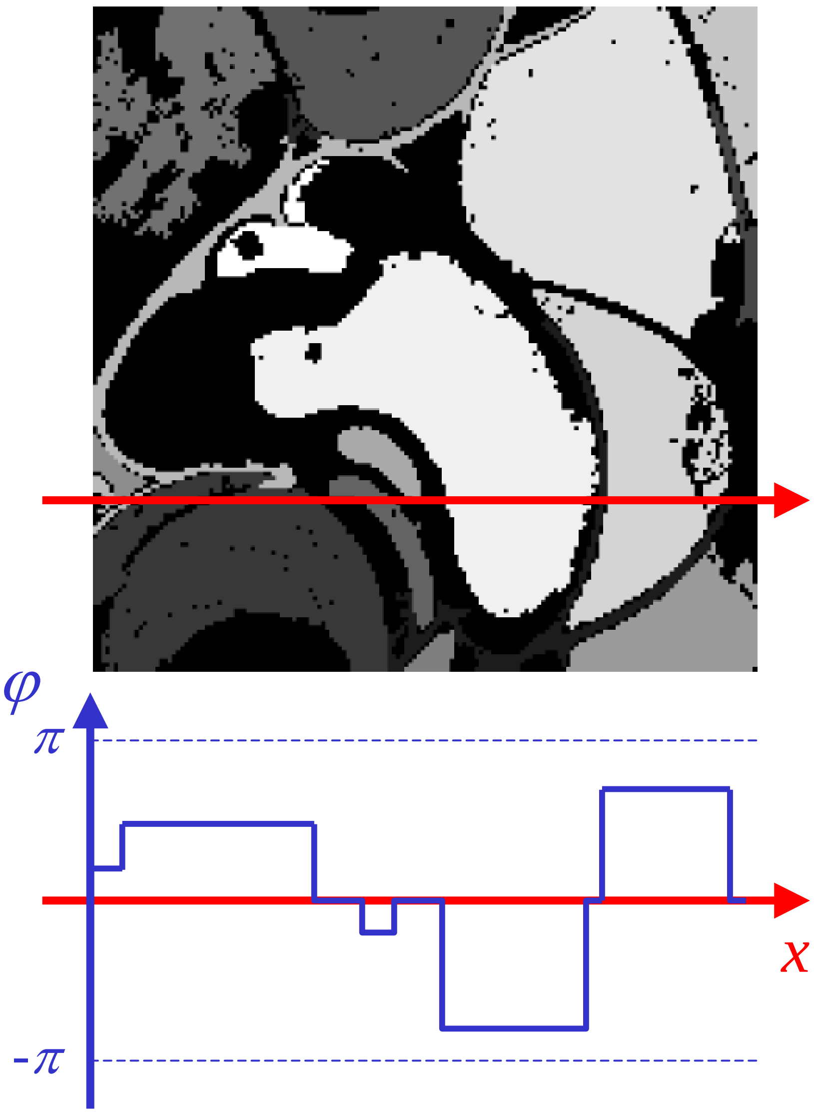
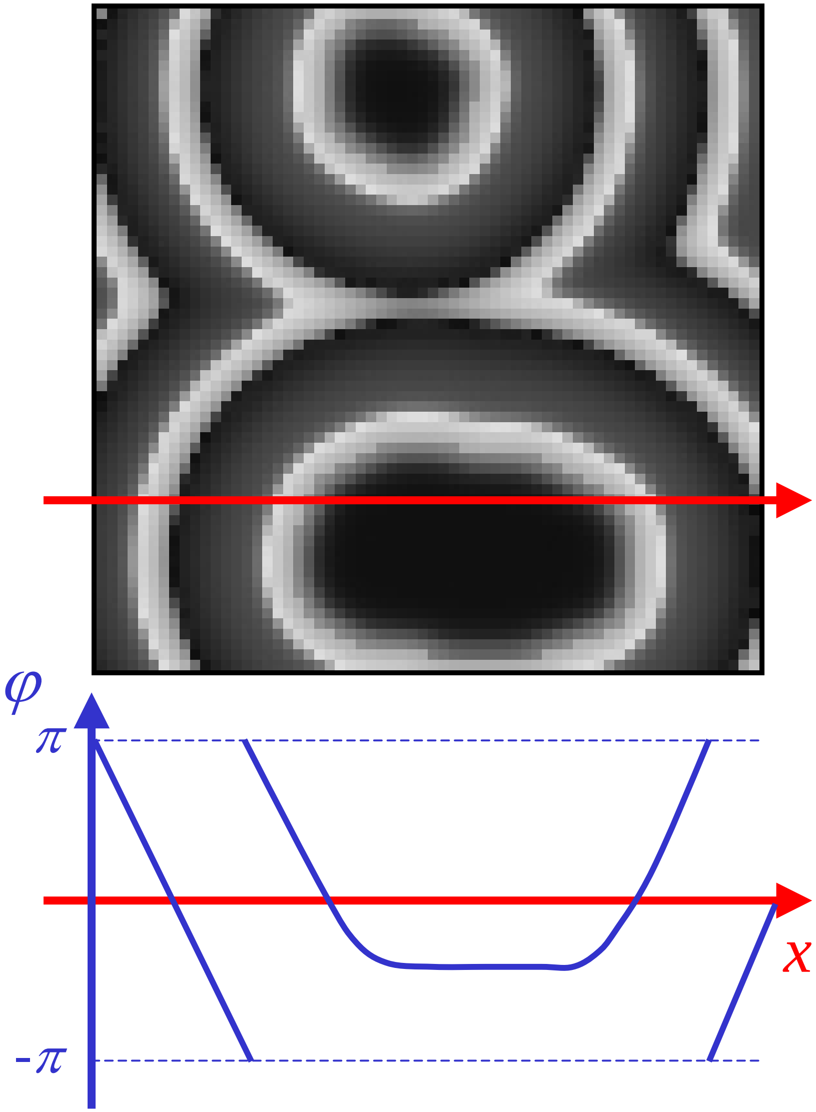
Synchronization in Spiking Neural Networks

1. **Temporal Coding**
2. **Coupled Oscillators**
   - Temporal tagging
   - Group synchronization
   - Traveling waves
     - Phase gradients, instead of plateaus
     - Wave propagation and collision
3. **Synfire Chains**

Traveling waves

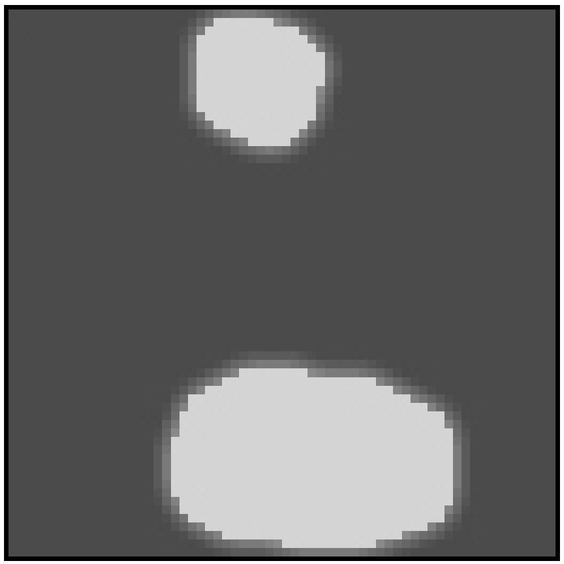
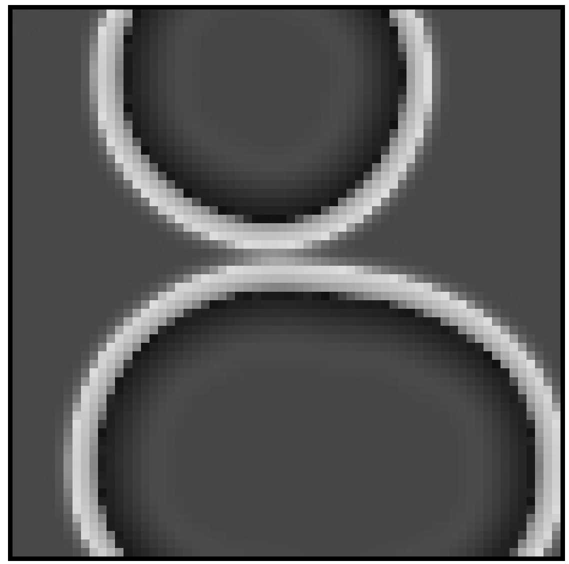
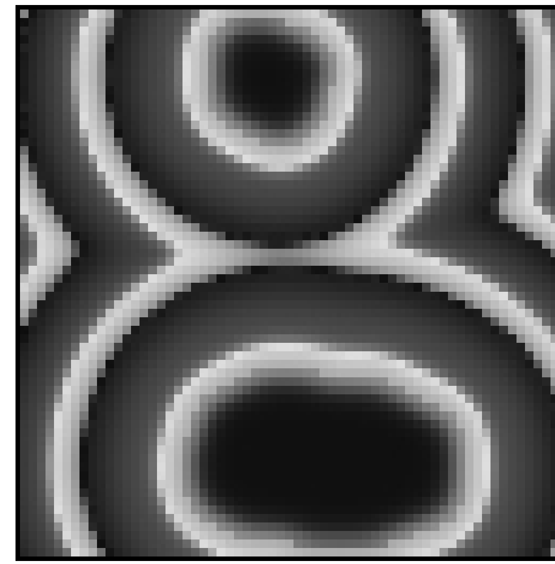
Phase gradients, instead of plateaus





