CS 790R Seminar
Modeling & Simulation

Neural Networks 1 – Synchronization in Spiking Neural Networks

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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**

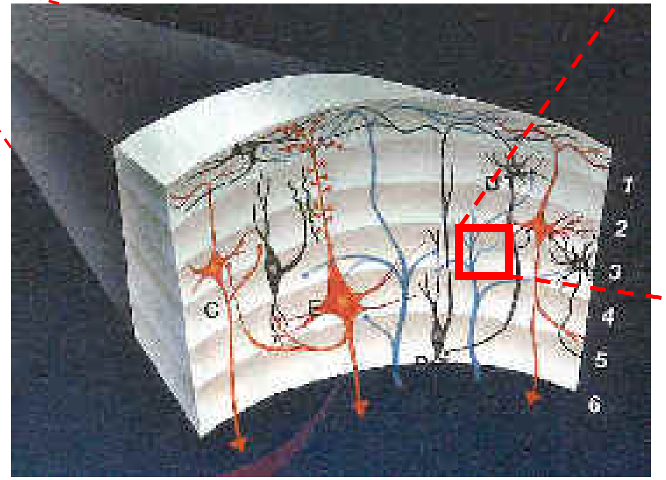
Neural networks

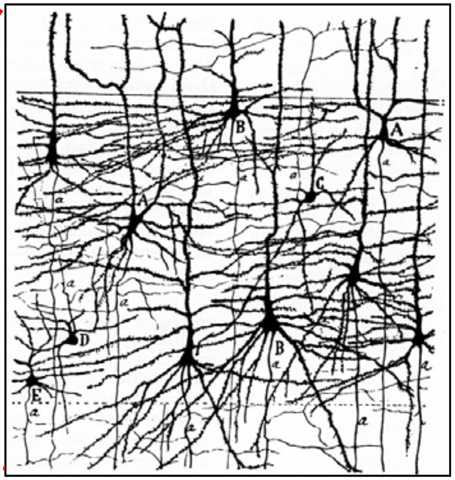
Structure of neural networks

Medial surface of the brain

(Virtual Hospital, University of Iowa)

Cortical layers





Pyramidal neurons and interneurons

(Ramón y Cajal 1900)

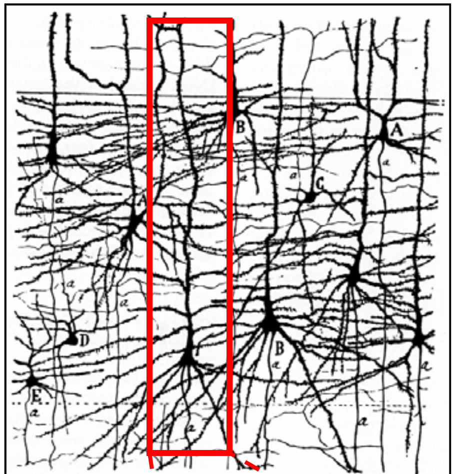
Phenomenon

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

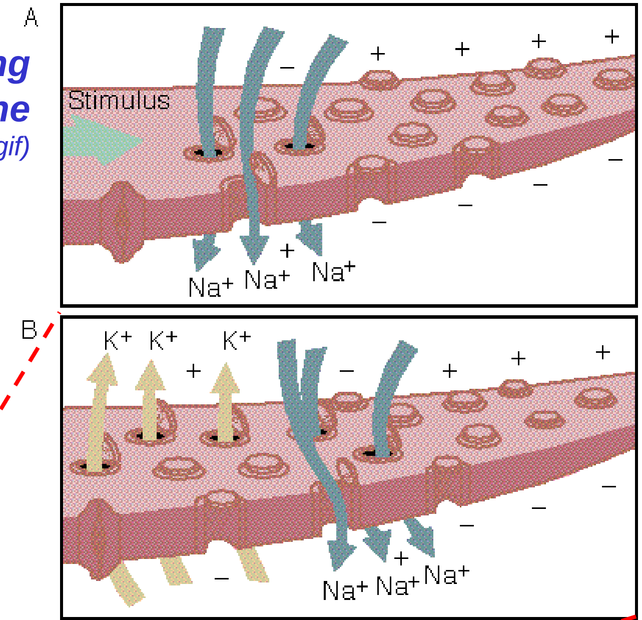
- ~10^{11} neurons in humans
- communicate with each other through (mostly) electrical potentials
- neural activity exhibits specific patterns of *spatial and temporal synchronization* ("temporal code")

Neural networks

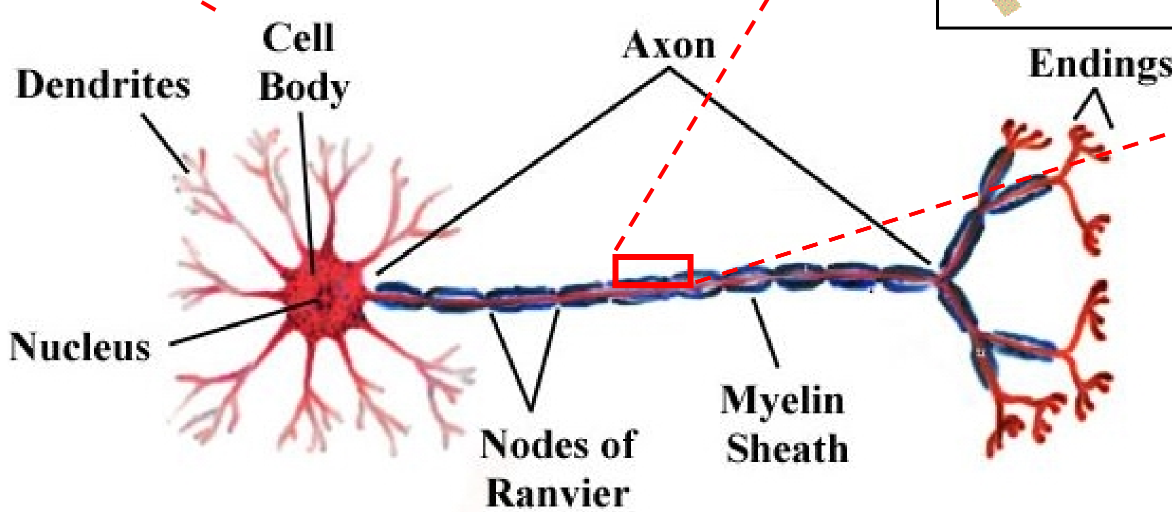
Structure of a neuron



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



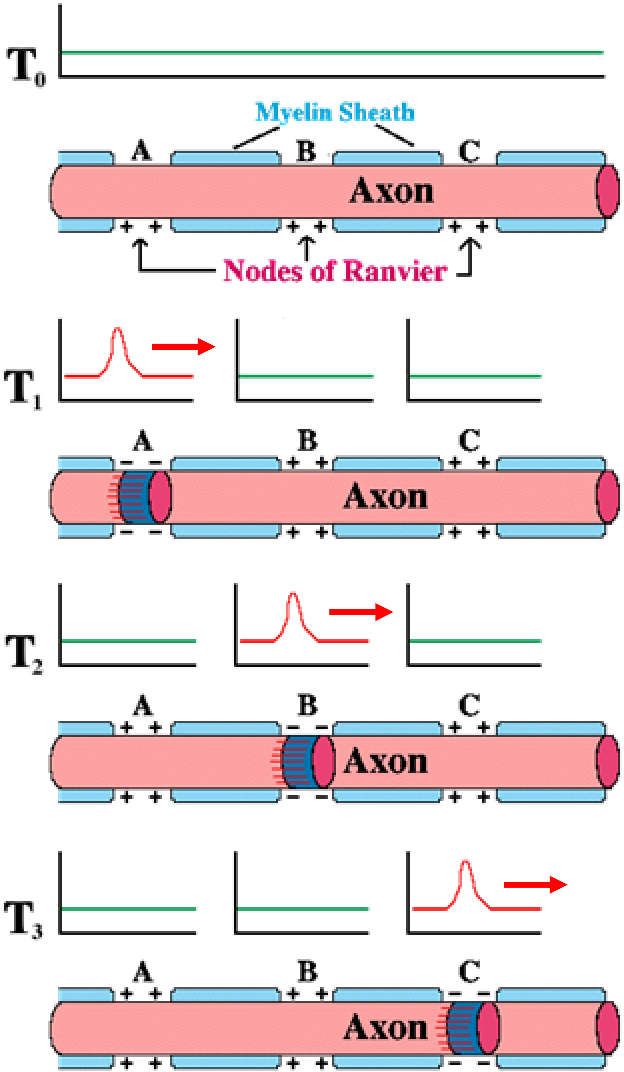
Pyramidal neurons and interneurons
(Ramón y Cajal 1900)

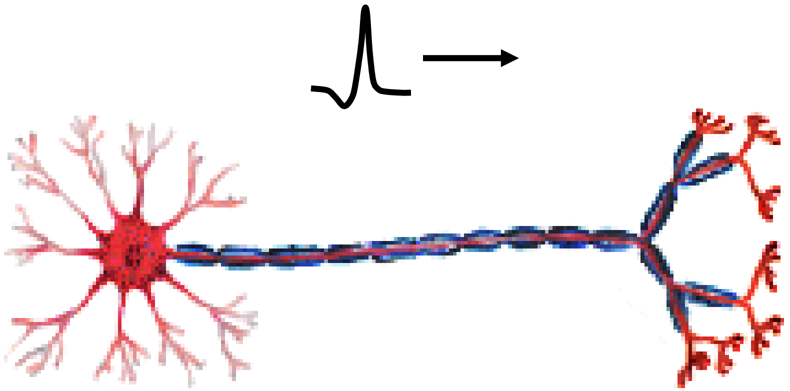


A typical neuron
(http://www.bio.brandeis.edu/biomath/mike/AP.html)

Neural networks

Propagation of a “spike”



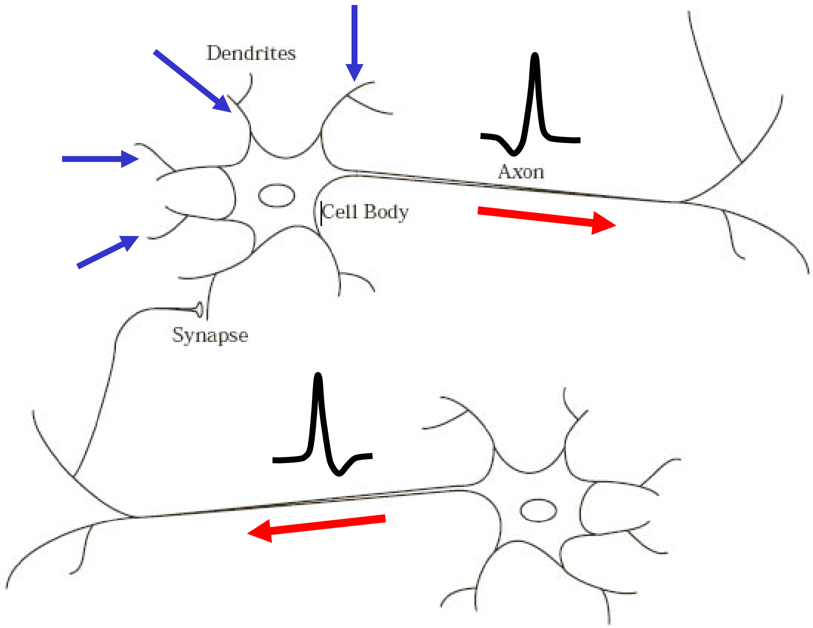


(http://www.bio.brandeis.edu/biomath/mike/AP.html)

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

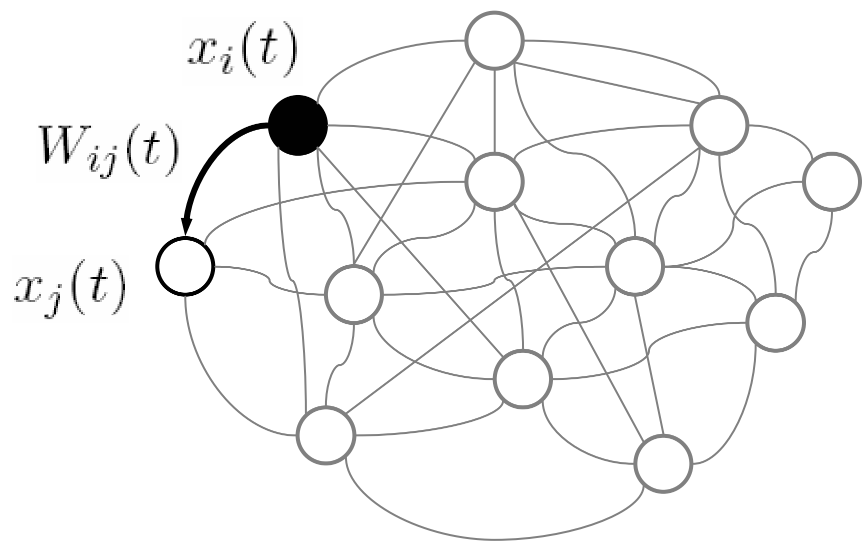
Neural networks

Model of neural network



Schematic neurons

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



A binary neural network

Mechanism

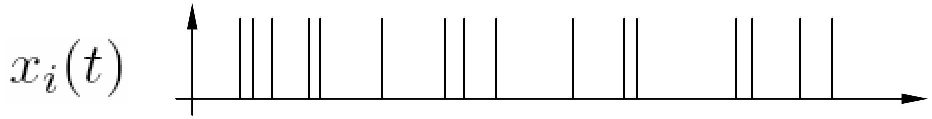
- each neuron receives signals from many other neurons through its *dendrites*
- the signals converge to the *soma* (cell body) and are integrated
- if the integration exceeds a threshold, the neuron fires a <u>spike</u> on its *axon*

