MORPHOGENETIC "NEURON-FLOCKING":

DYNAMIC SELF-ORGANIZATION OF NEURAL ACTIVITY INTO MENTAL SHAPES

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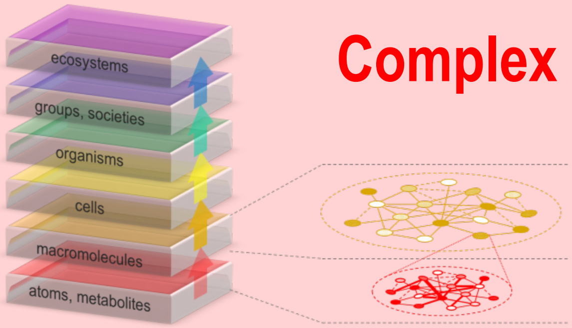
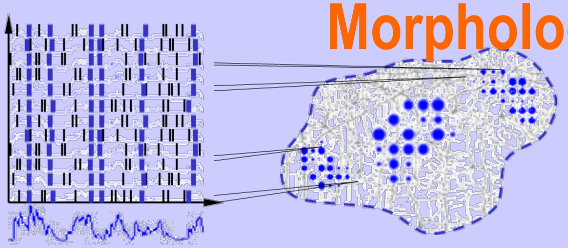
MORPHOGENETIC "NEURON-FLOCKING"