Traveling waves
Wave propagation and collision

$t = 5$ $t = 18$ $t = 32$

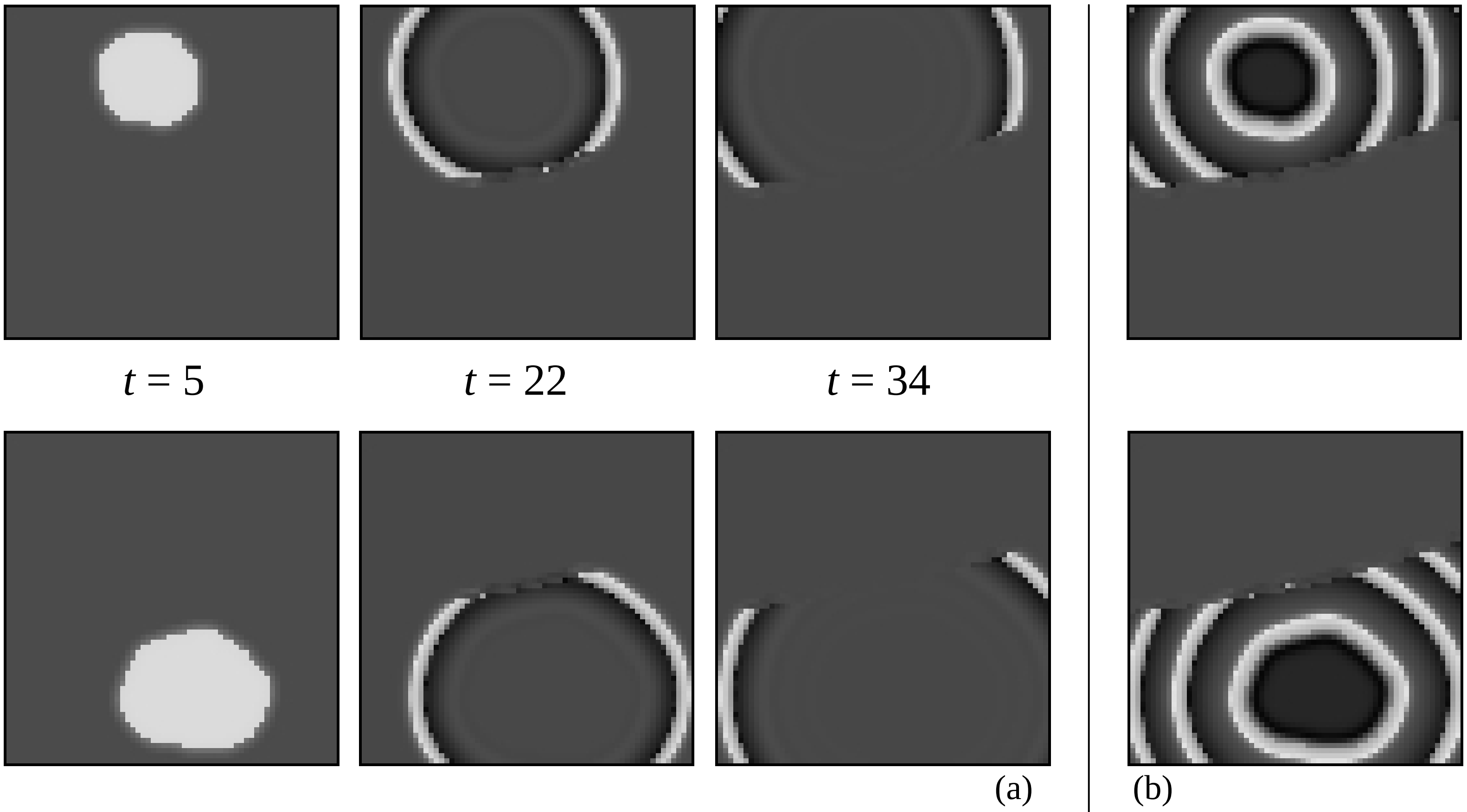




64 x 64 lattice of locally coupled Bonhoeffer-van der Pol oscillators

Doursat, R. & Petitot, J. (2005) Dynamical Systems and Cognitive Linguistics: Toward an Active Morphodynamical Semantics. *IJCNN'05*, to appear in *Neural Networks*.

Traveling waves

Wave propagation and collision



Two cross-coupled, mutually inhibiting lattices of coupled oscillators

Doursat, R. & Petitot, J. (2005) Dynamical Systems and Cognitive Linguistics: Toward an Active Morphodynamical Semantics. *IJCNN'05*, to appear in *Neural Networks*.

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3. **Synfire Chains**
   - The compositionality of cognition
   - A model of synfire self-organization
   - Simulations of synfire growth
   - Synfire chain bibliography

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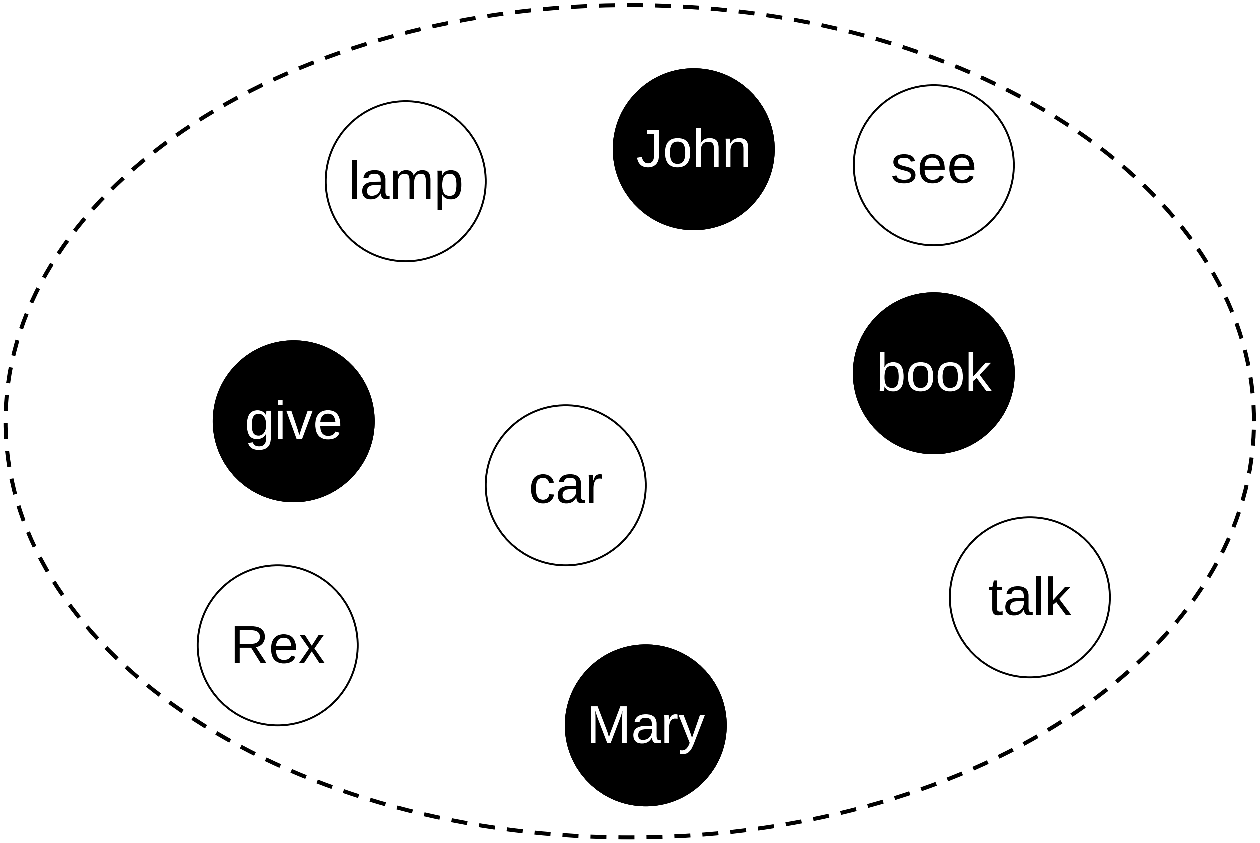
- The compositionality of cognition
  - Compositionality in language
  - Compositionality in vision
  - Structural bonds
- A model of synfire self-organization
- Simulations of synfire growth
- Synfire chain bibliography

The compositionality of cognition

Compositionality in language

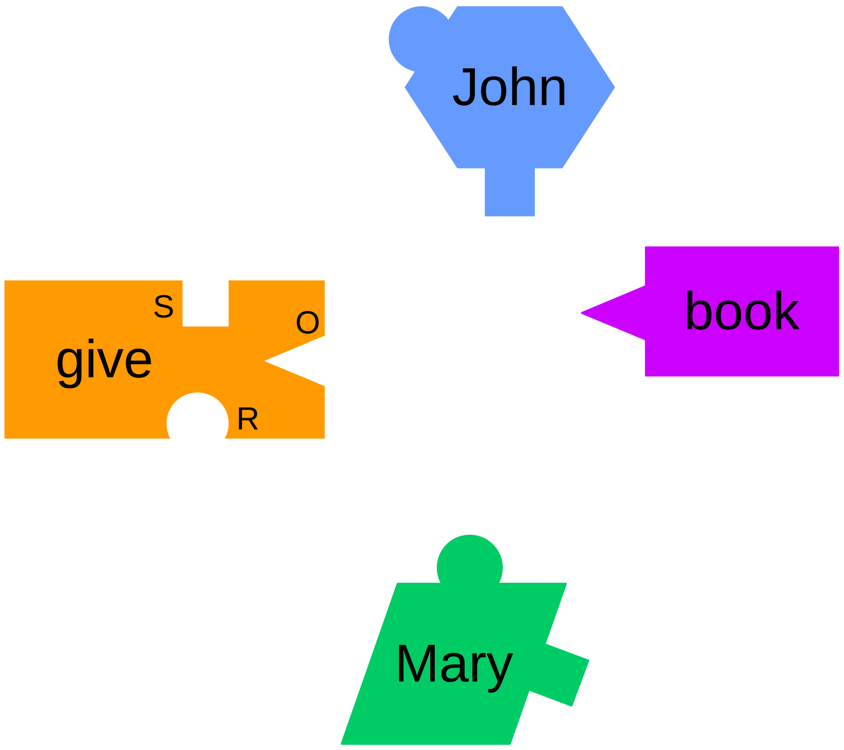


(a) John gives a book to Mary.