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



- 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

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

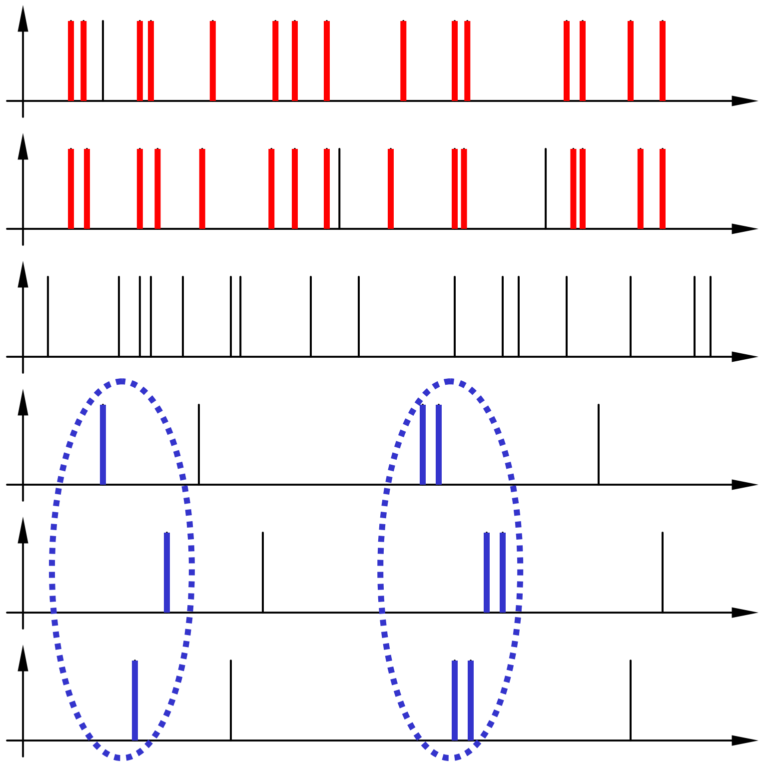
$$\langle\, x_i(t)\, x_j(t-\tau_{ij})\,\rangle$$

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

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



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

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

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

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

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

$x_6(t)$ — $\langle x_6(t) \rangle =$ ○ 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

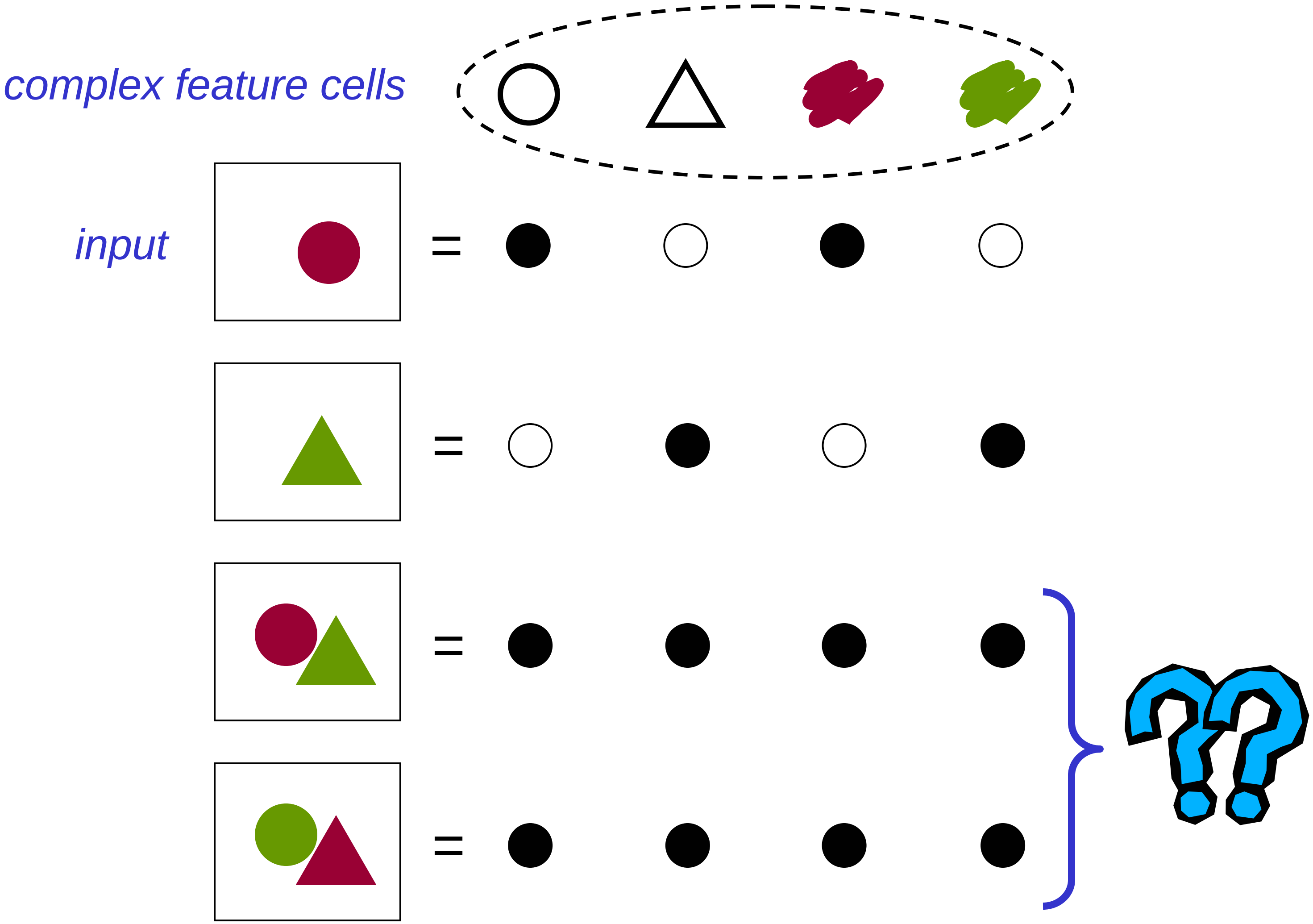
- Recent <u>temporal coding</u> “boom”: a few milestones
  - von der Malsburg (1981): *theoretical proposal to consider <u>correlations</u>*
  - Abeles (1982, 1991): *precise, <u>reproducible spatiotemporal spike rhythms</u>, named “synfire chains”*
  - Gray & Singer (1989): *stimulus-dependent <u>synchronization 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>*

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

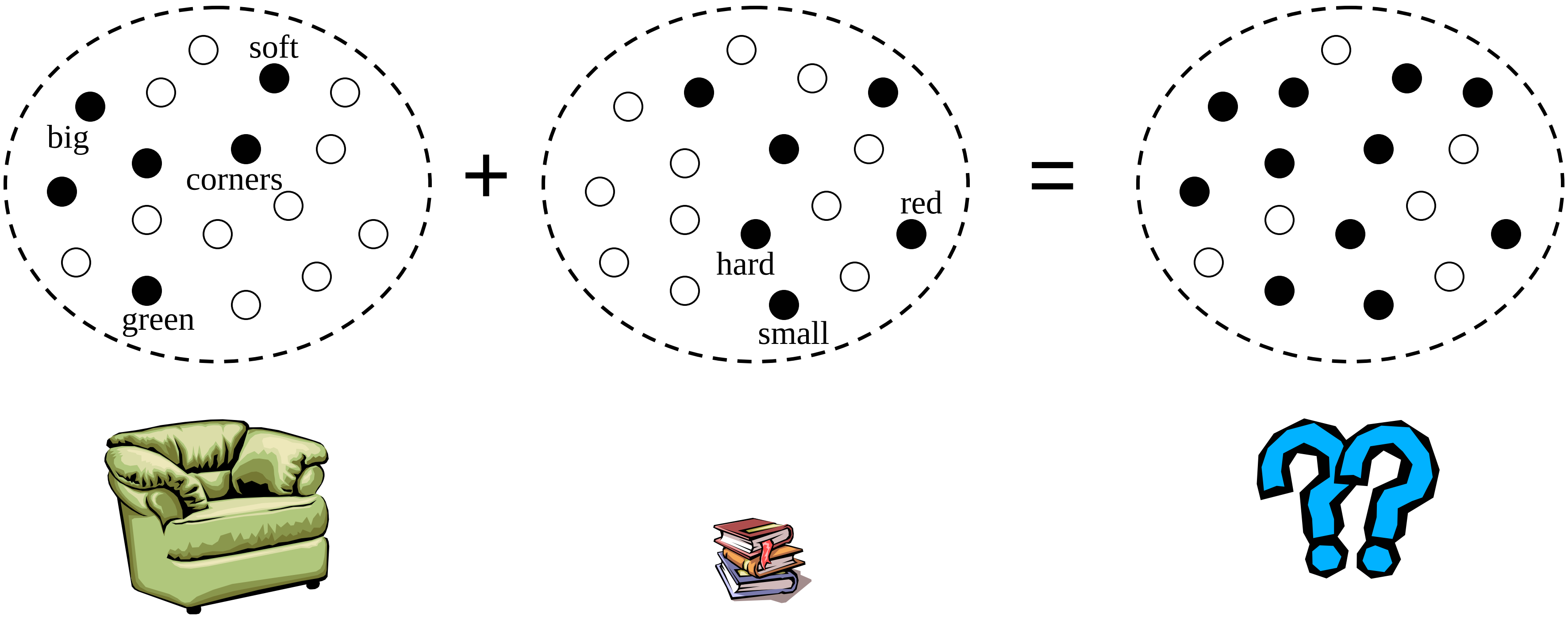
The “binding problem”