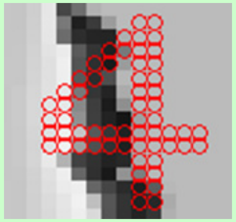
Complex Systems Levels

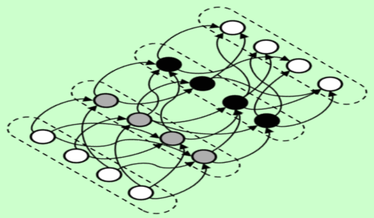


Temporal Code, Patterns, Morphology

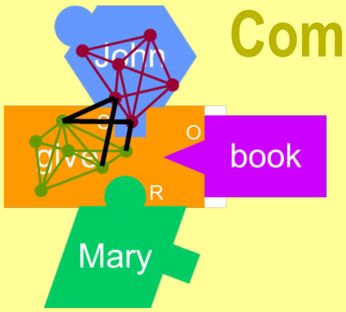


Waves, Chains, Phase Shapes

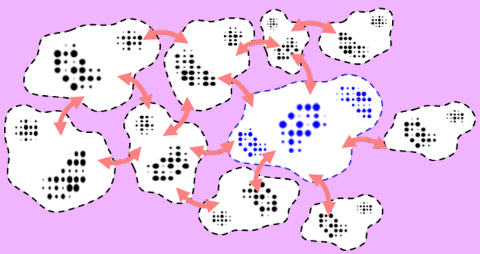




Compositionality

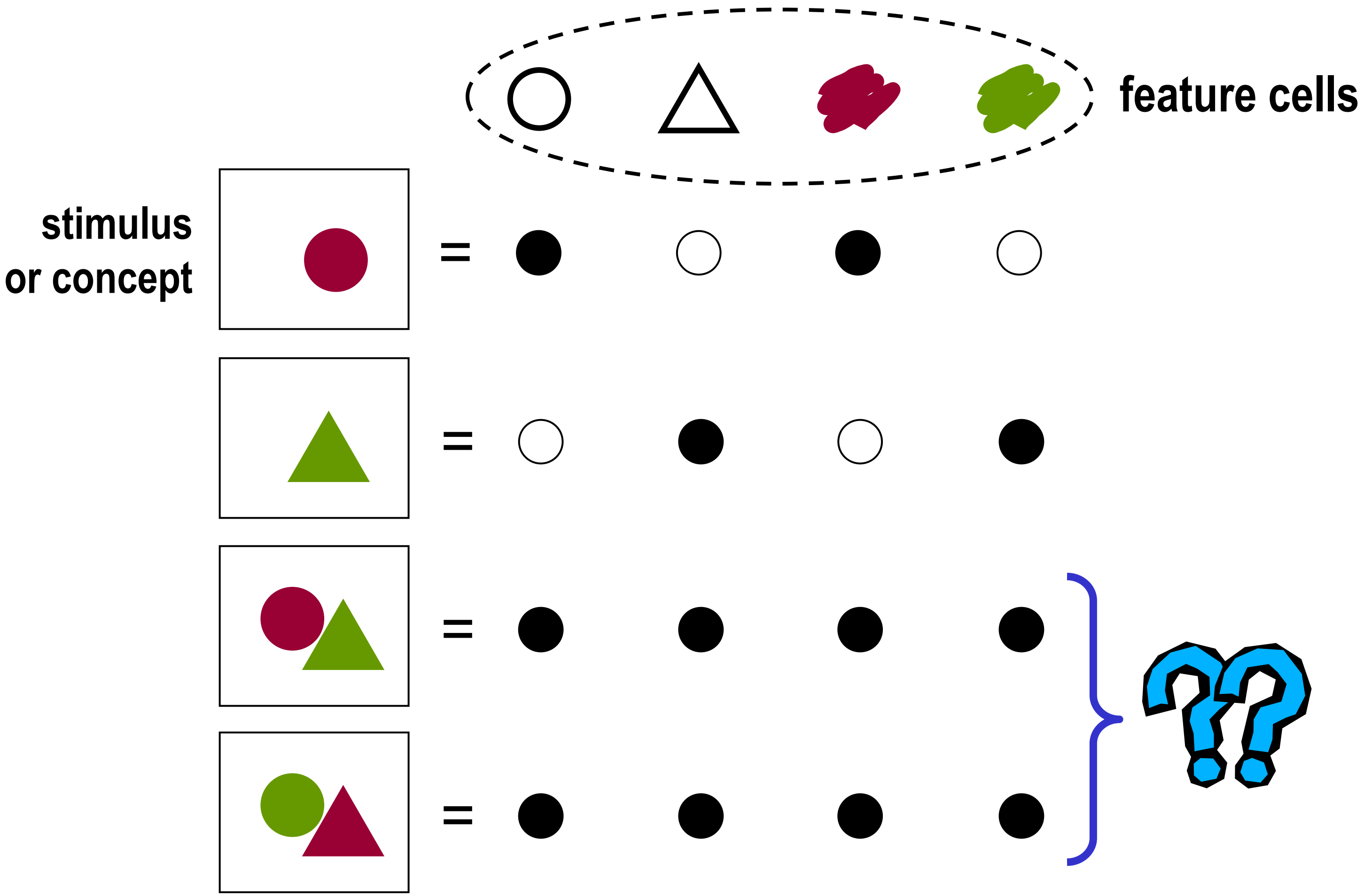


Emergent Neurodynamics



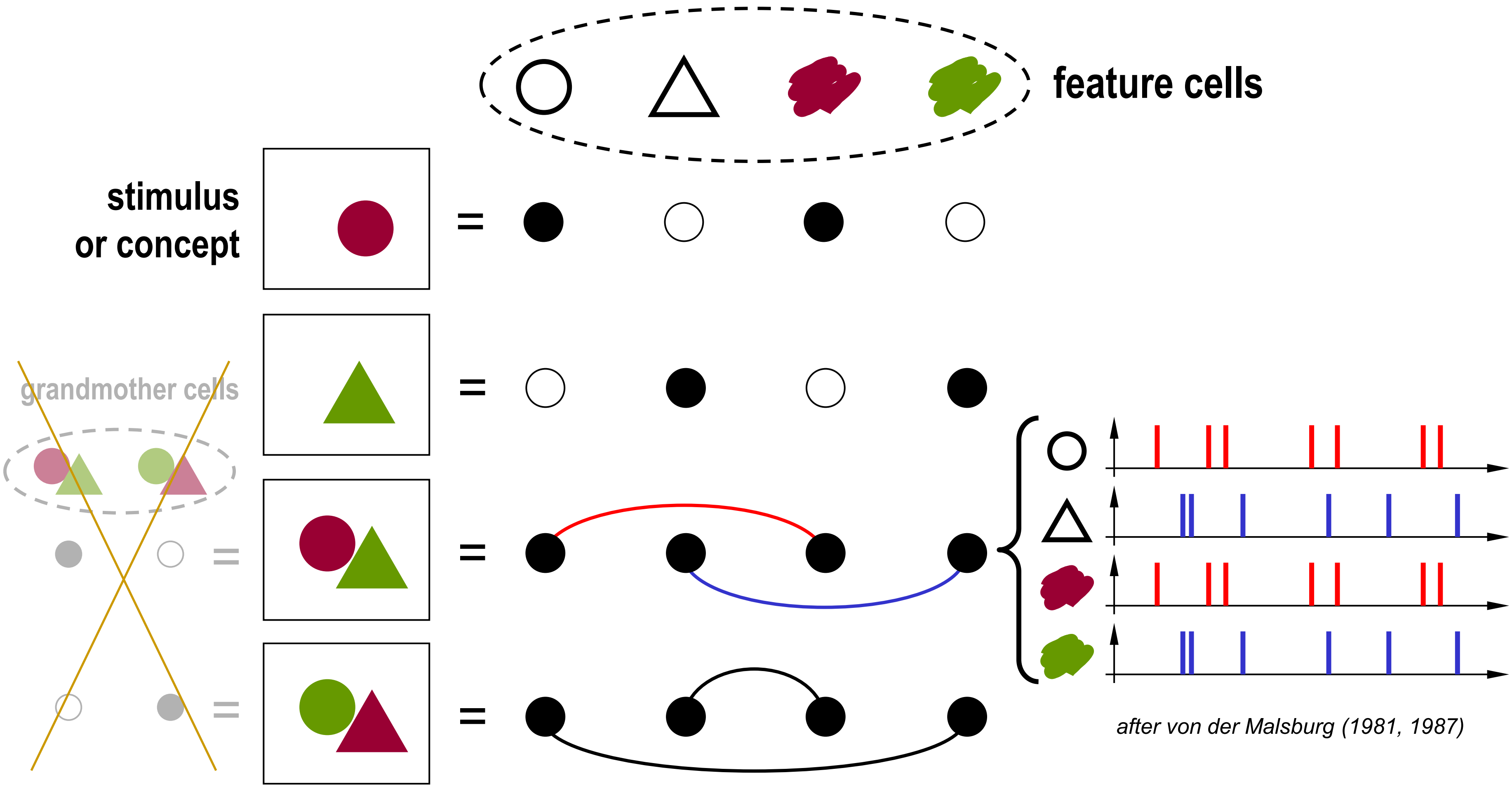
Compositionality from Temporal Correlations