(b) Mary gives a book to John.

(c)* Book John Mary give.

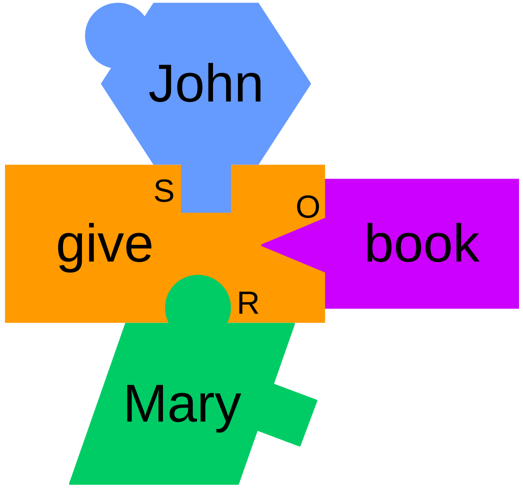
The compositionality of cognition
Compositionality in language



→ language is a
"building block"
construction game

The compositionality of cognition

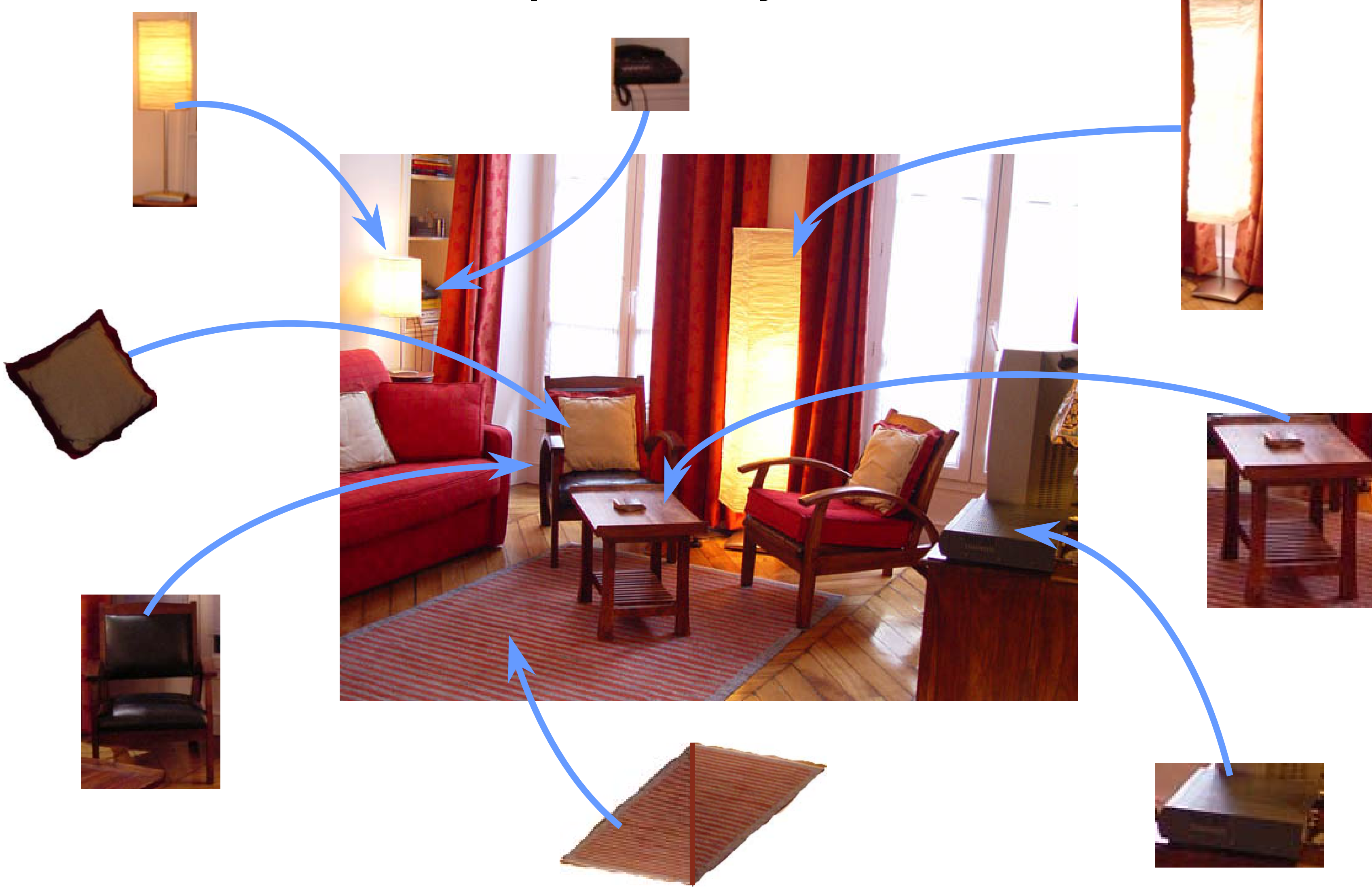
Compositionality in language



→ language is a "building block" construction game

The compositionality of cognition

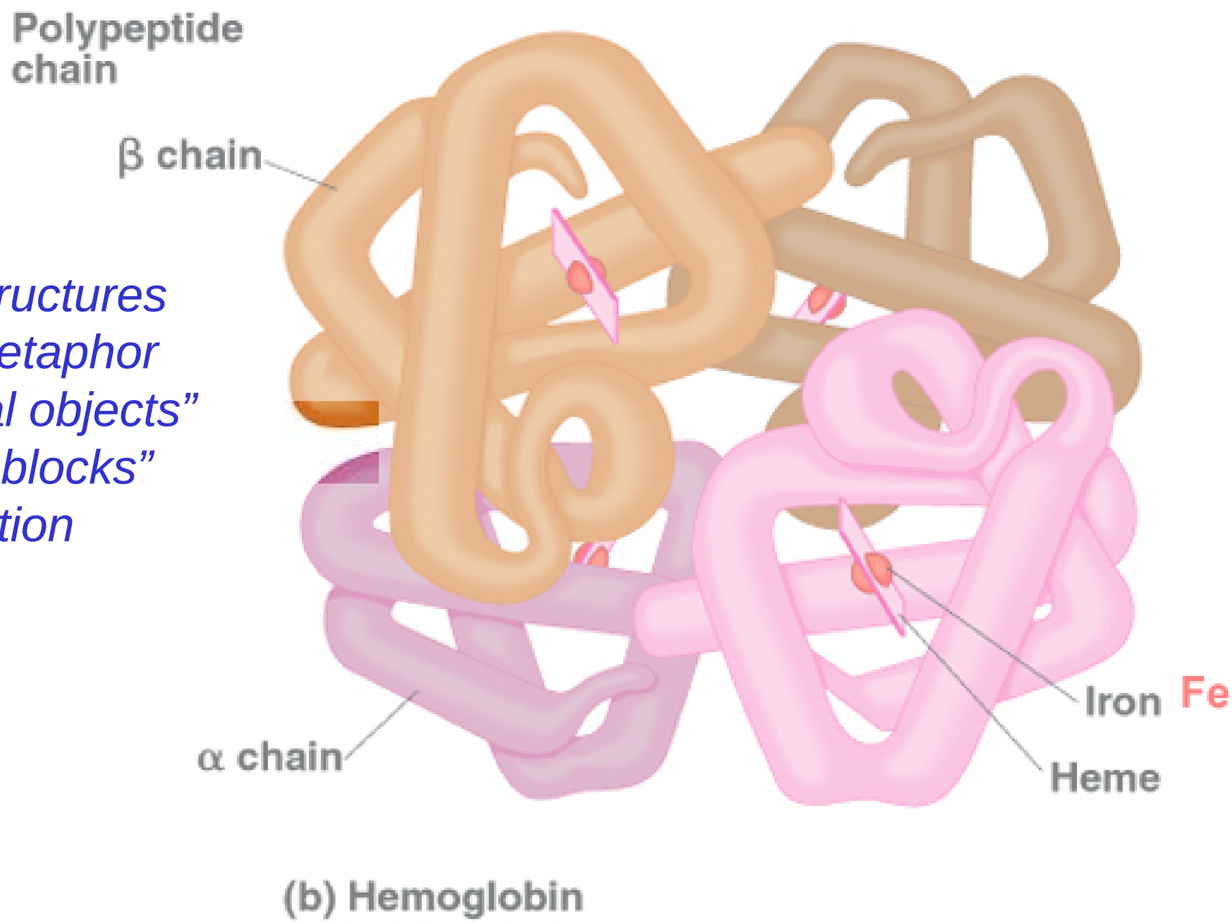
Compositionality in vision



(http://www.rentparis.com/17/17.en.html)