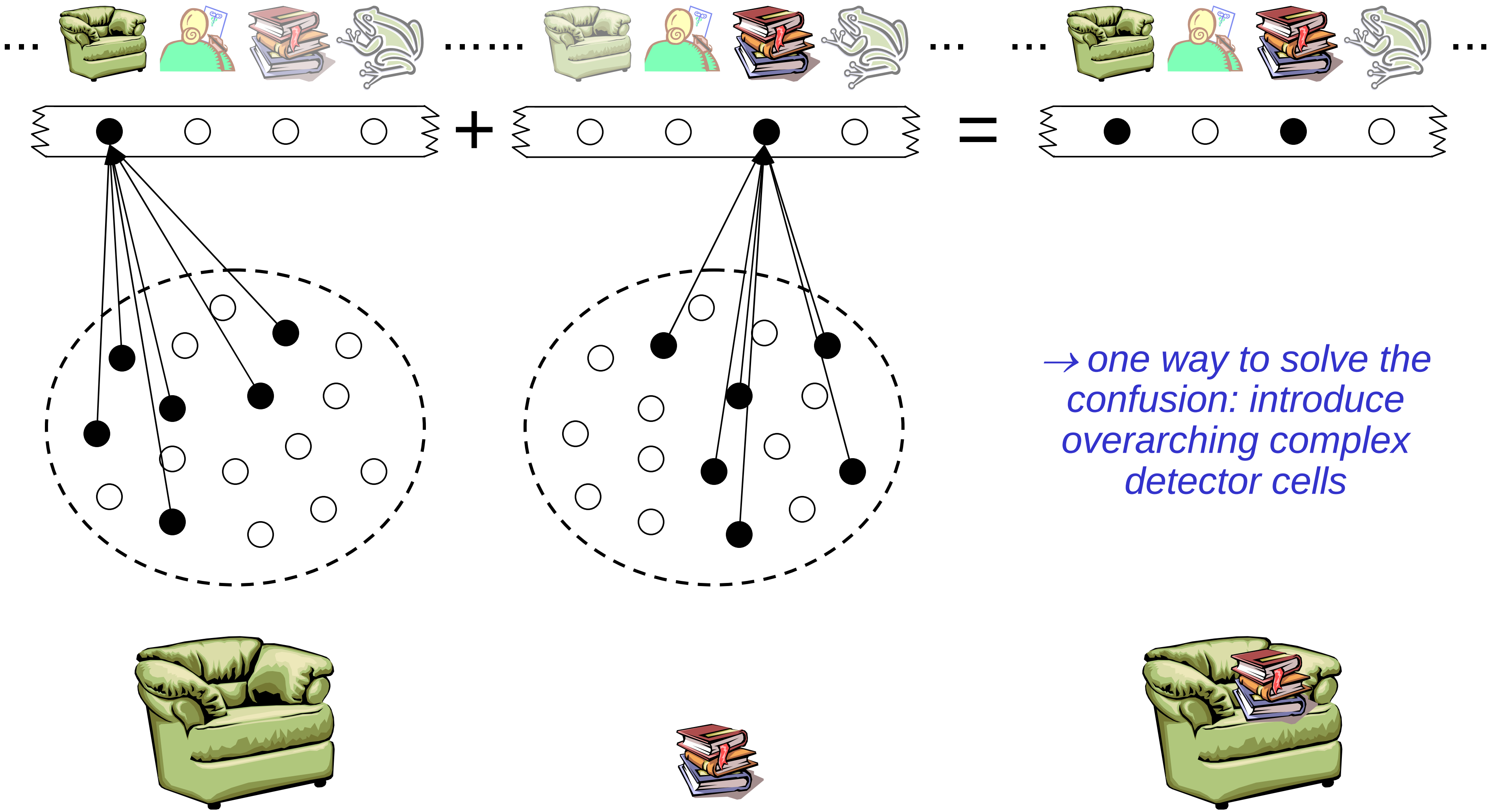
Questions of representation

Feature binding in cell assemblies

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



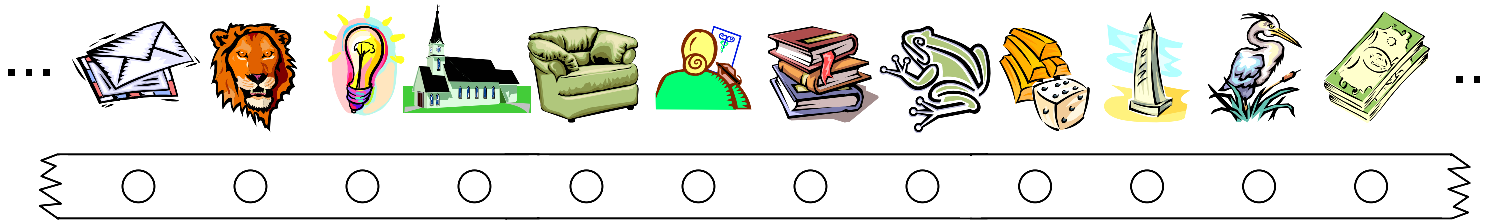
Questions of representation
“Grandmother” cells



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

Questions of representation

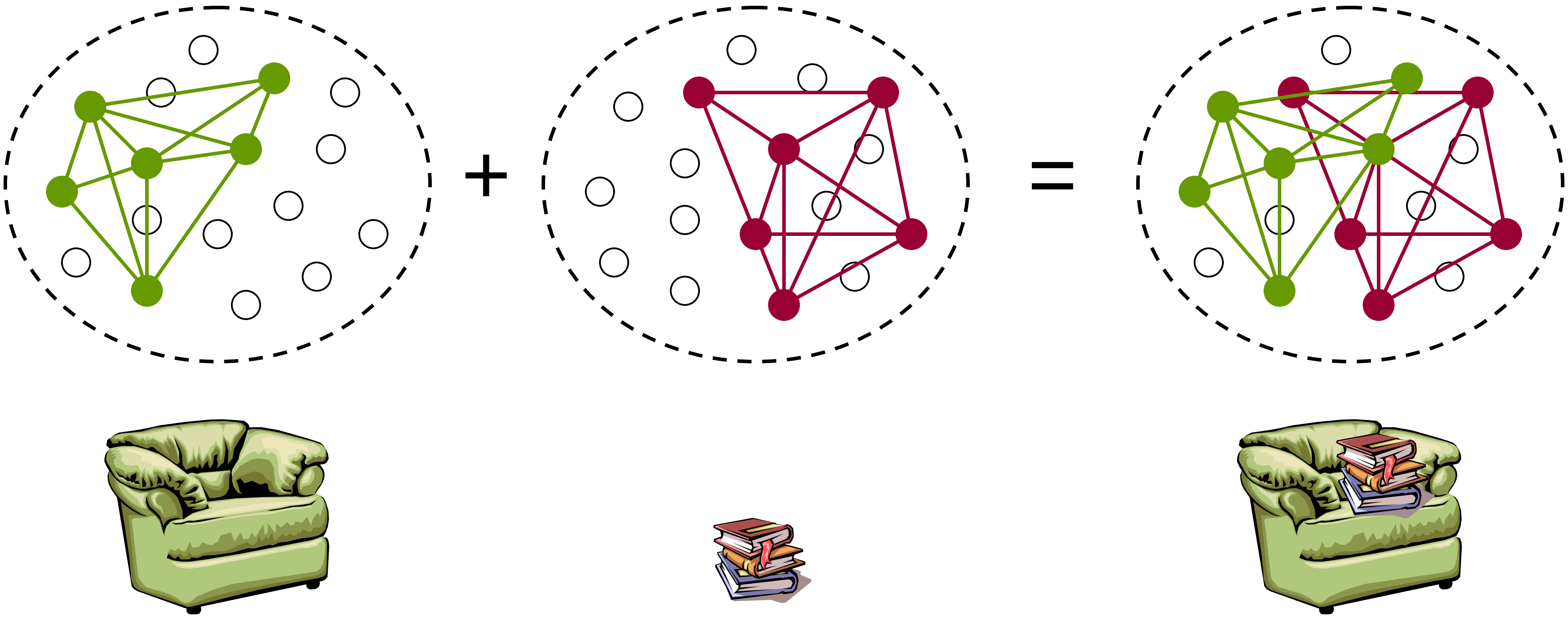
"Grandmother" cells



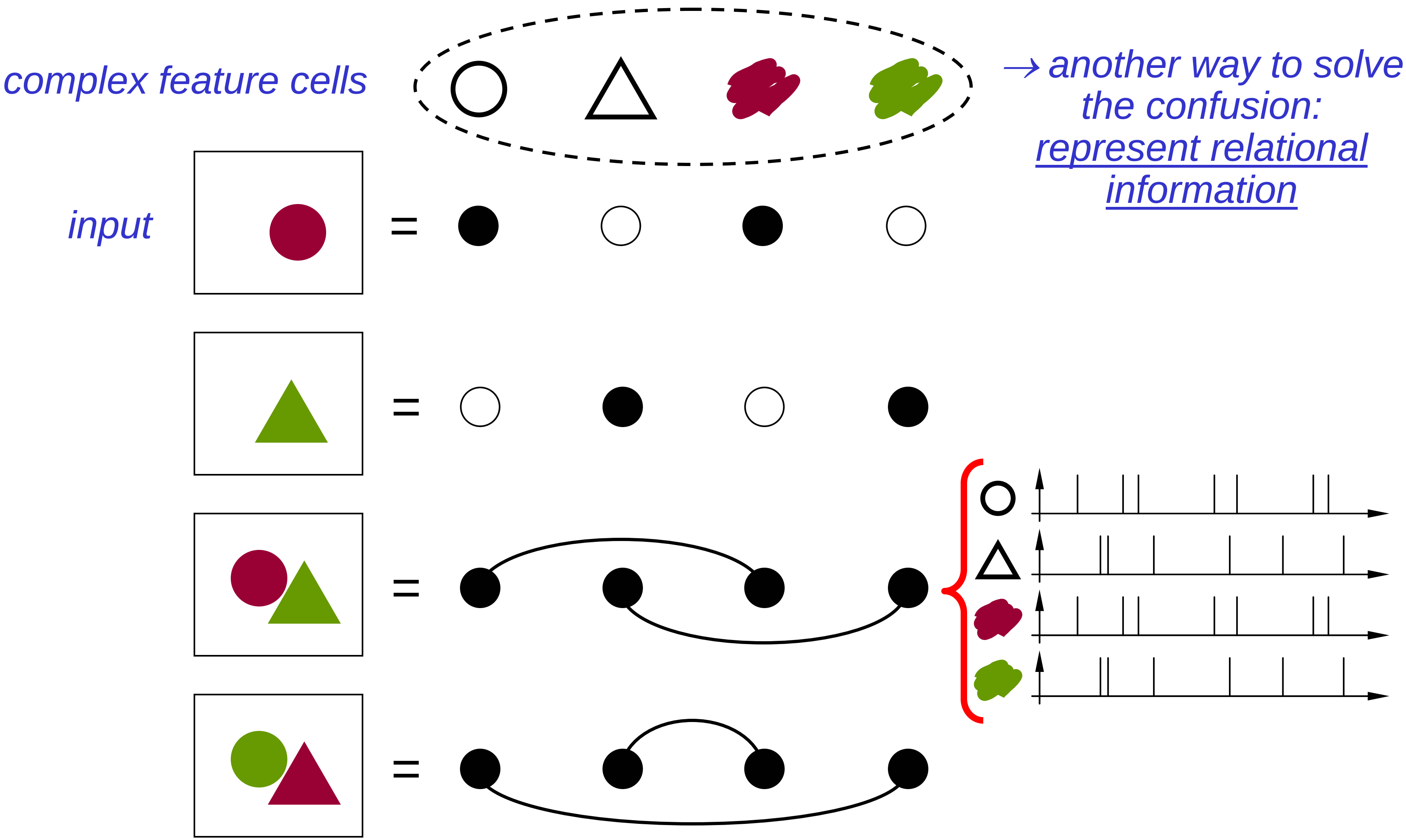
. . . however, this soon leads to an unacceptable combinatorial explosion!

Questions of representation
Relational graph format

→ another way to solve the confusion: <u>represent relational information</u>



Questions of representation
Solving the binding problem with temporal coding

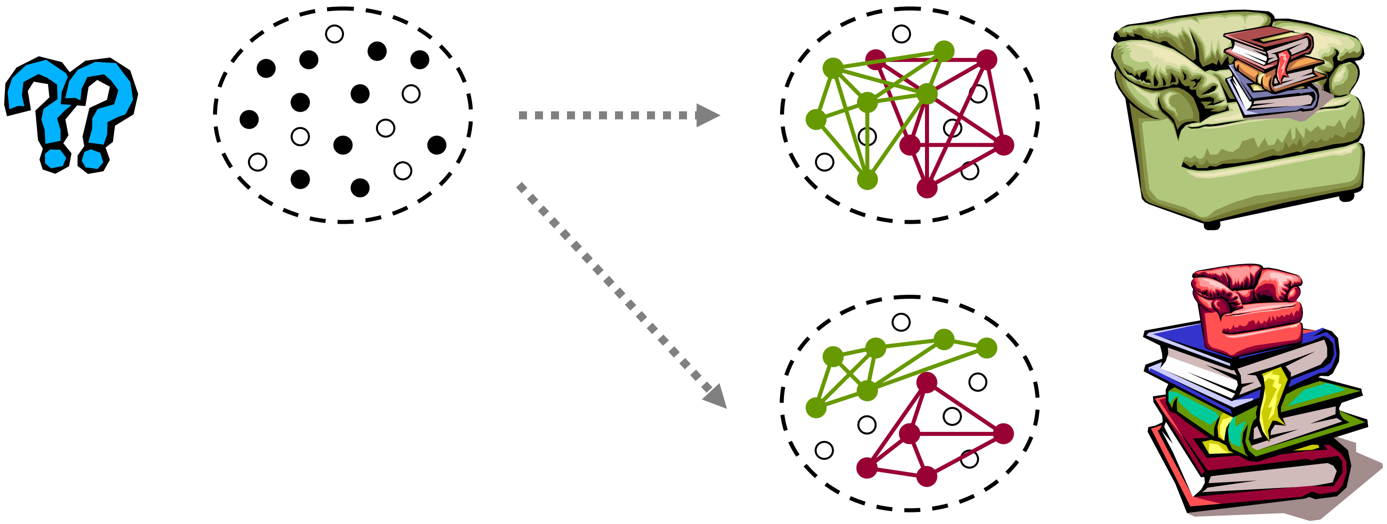


→ *another way to solve the confusion: represent relational information*

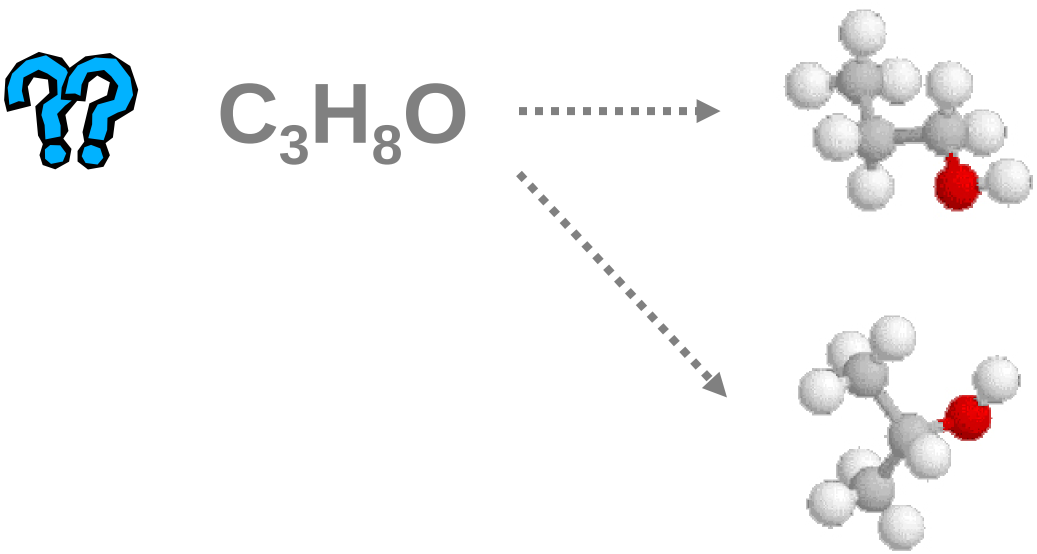
von der Malsburg, C. (1981) The correlation theory of brain function.