The compositionality of cognition
Structural bonds

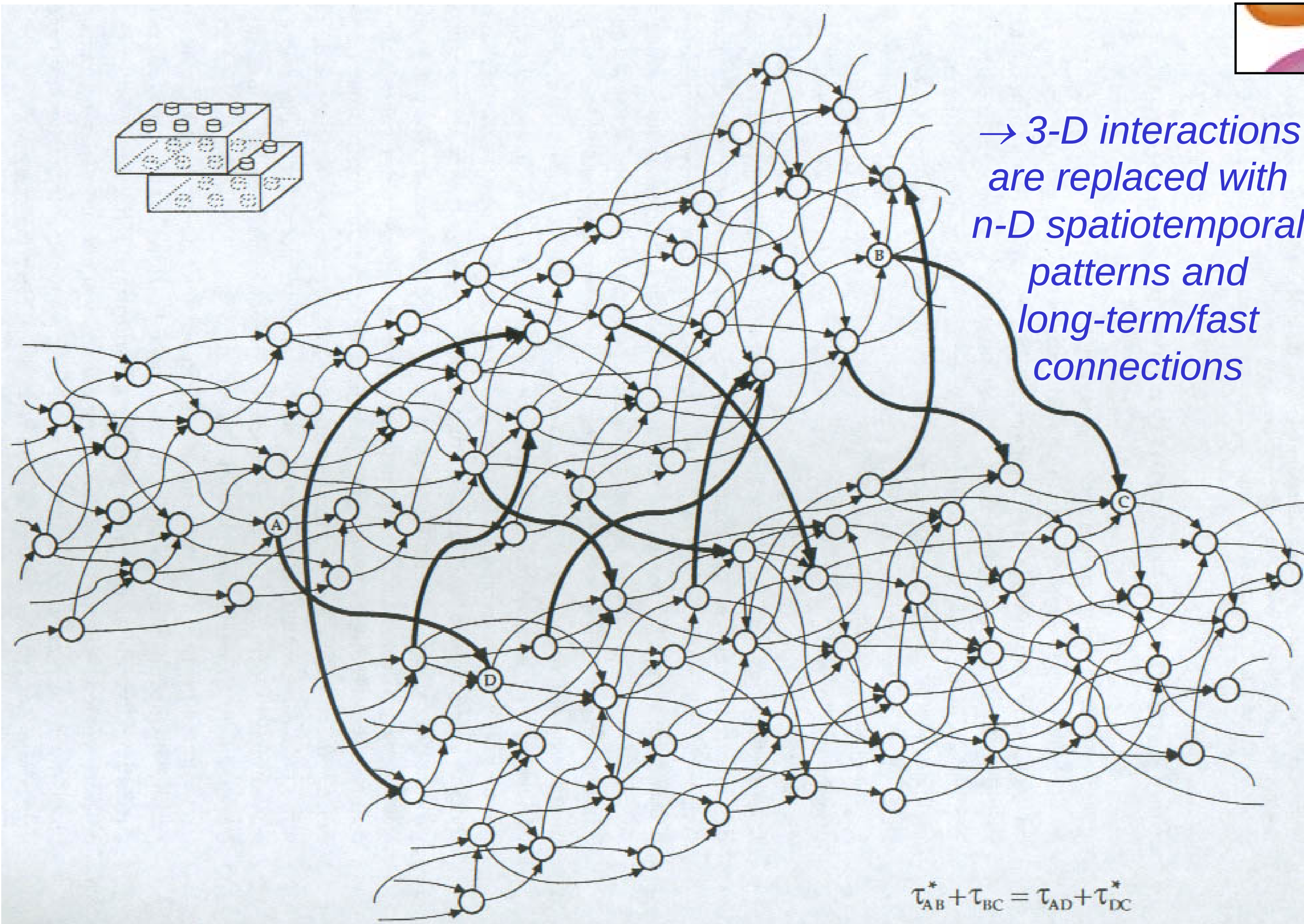
→ protein structures provide a metaphor for the “mental objects” or “building blocks” of cognition



(http://fig.cox.miami.edu/~cmallery/150/chemistry/hemoglobin.jpg)

The compositionality of cognition

Structural bonds



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

Synchronization in Spiking Neural Networks

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     - Focusing of the innervation
     - A simple binary model
     - The growth of a synfire chain
     - Crystallization from seed neurons
     - Dynamic composition of two chains
   - Simulations of synfire growth
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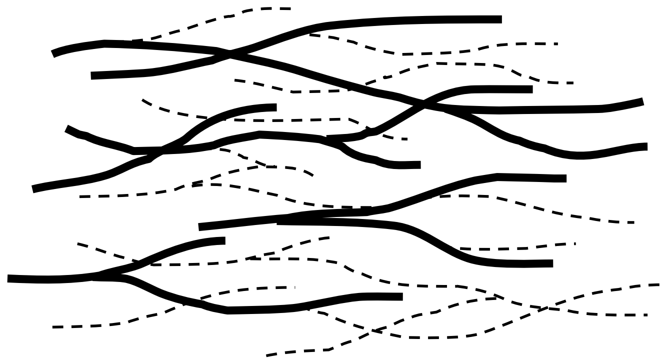
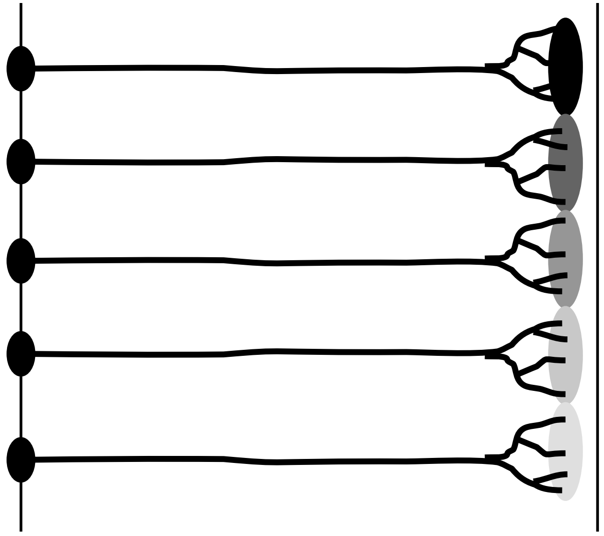
A model of synfire self-organization

Focusing of the innervation



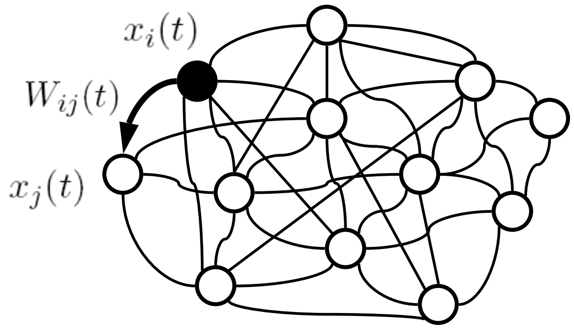
“selective stabilization” (Changeux & Danchin, 1976)



retinotopic projection (Willshaw & von der Malsburg, 1976)

A model of synfire self-organization

A simple binary model



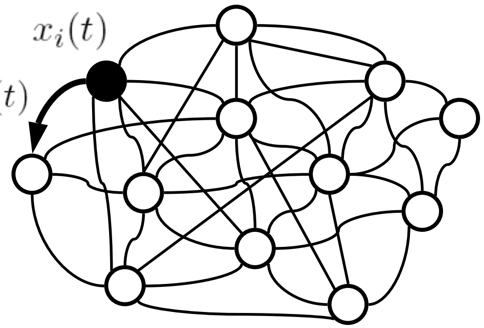
- Neuronal dynamics: fast McCulloch & Pitts

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

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

A model of synfire self-organization

A simple binary model



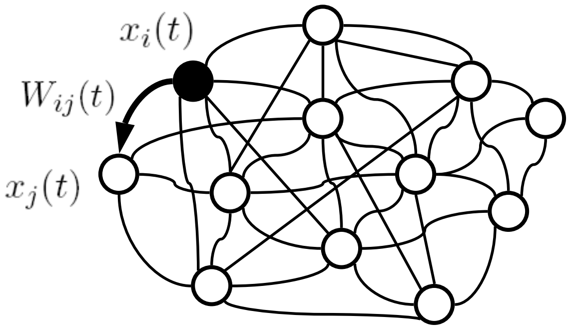
- Synaptic dynamics: fast Hebbian cooperation

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

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

A model of synfire self-organization

A simple binary model



- Synaptic dynamics: competition

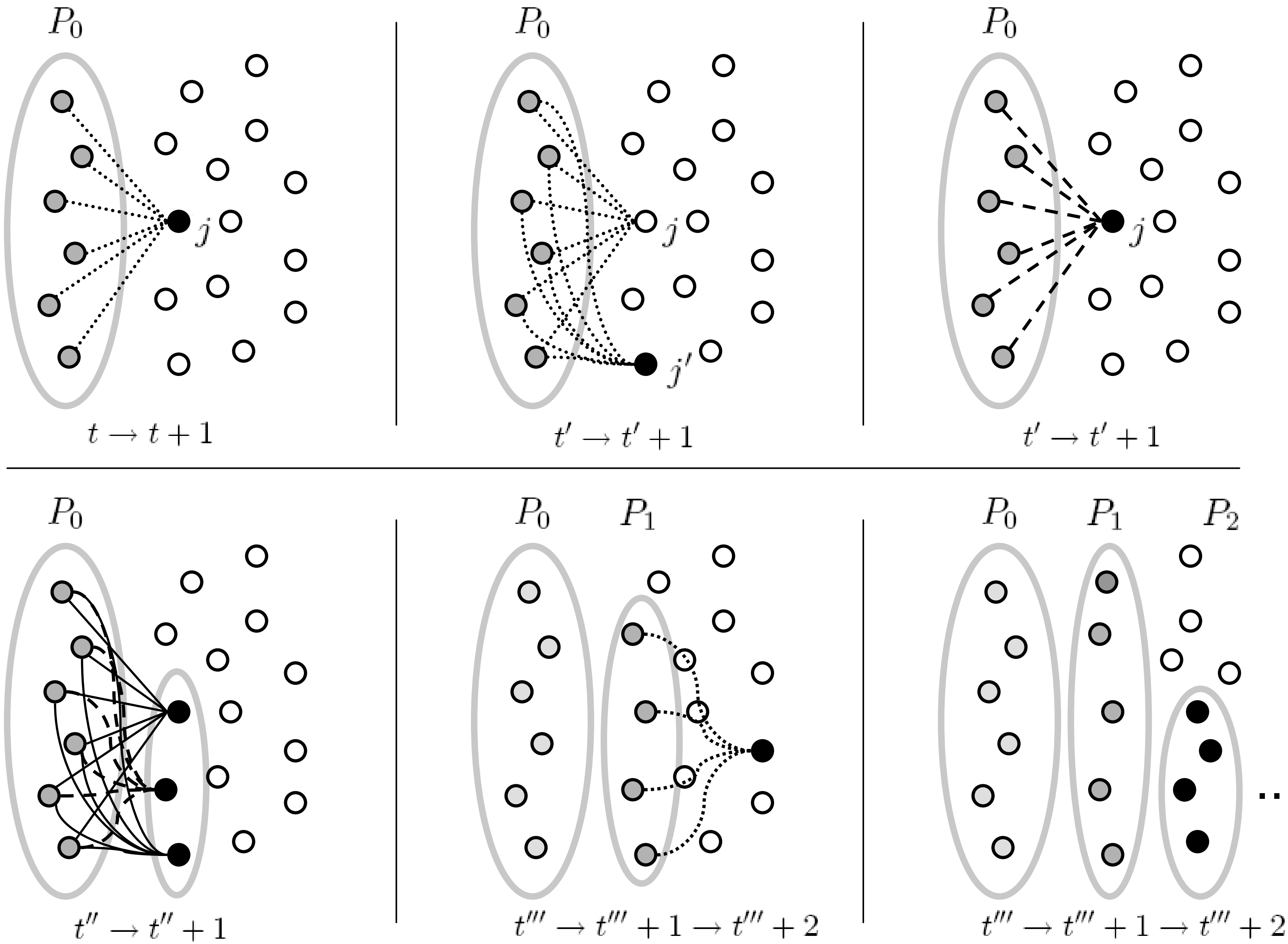
$$W_{ij}(t) = W_{ij}(t-1) + A_{ij}(t) + \underbrace{B_{ij}(t)}$$

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

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

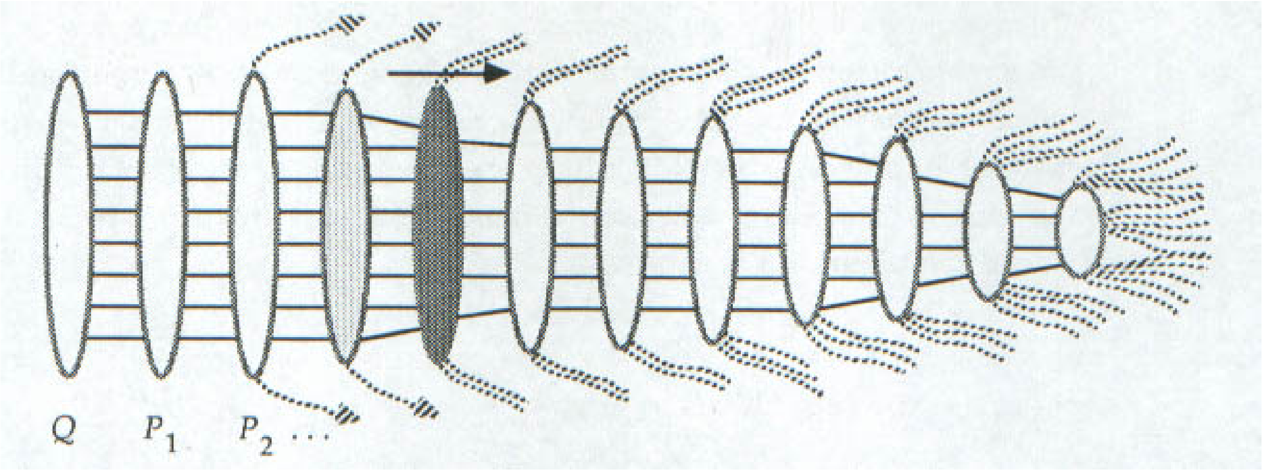
A model of synfire self-organization

The growth of a synfire chain



A model of synfire self-organization

The growth of a synfire chain

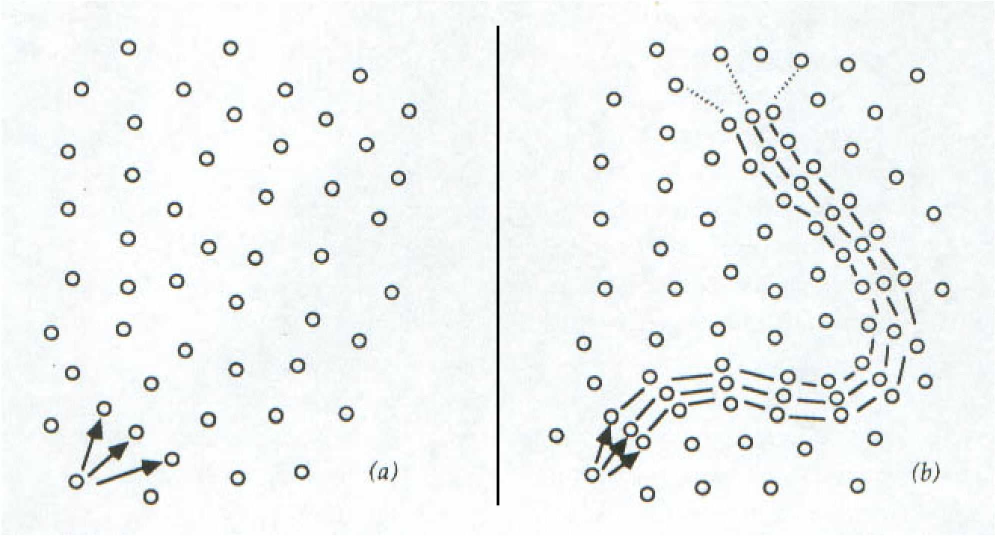


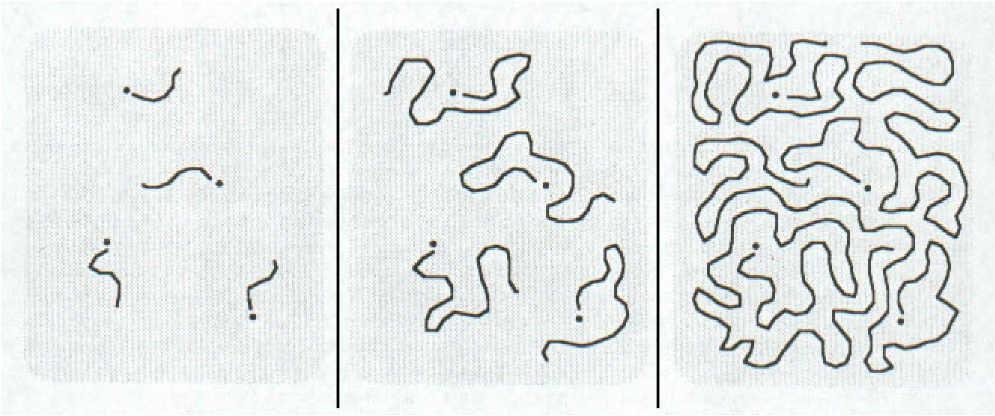
→ synchronous pools start creating new pools ahead of them before reaching maturity, making a "beveled head" (along propagation axis)

Doursat (1991) An epigenetic development model of the nervous system. In: *A contribution to the study of representations in the nervous system and in artificial neural networks*, Ph.D. dissertation, Université Paris VI. (Supervised by Bienenstock, E.)