Questions of representation

A molecular metaphor



"cognitive isomers" made of the same atomic features



1-propanol

2-propanol

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   - Temporal tagging
   - Group synchronization
   - Traveling waves
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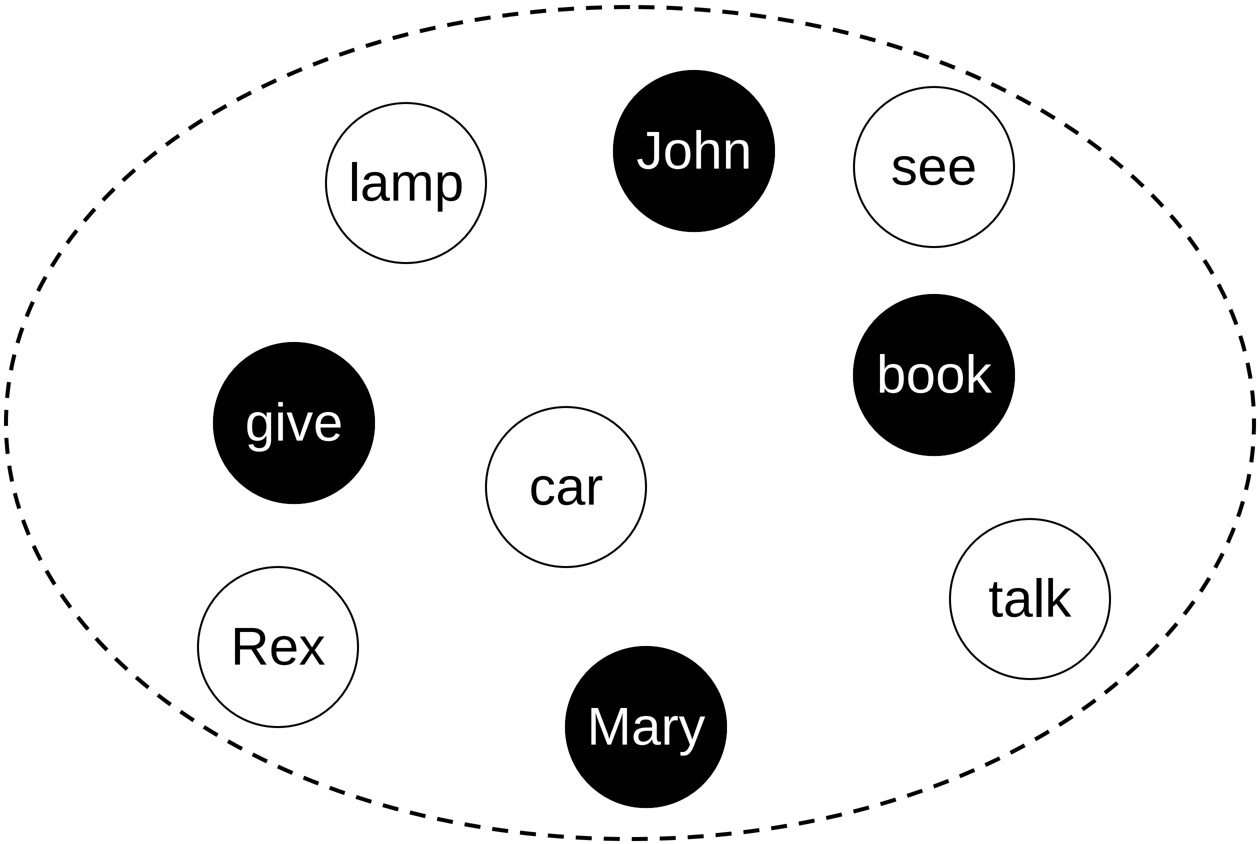
Synchronization in Spiking Neural Networks

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.

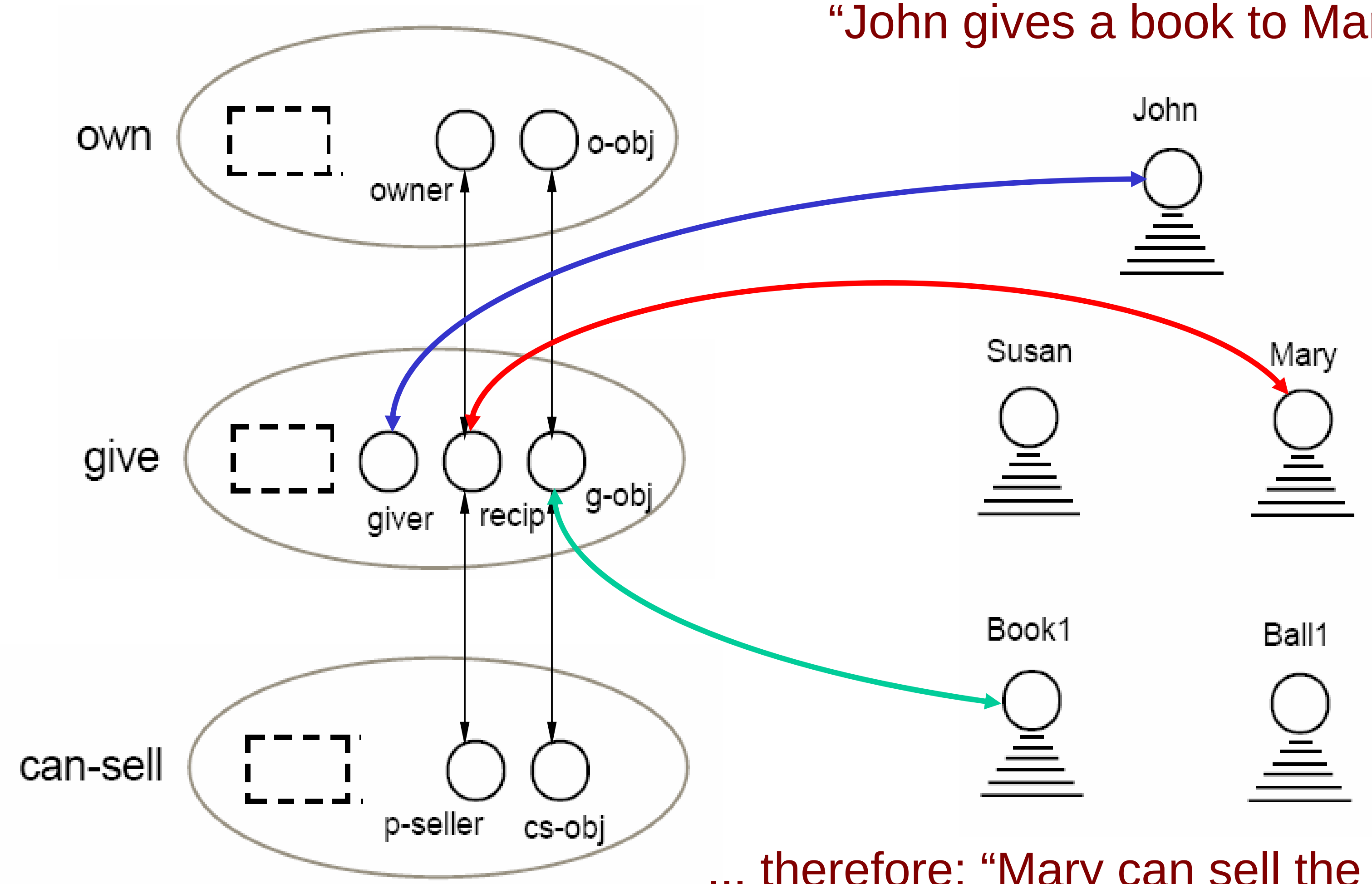
(b) Mary gives a book to John.

(c)* Book John Mary give.

Temporal tagging

A model of semantic binding: SHRUTI

"John gives a book to Mary."

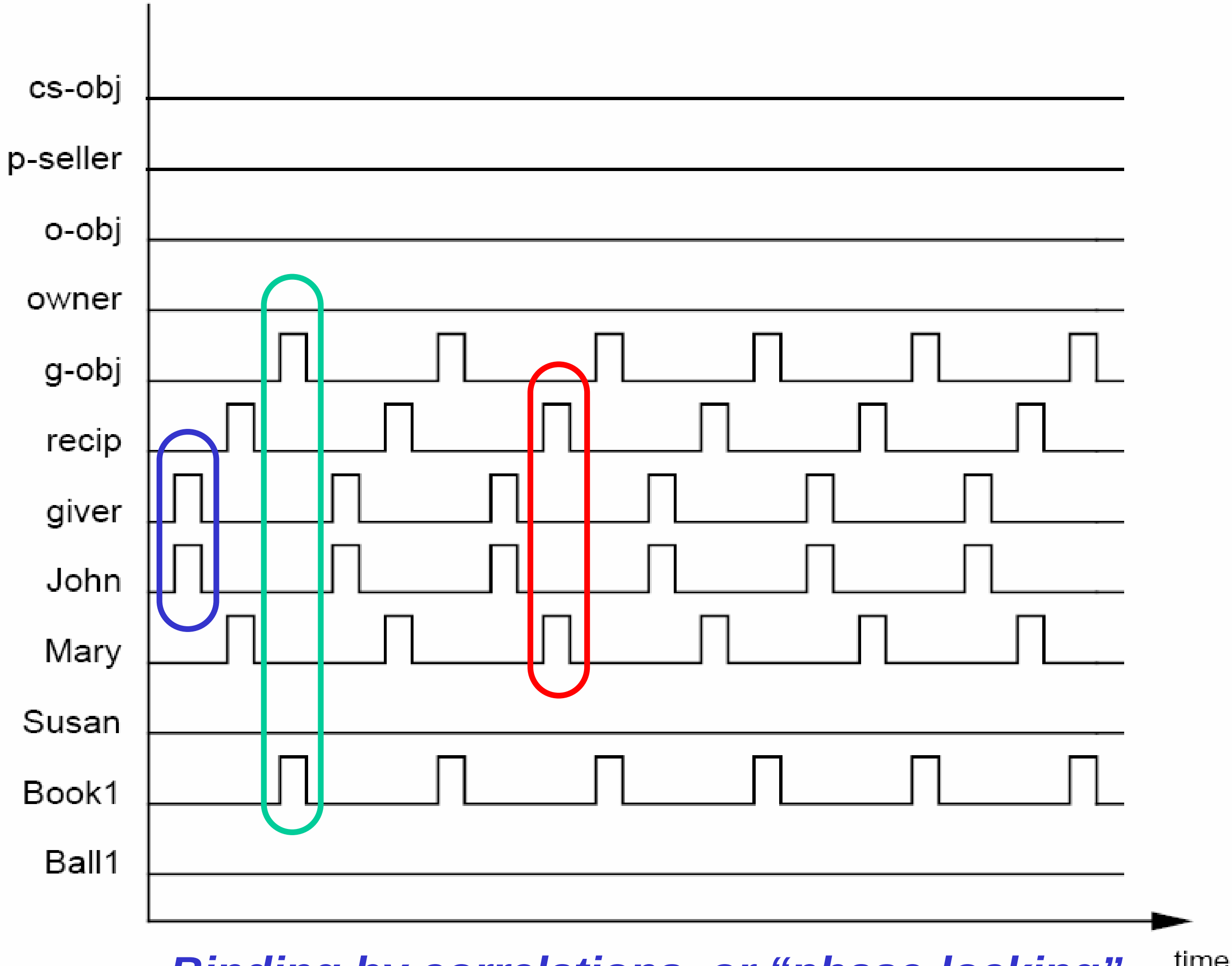


... therefore: "Mary can sell the book."

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

Temporal tagging

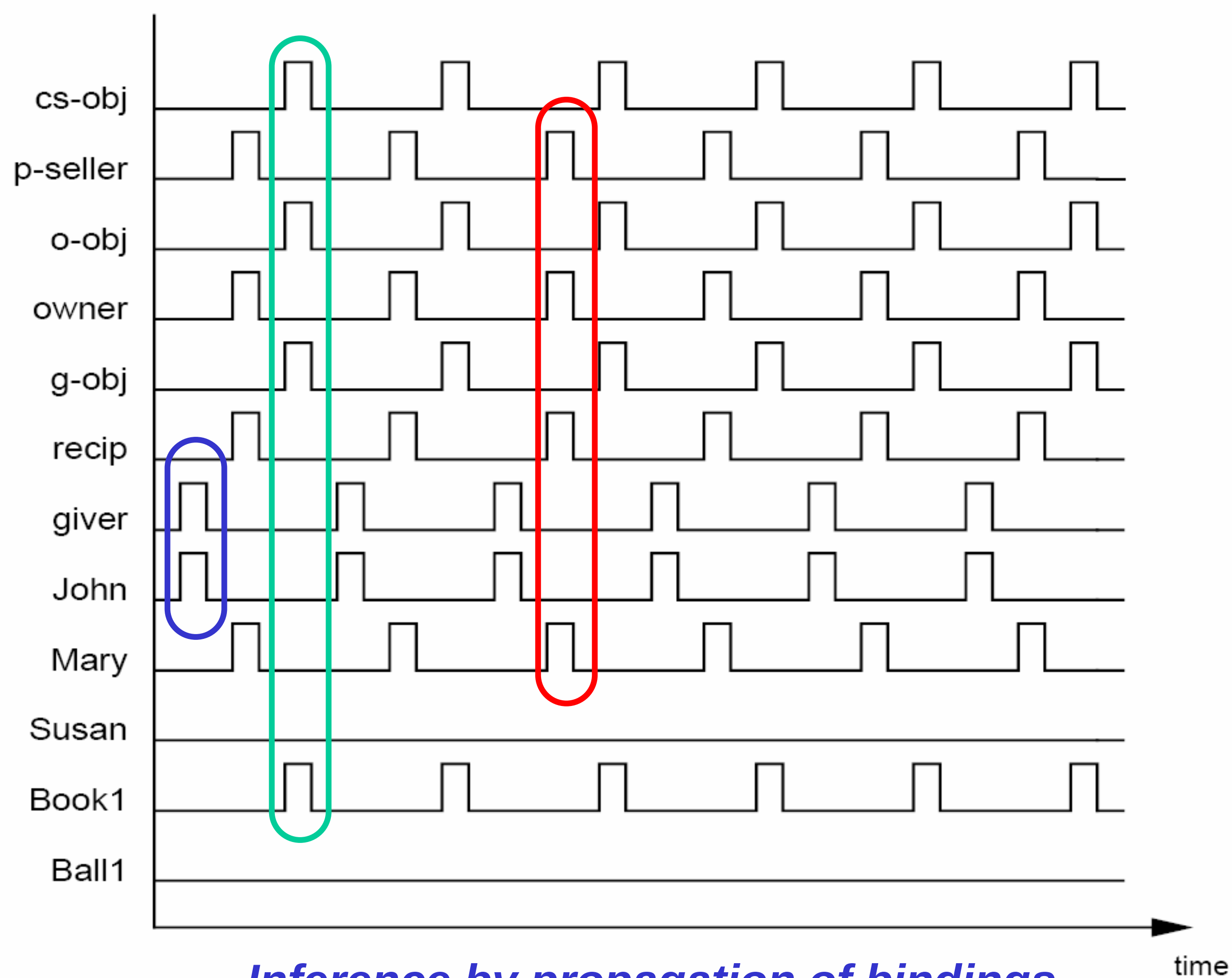
Using correlations to implement binding



Binding by correlations, or "phase-locking"

Temporal tagging

Using correlations to implement binding



Inference by propagation of bindings

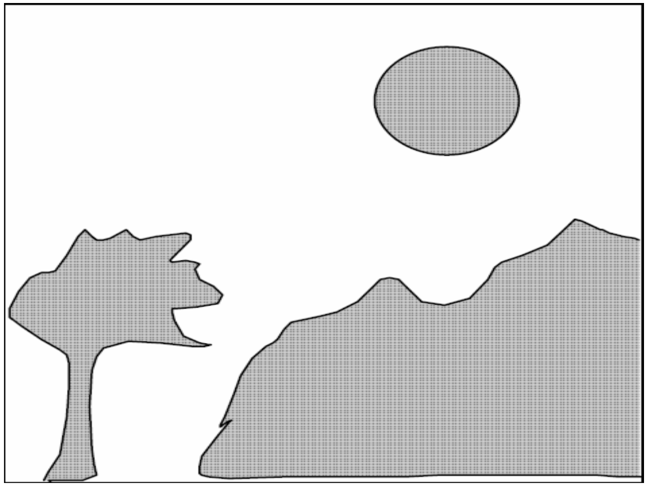
Synchronization in Spiking Neural Networks

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)



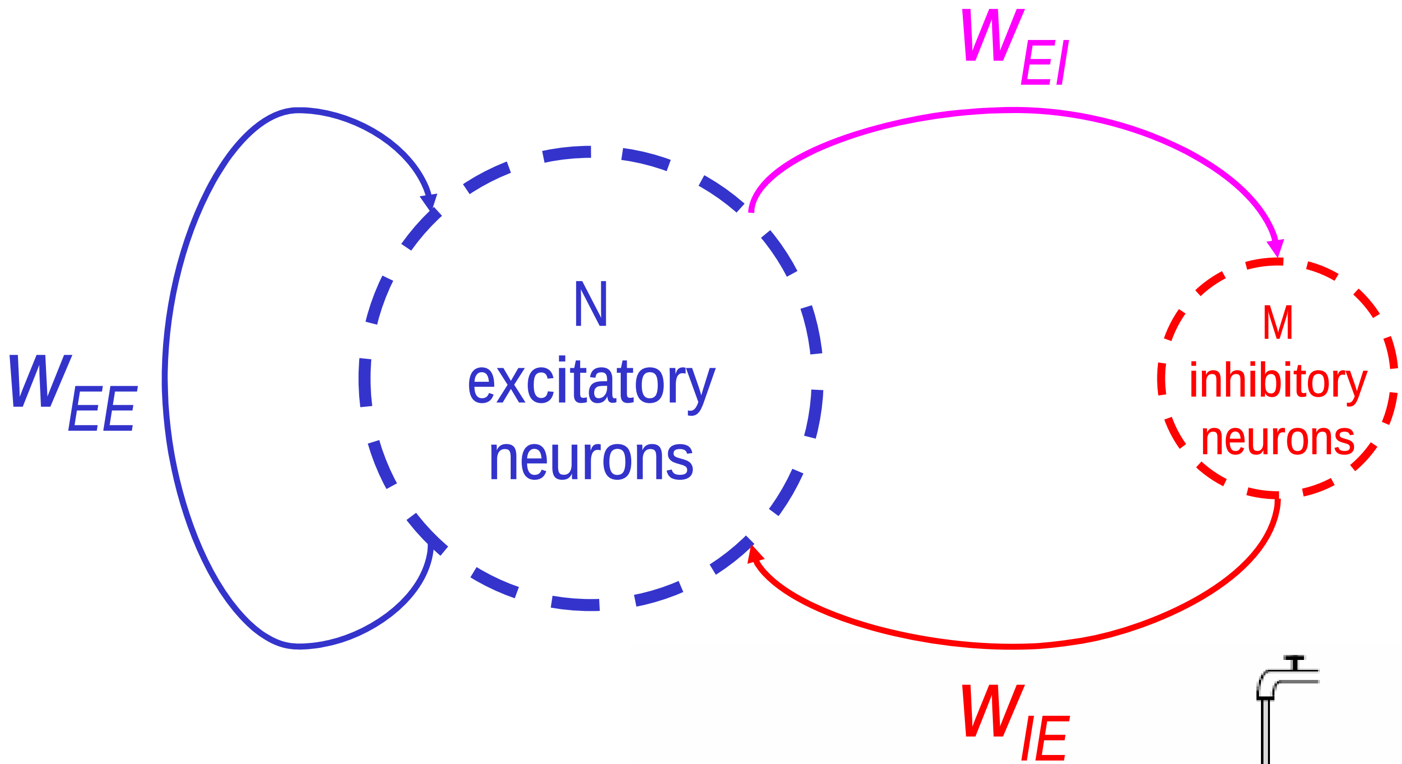
Schematic scene

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

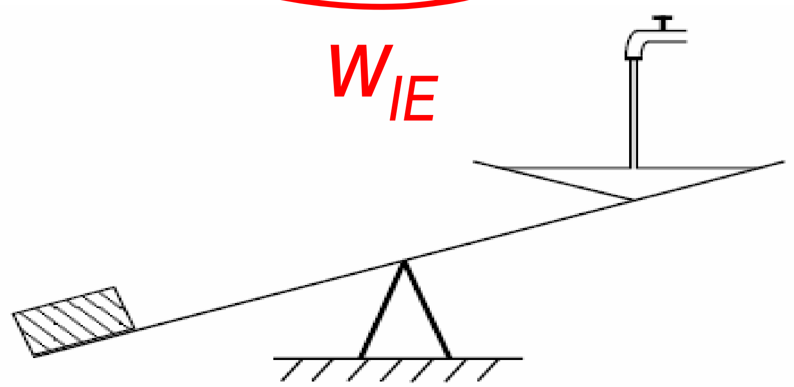
- scene analysis and segmentation is a fundamental aspect of perception
- ability to group elements of a perceived scene or sensory field into coherent clusters or objects
- can be addressed with temporal correlations, especially:
- dynamics of large networks of coupled neural oscillators
- how does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

Group synchronization

Excitatory-inhibitory relaxation oscillator



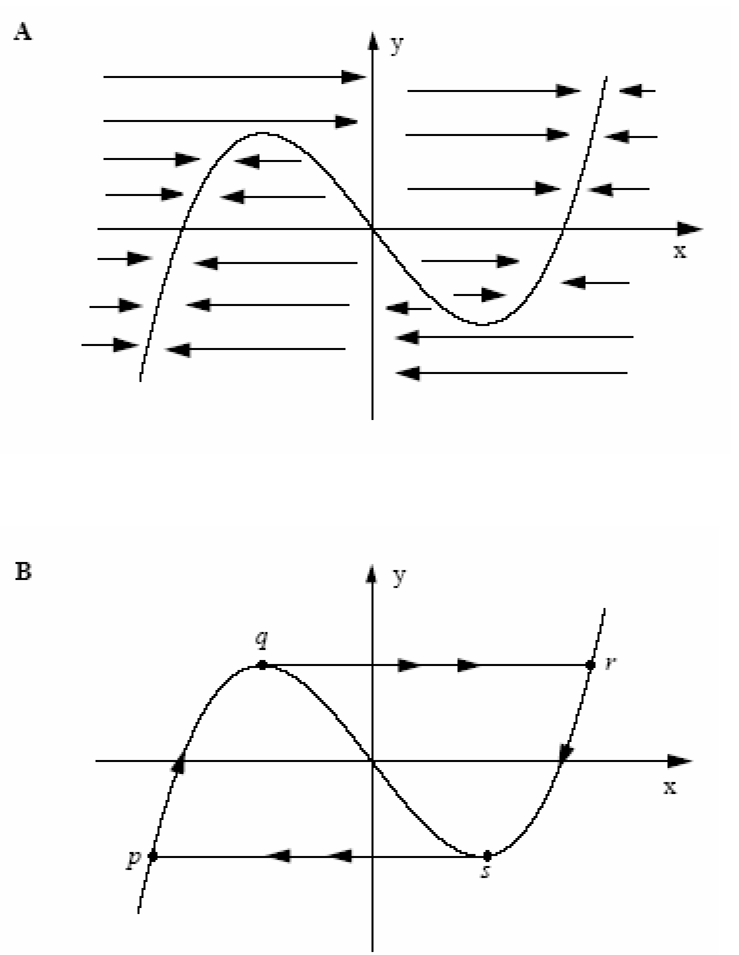
- relaxation oscillators exhibit discontinuous jumps
- different from sinusoidal or harmonic oscillations