A model of synfire self-organization

Crystallization from seed neurons

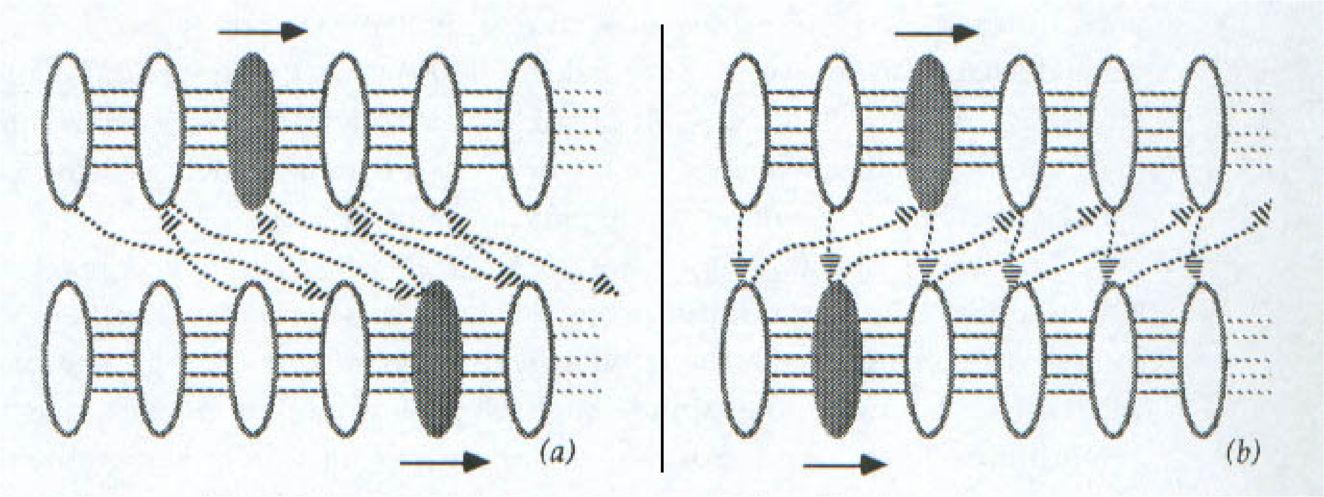




Doursat (1991)

A model of synfire self-organization

Dynamics composition of two chains



→ *"zipper-matching"*

Doursat (1991)

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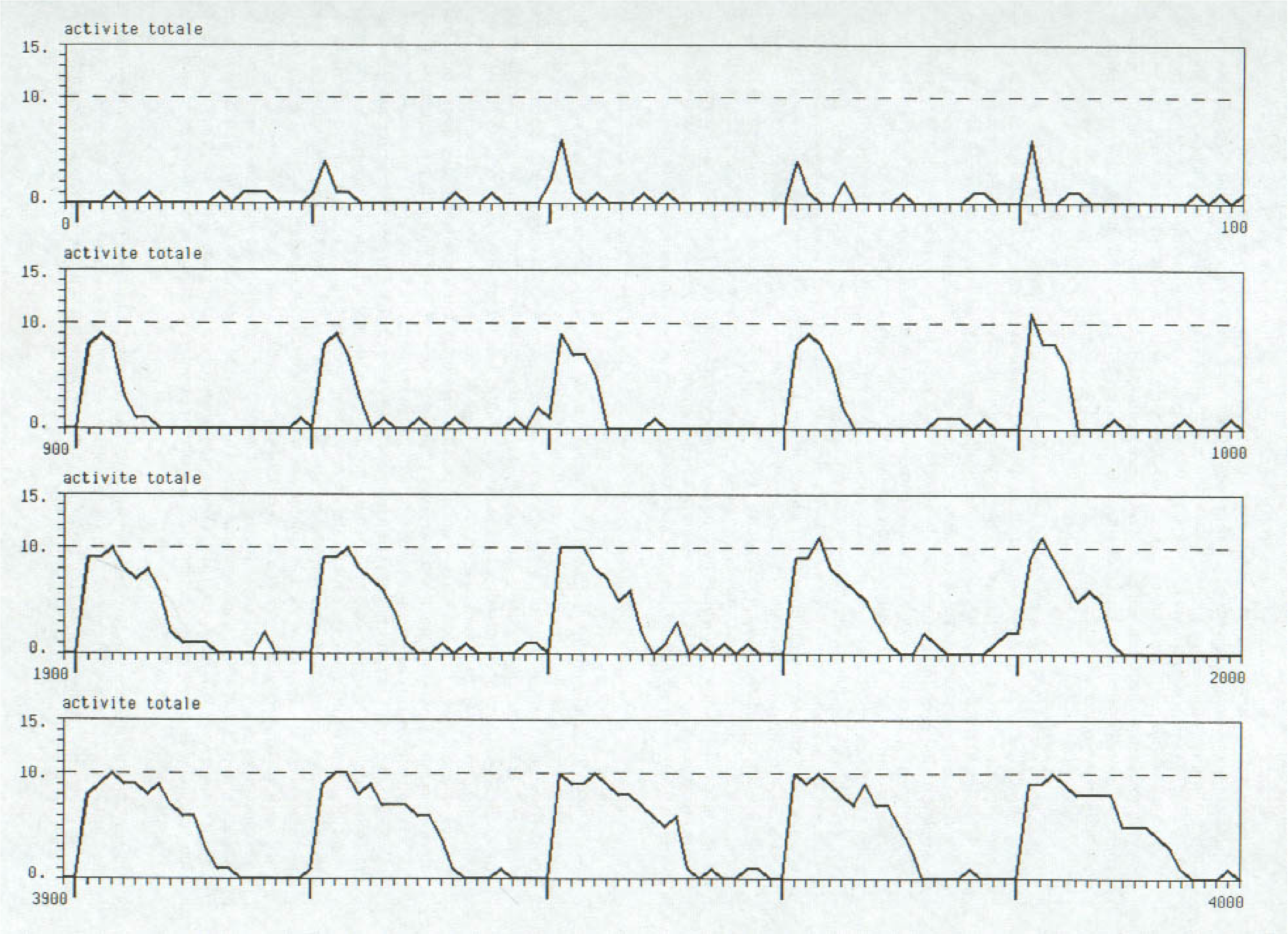
  - Network self-organization
  - Cross-correlograms
  - Synaptic evolution
  - Synfire braids
- Synfire chain bibliography

Simulations of synfire growth

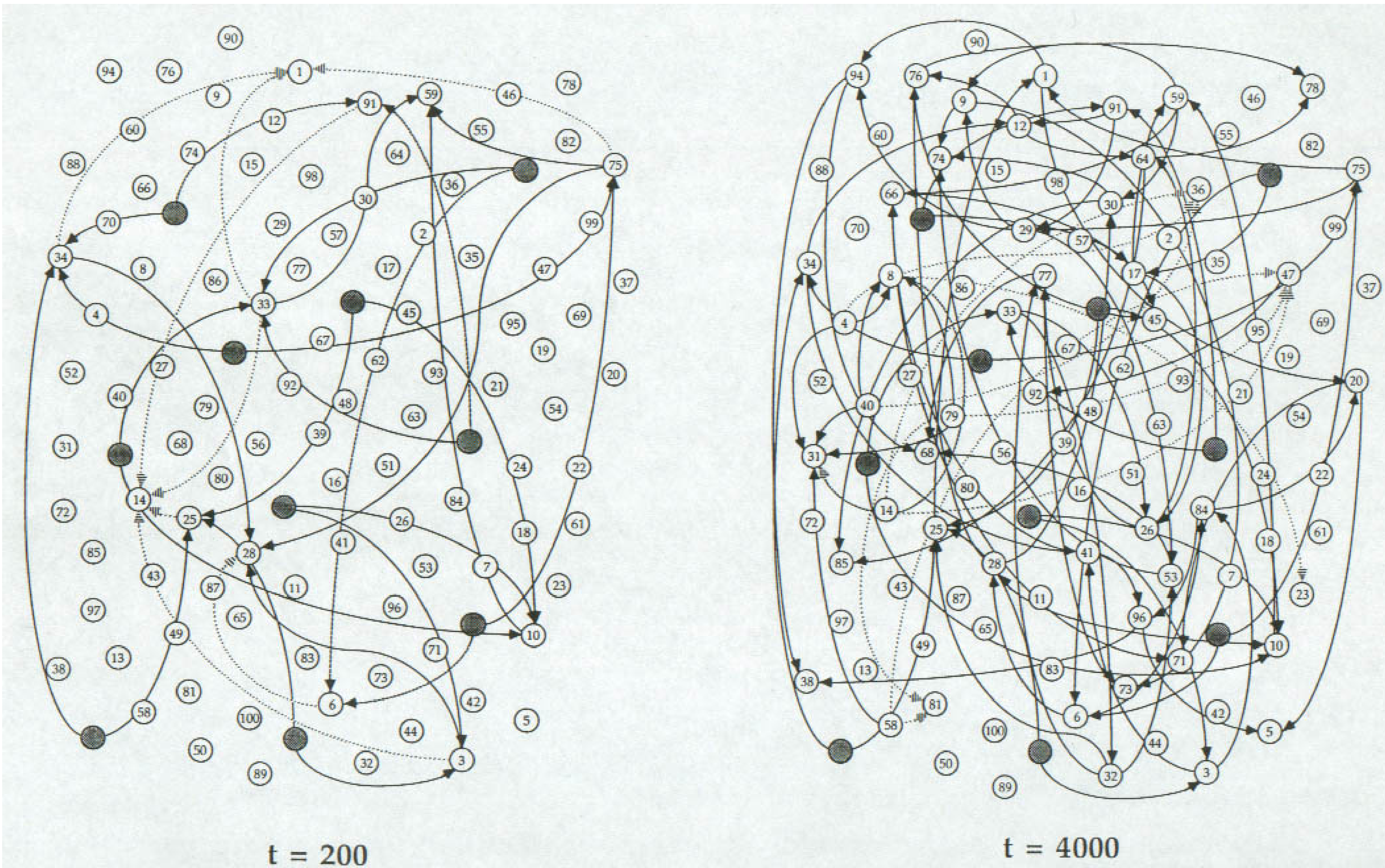
Network activity



Doursat (1991)