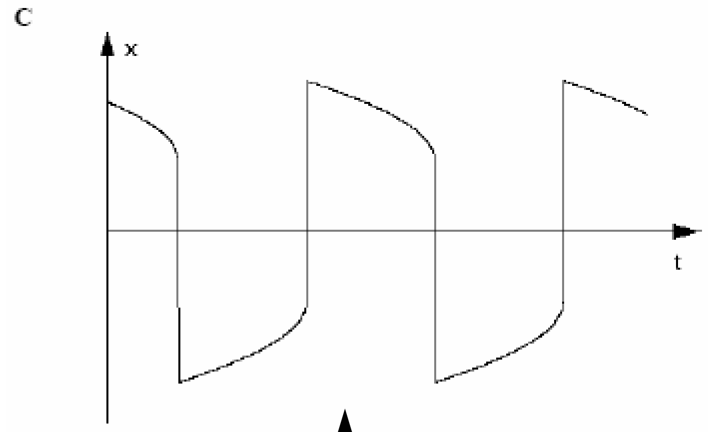


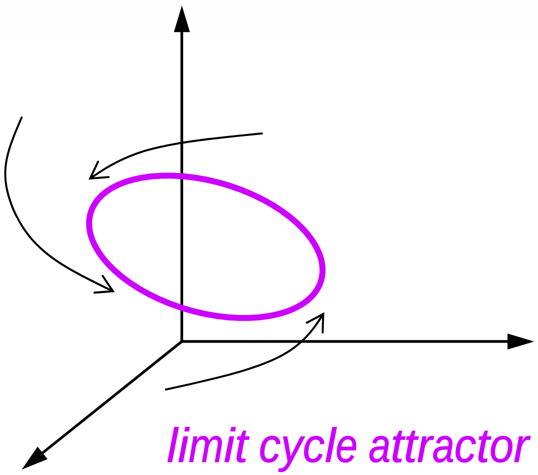
Wang, DeLiang (http://www.cse.ohio-state.edu/~dwang/)

Group synchronization

Van der Pol relaxation oscillator







Van der Pol relaxation oscillator

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

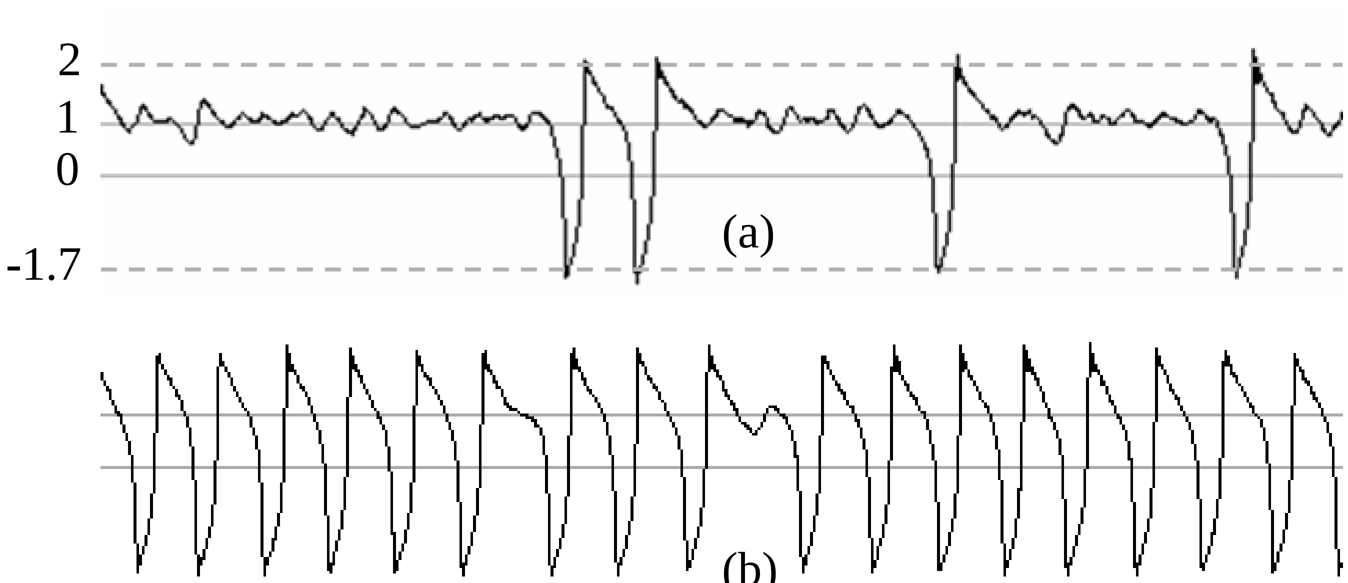
$$\ddot{x} + x = c(1 - x^2)\dot{x} \quad \Leftrightarrow \quad \begin{cases} \dot{x} = c(y - f(x)) \\ \dot{y} = -x / c \end{cases}$$

Oscillators and excitable units

Bonhoeffer-Van der Pol (BVP) stochastic oscillator

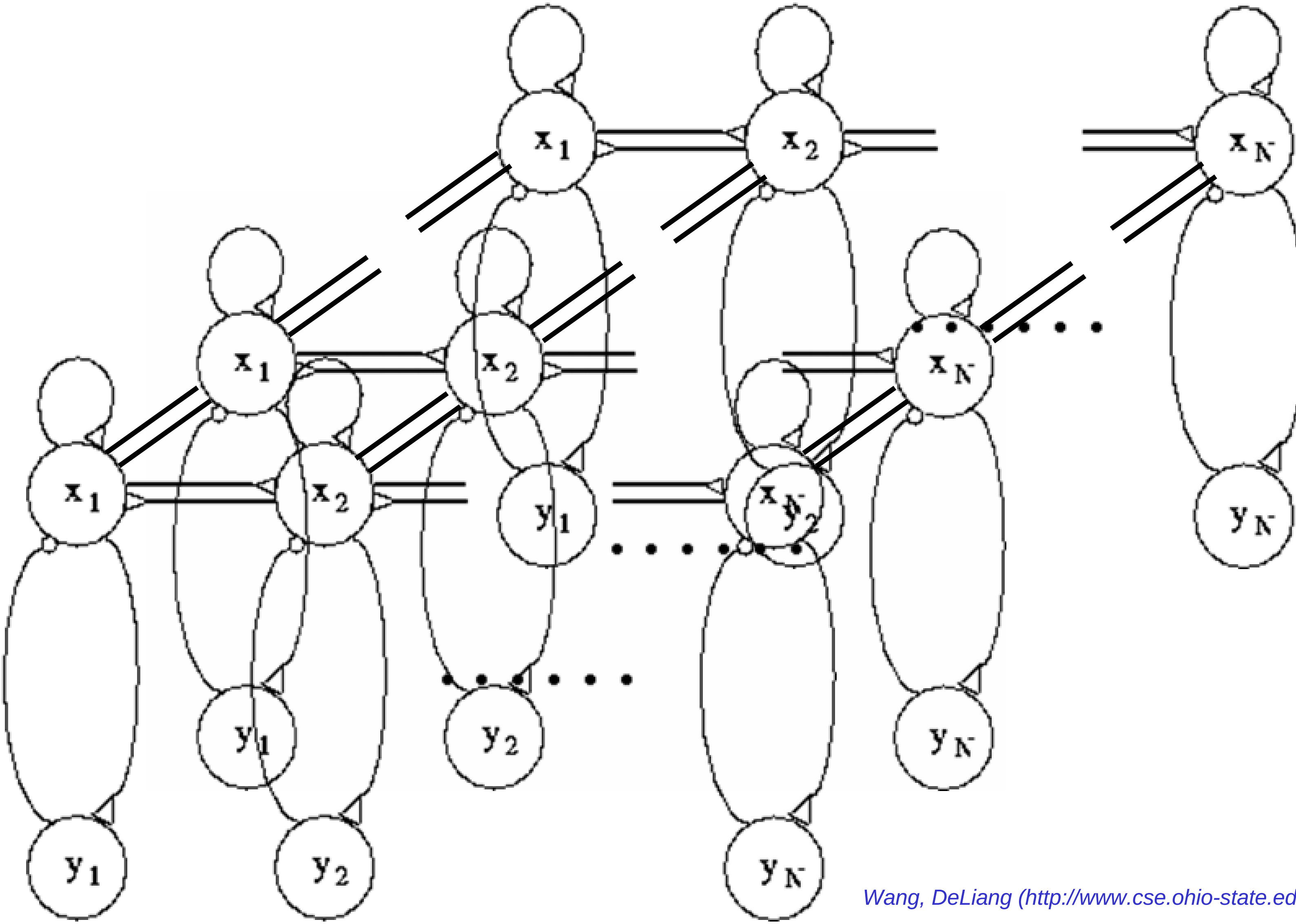
$$\begin{cases} \dot{u}_i = c\left(u_i - u_i^{\,3}/3 + v_i + z\right) + \eta + k\sum_j \left(u_j - u_i\right) + I_i \\ \dot{v}_i = \left(a - u_i - bv_i\right)/c + \eta \end{cases}$$

- *two activity regimes: (a) sparse stochastic and (b) quasi periodic*



Group synchronization

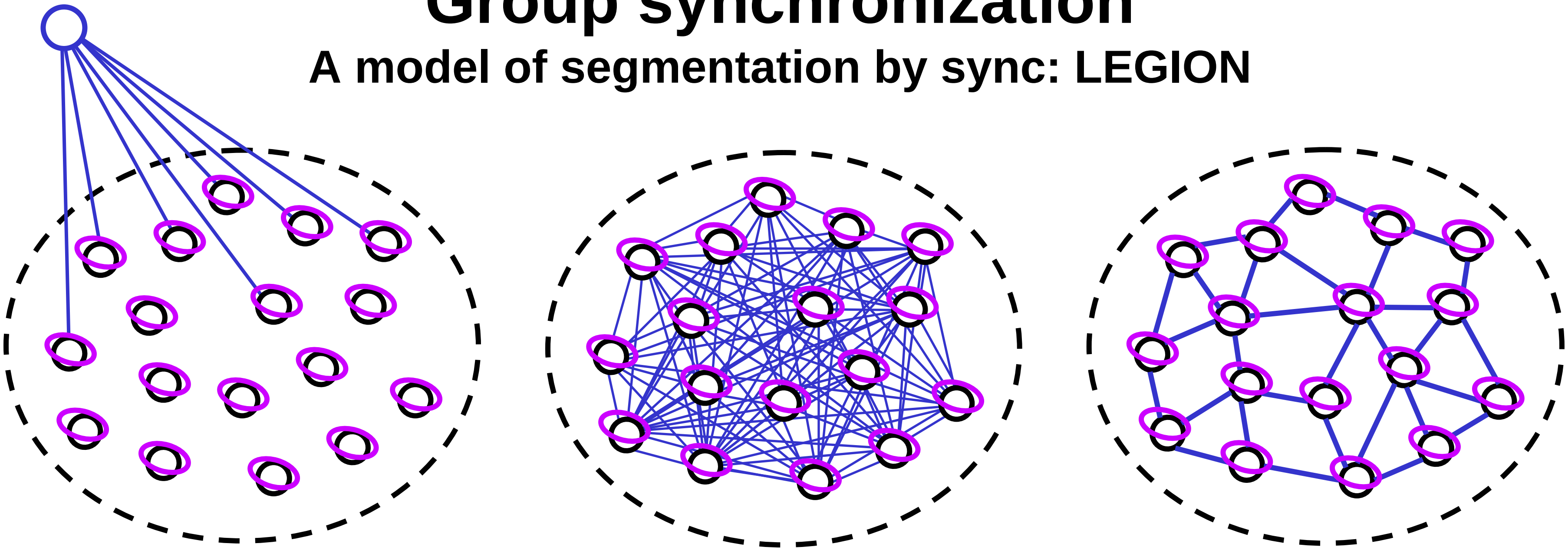
Networks of coupled oscillators



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

Group synchronization

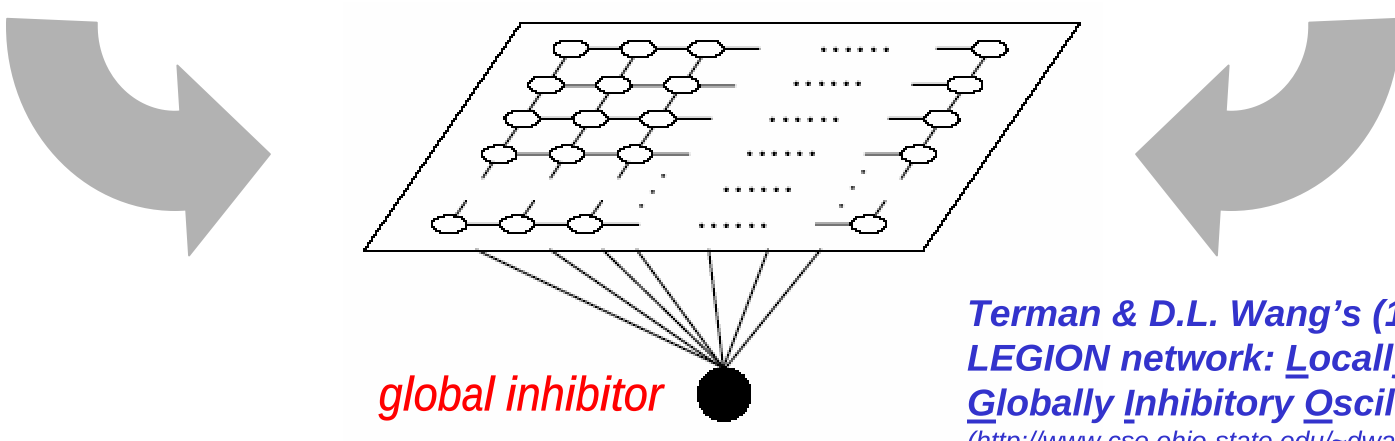
A model of segmentation by sync: LEGION



indirectly coupled through central pacemaker

globally coupled

locally coupled



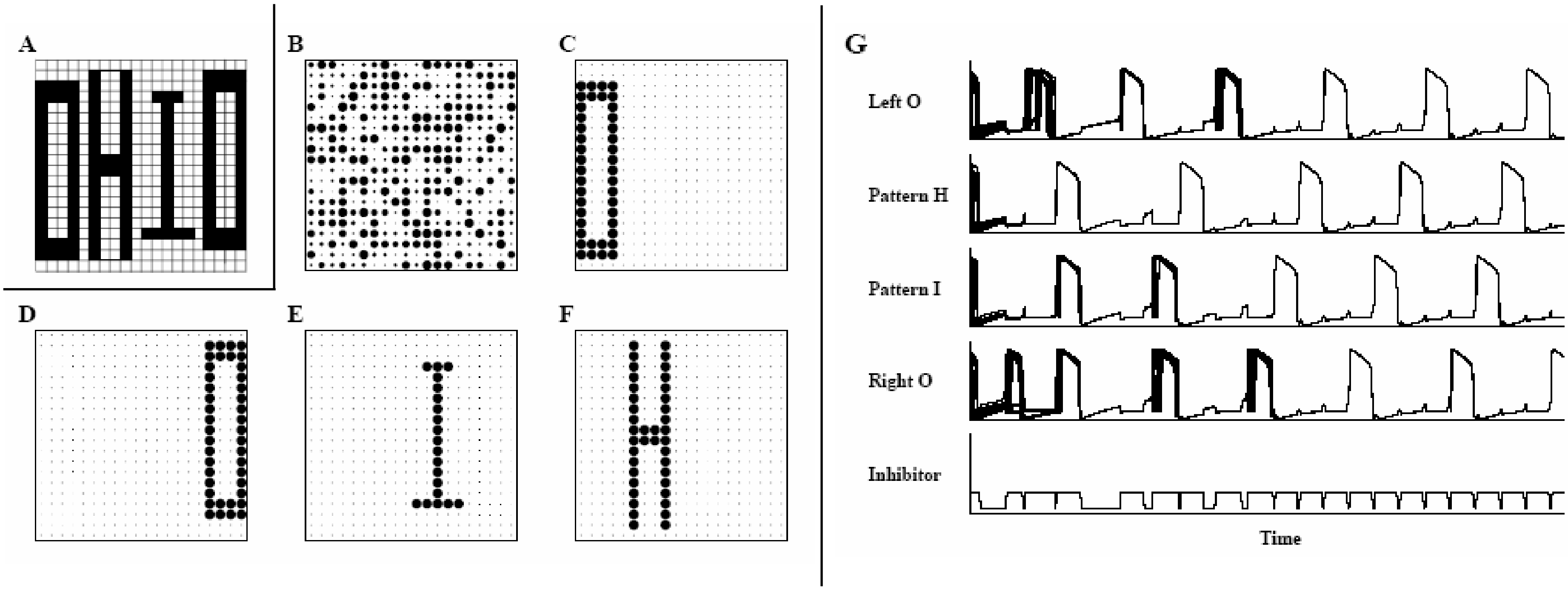
Terman & D.L. Wang's (1995) LEGION network: Locally Excitatory Globally Inhibitory Oscillator Network

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

Group synchronization

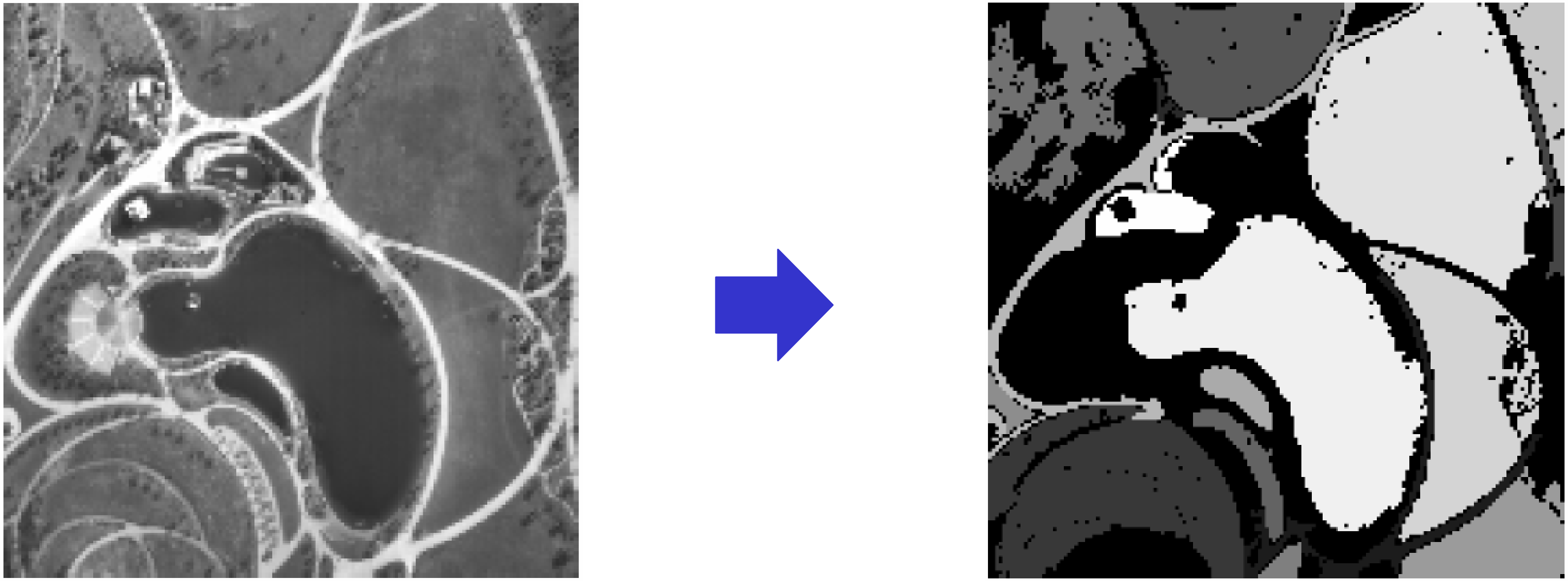
A model of segmentation by sync: LEGION

- achieving fast synchronization with local, topological coupling only



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

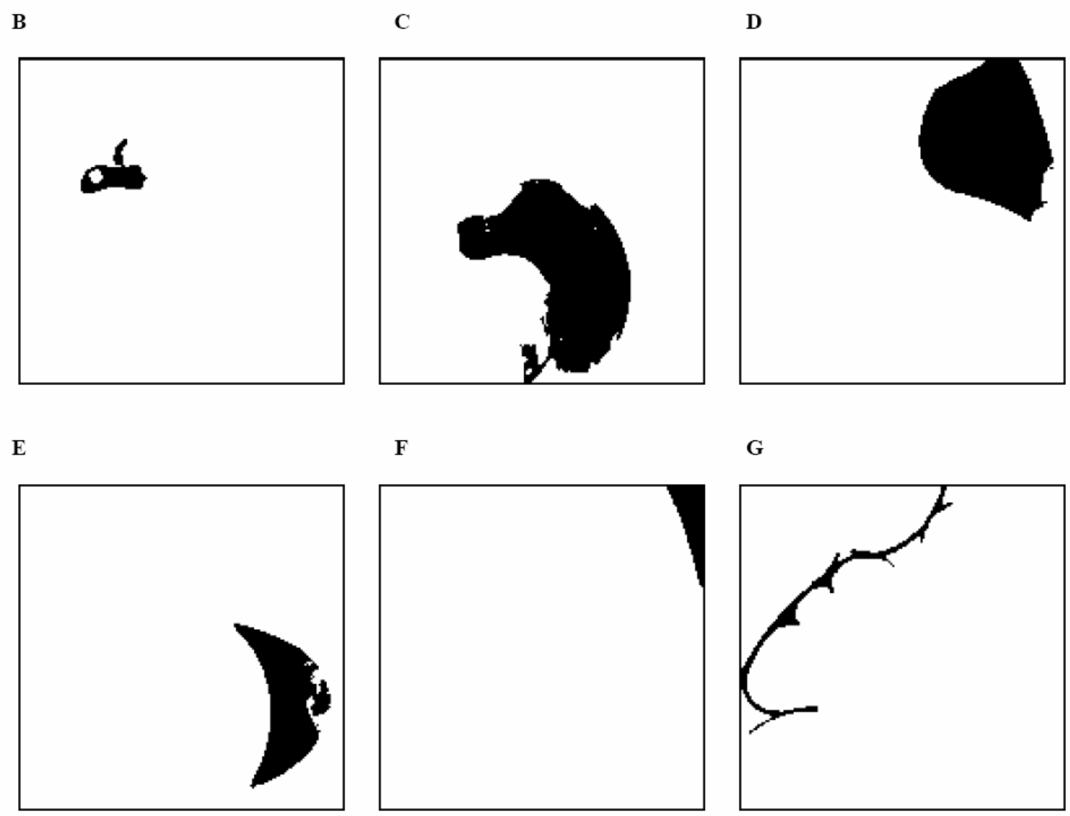
Group synchronization
A model of segmentation by sync: LEGION



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

Group synchronization

A model of segmentation by sync: LEGION



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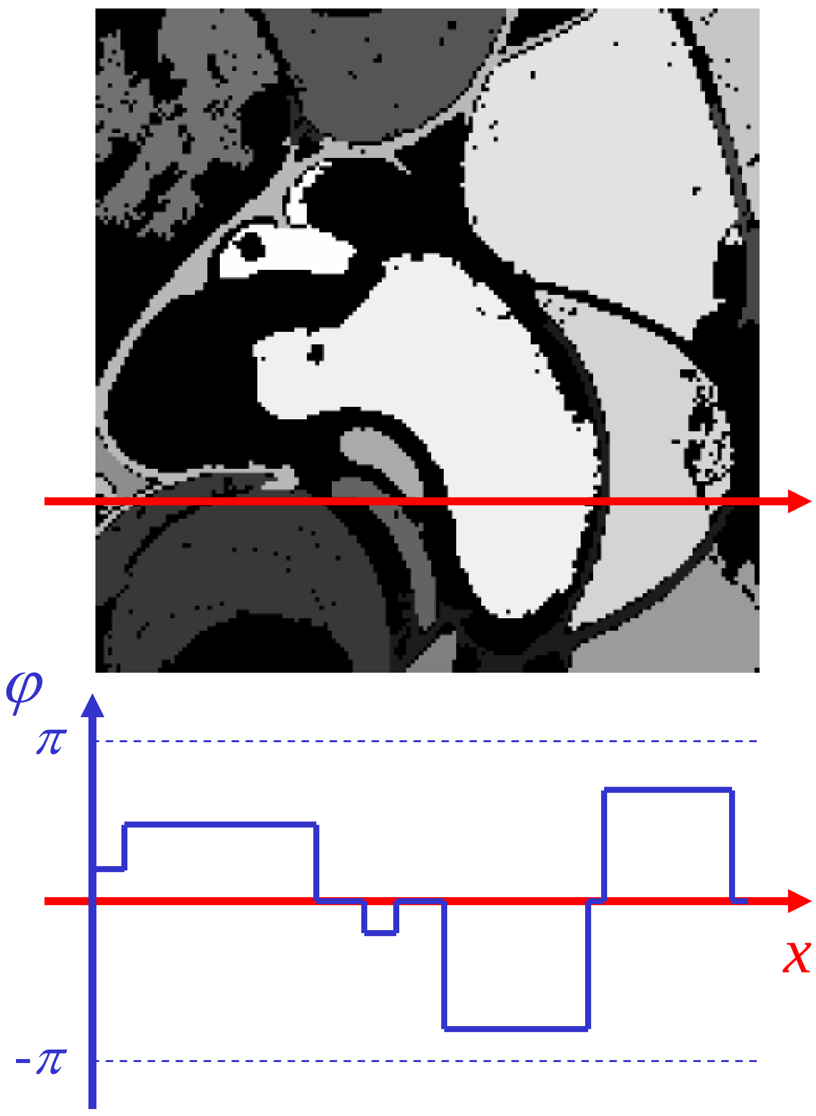
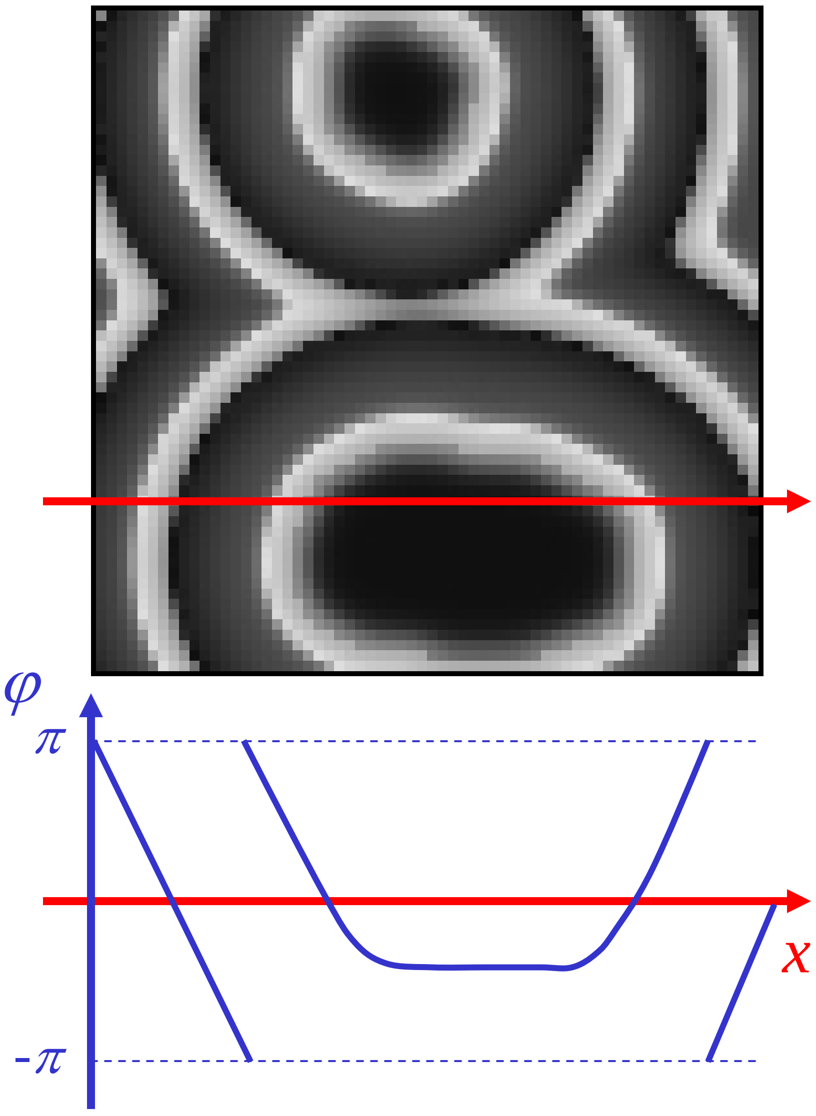
   - Temporal tagging
   - Group synchronization
   - Traveling waves
     - Phase gradients, instead of plateaus
     - Wave propagation and collision
3. **Synfire Chains**