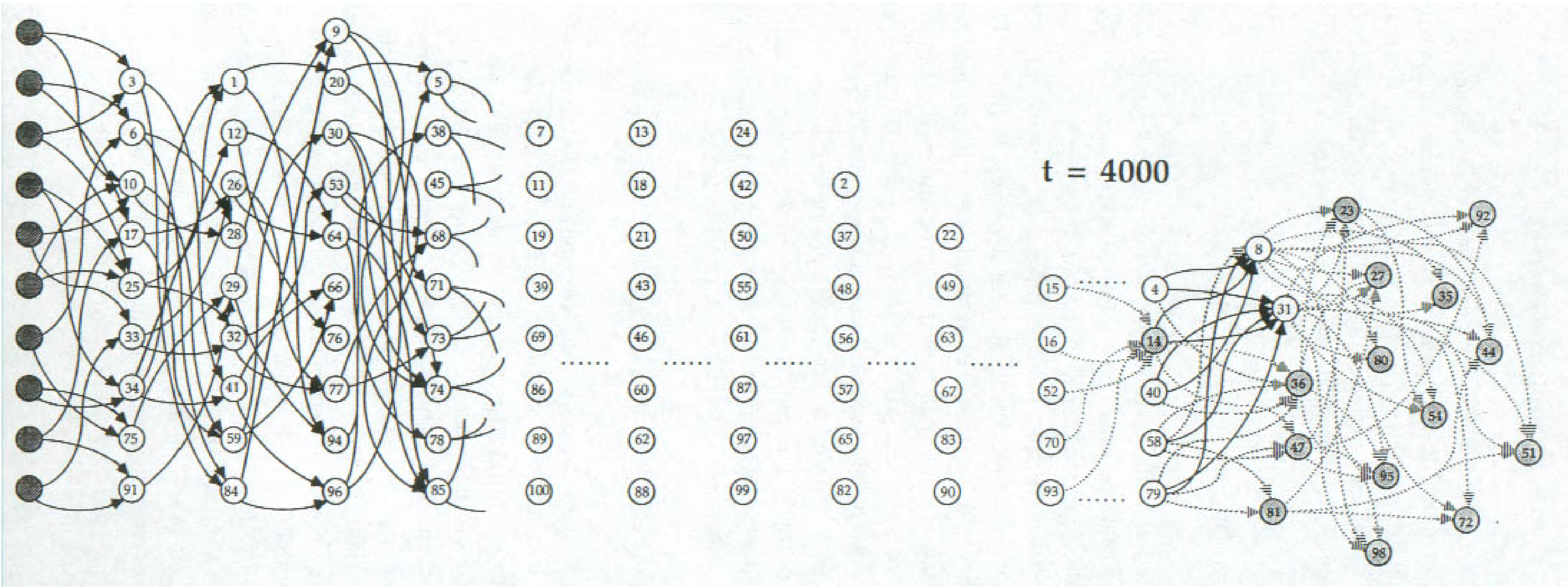
Simulations of synfire growth

Network self-organization



Doursat (1991)

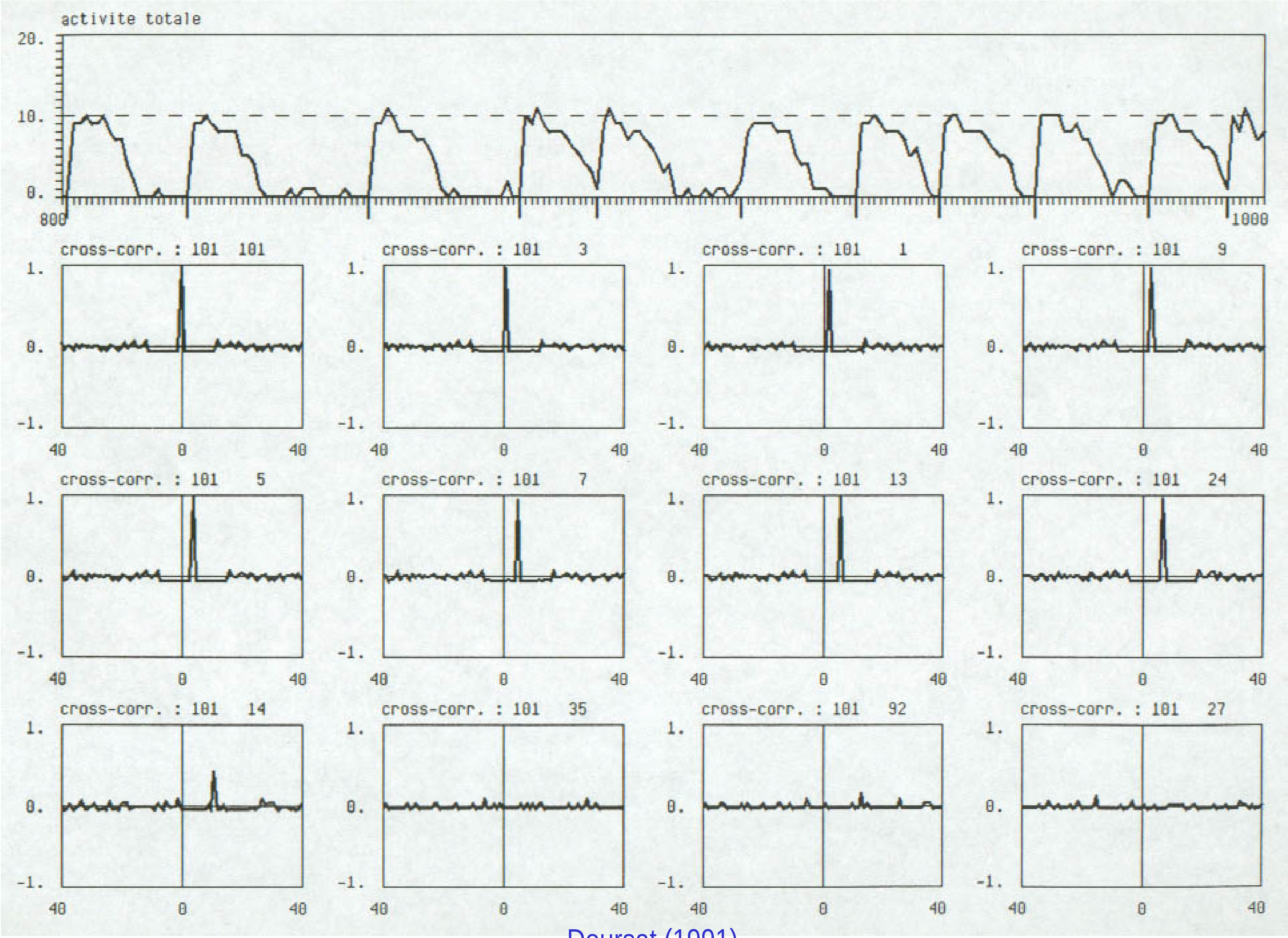
Simulations of synfire growth
Network self-organization



Doursat (1991)