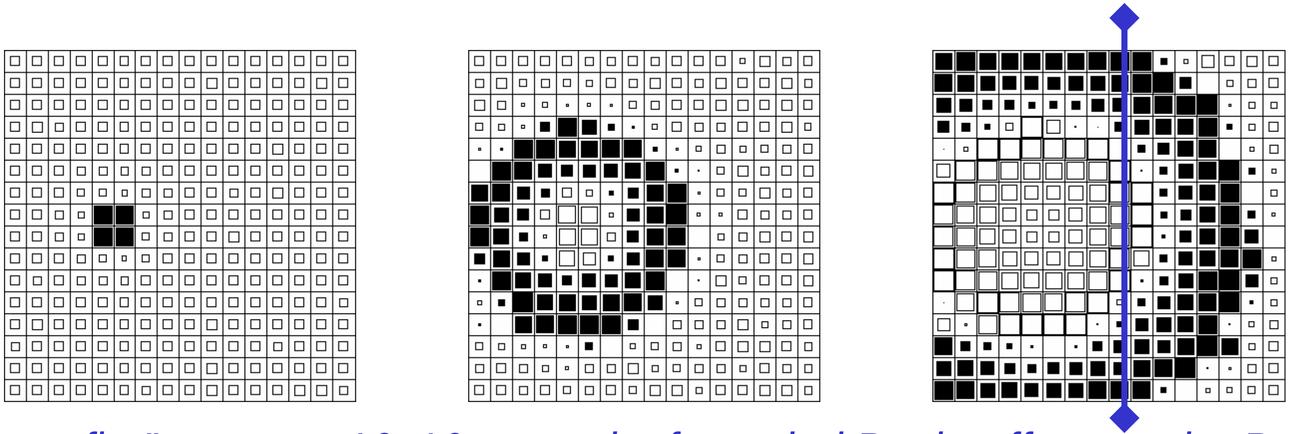
Traveling waves

Phase gradients, instead of plateaus

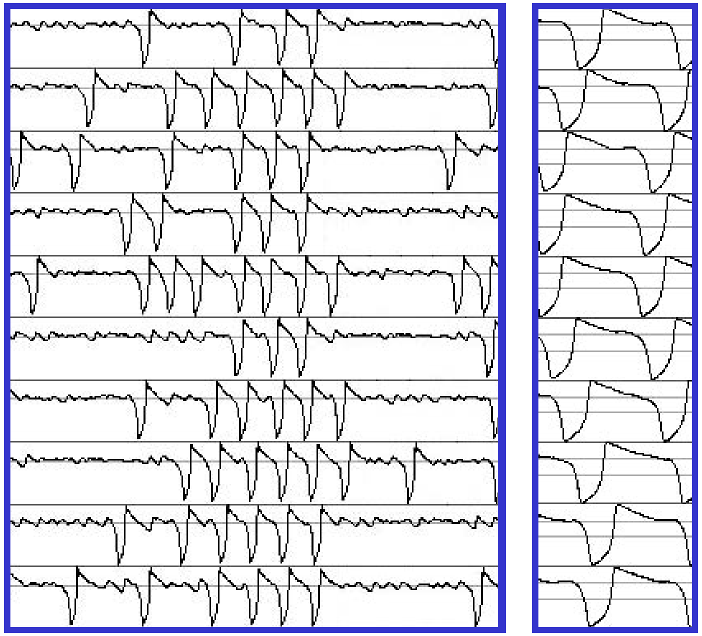




Traveling waves
Detail

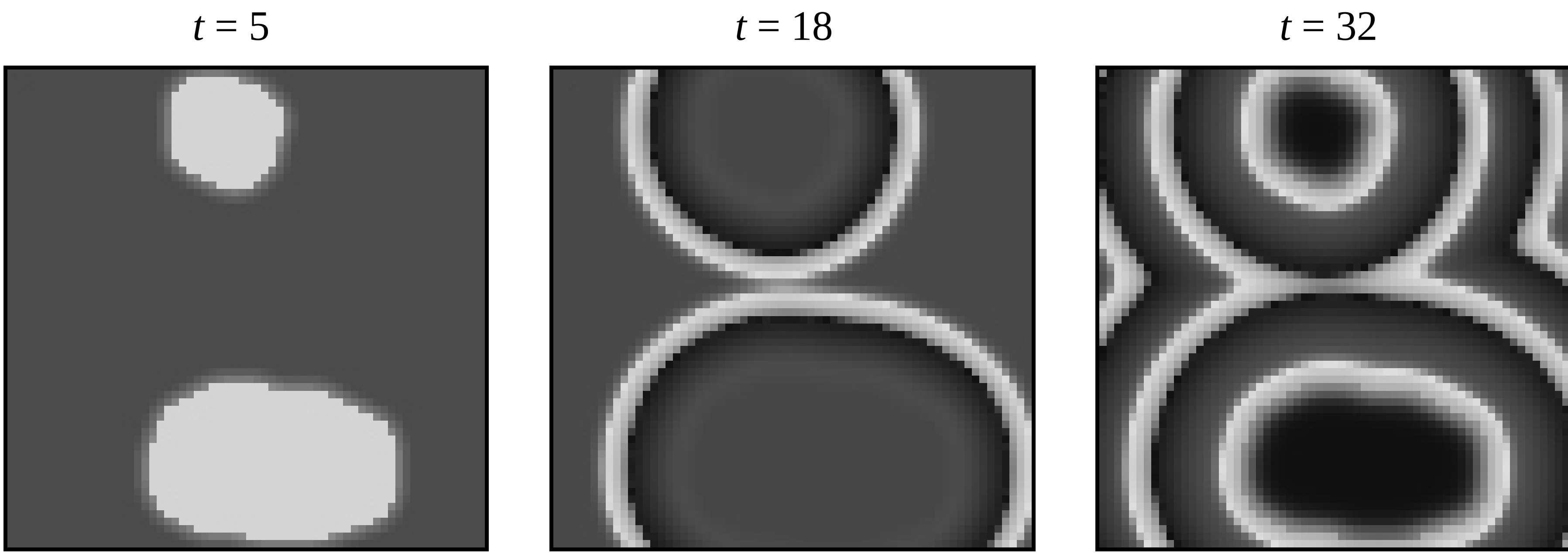


- *"Grass-fire" wave on 16x16 network of coupled Bonhoeffer-van der Pol units*



Traveling waves

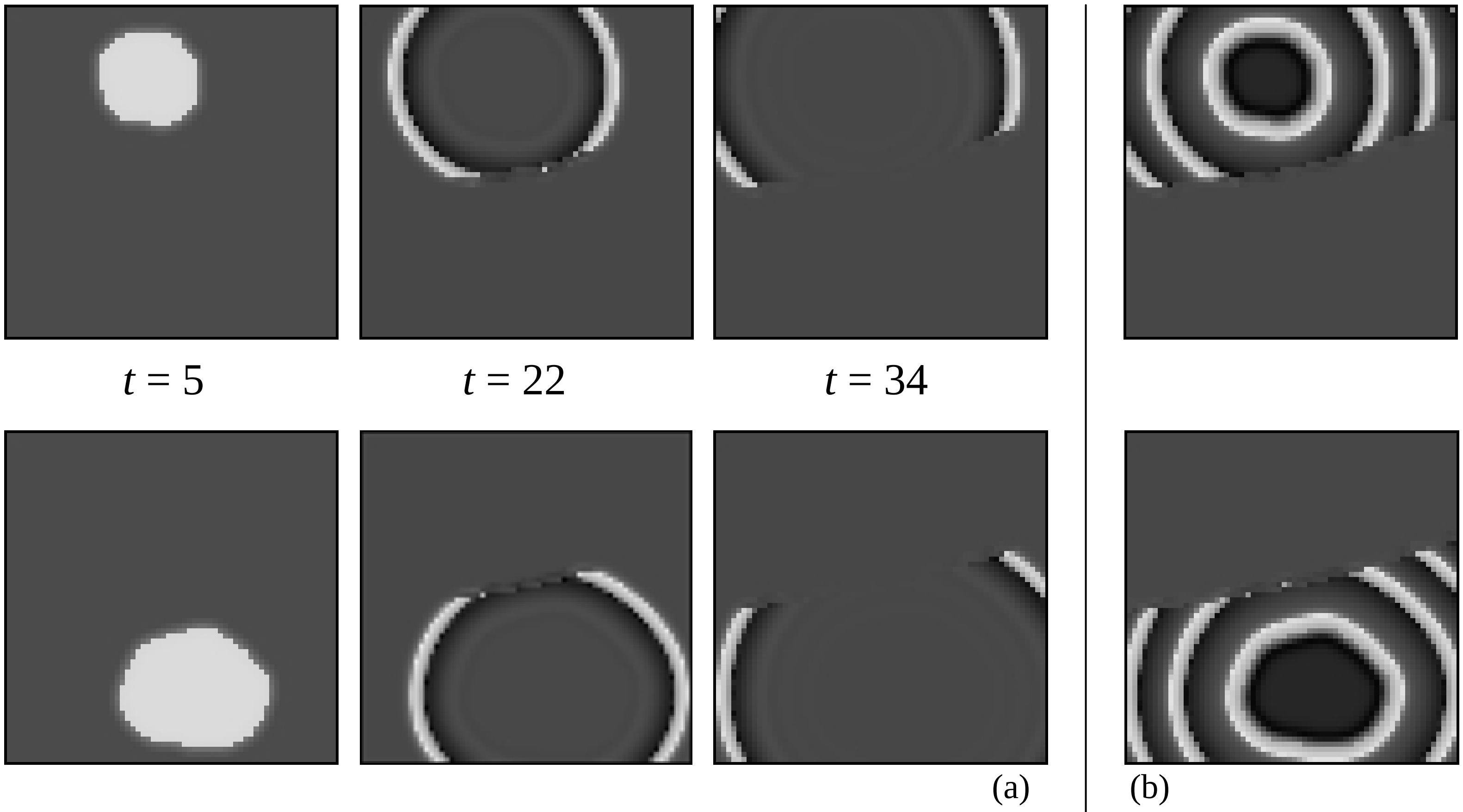
Wave propagation and collision



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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