Simulations of synfire growth

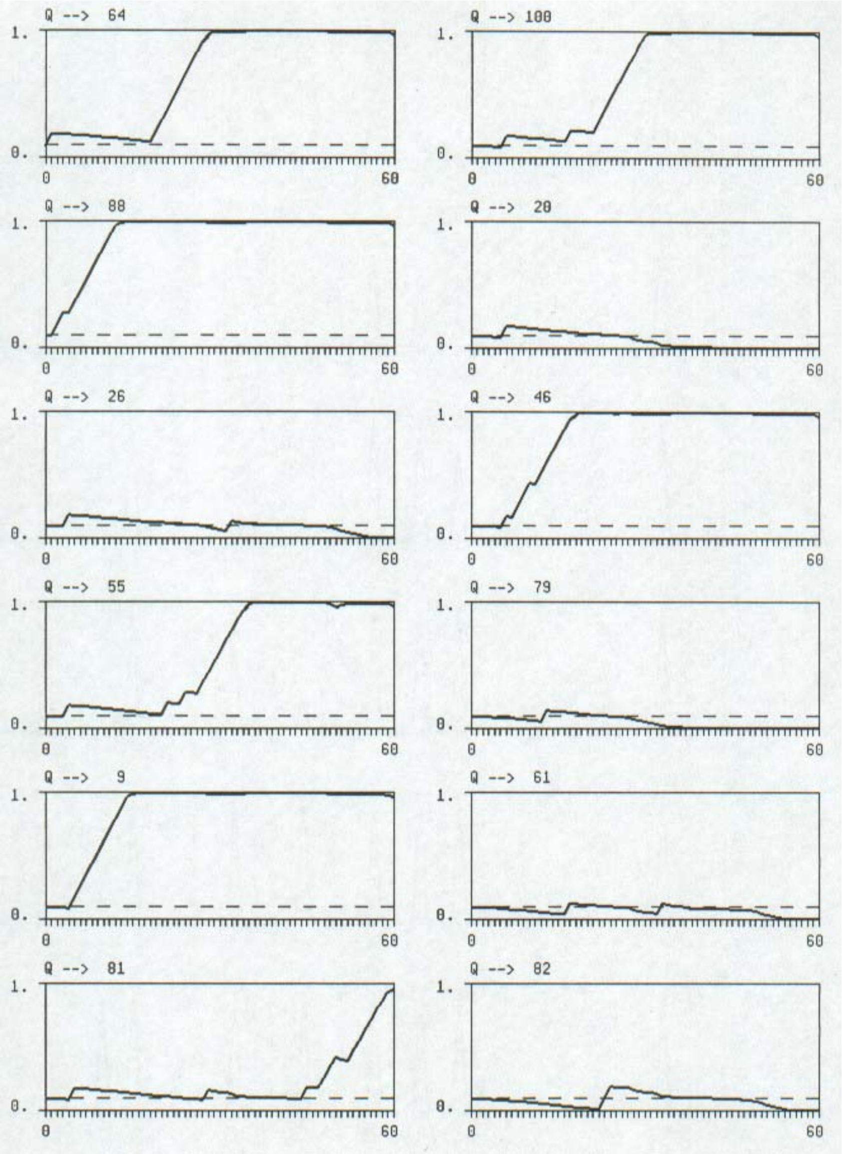
Cross-correlograms



Doursat (1991)

Simulations of synfire growth

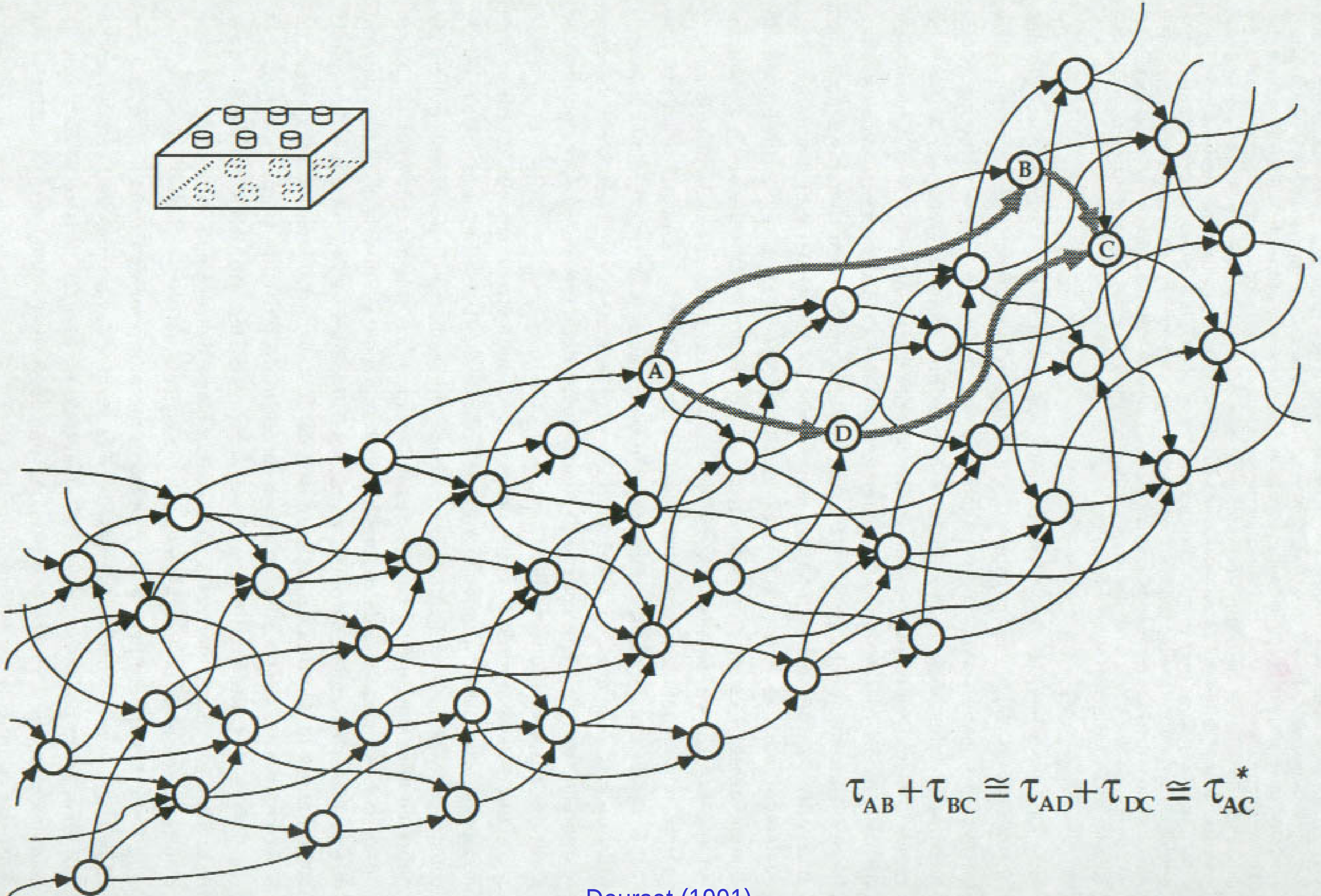
Synaptic evolution



Doursat (1991)

Simulations of synfire growth

Synfire braids



$$\tau_{AB} + \tau_{BC} \cong \tau_{AD} + \tau_{DC} \cong \tau^*_{AC}$$

Doursat (1991)

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     - Origins (Abeles)
     - Growth & compositionality models (Bienenstock, Doursat)
     - Other experiments and models

Synfire chain bibliography
Origins (Abeles)

- M. Abeles, Hebrew University, Jerusalem
  - Abeles (1982) *Local cortical circuits: An Electrophysiological Study*. Springer-Verlag.
  - Abeles (1991) *Corticonics: Neural Circuits of the Cerebral Cortex*. Cambridge University Press.
  - Abeles, Hayon & Lehmann (2004) Modeling compositionality by dynamic binding of synfire chains. *Journal of Computational Neuroscience*, 17: 179-201.

Synfire chain bibliography

Growth & compositionality models (Bienenstock, Doursat)

- E. Bienenstock, CNRS & Brown University

  - Doursat (1991) An epigenetic development model of the nervous system. In: *A contribution to the study of representations in the nervous system and in artificial neural networks*, Ph.D. dissertation, Université Paris VI. (Supervised by Bienenstock, E.)
  - Bienenstock (1995) A model of neocortex. *Network*, 6: 179-224.
  - Bienenstock & Geman (1995) Compositionality in neural systems. In: *The Handbook of Brain Theory and Neural Networks*, M. Arbib ed, Bradford Books/MIT Press, pp 223-226.
  - Bienenstock (1996) Composition. In: A. Aertsen & V. Braitenberg (Eds.), Brain Theory (pp. 269-300). Elsevier.
  - Bienenstock and Doursat (2005) The Hebbian development of synfire chains. (Article in preparation.)

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Other experiments and models

- A. Aertsen, Universität Freiburg
  - Diesmann, Gewaltig & Aertsen (1999) Stable propagation of synchronous spiking in cortical neural networks. *Nature*, 402: 529-532.
    - ➢ *The stable propagation of precisely synchronized APs happens despite noisy dynamics.*

- C. Koch, Caltech
  - Marsalek, Koch & Maunsell (1997) On the relationship between synaptic input and spike output jitter in individual neurons. *Proc. Natl. Acad. Sci. USA*, 94: 735-740.
    - ➢ *Preservation of highly accurate spike timing in cortical networks (e.g., macaque MT area), explained by analysis of output/input jitter in I&F model.*

Synfire chain bibliography
Other experiments and models

- R. Yuste, Columbia University
  - Mao, Hamzei-Sichani, Aronov, Froemke & Yuste (2001) Dynamics of spontaneous activity in neocortical slices. *Neuron*, 32: 883–898.
    - *Recording of spontaneous activity with statistically significant delayed correlations in slices mouse visual cortex, using calcium imaging*
  - Ikegaya, Aaron, Cossart, Aronov, Lampl, Ferster & Yuste (2004) Synfire chains and cortical songs: temporal modules of cortical activity. *Science*, 304: 559-564.
    - *"Cortical songs" in vitro and in vivo (mouse and cat visual cortex)*
- E. Izhikevich, The Neurosciences Institute, San Diego
  - Izhikevich, Gally & Edelman (2004) Spike-timing dynamics of neuronal groups. *Cerebral Cortex*, 14: 933–944.
    - *Self-organization of spiking neurons in a biologically detailed "small-world" model of the cortex*

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