- **The "binding problem": using temporal code**
  - ✓ how to represent relationships?



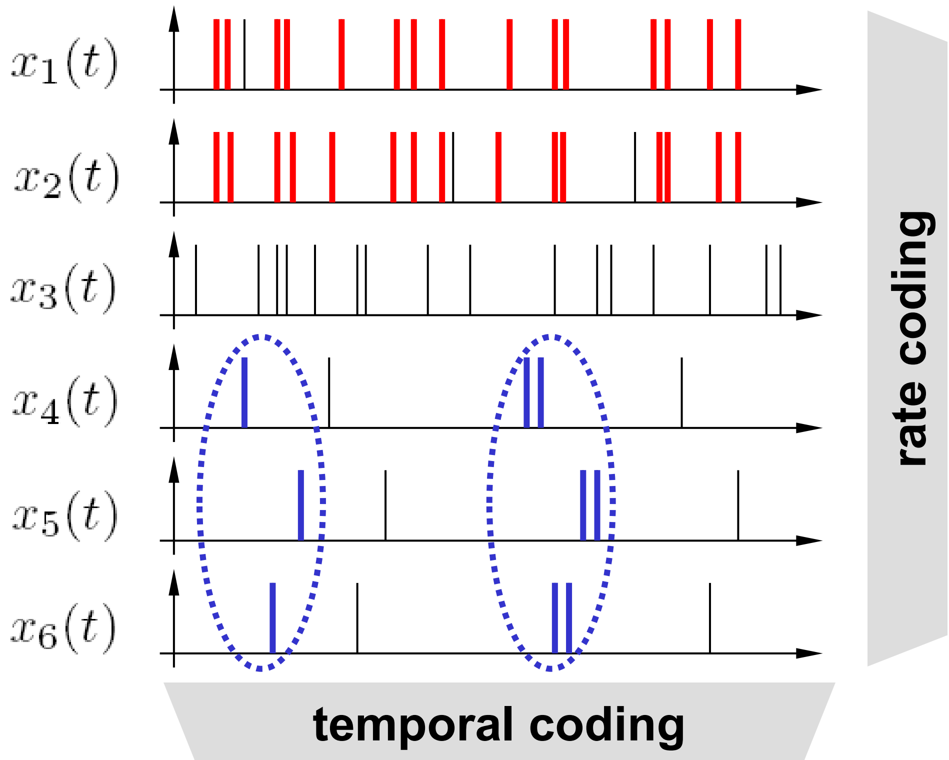
Compositionality from Temporal Correlations

➤ Idea: relational information can be encoded *temporally*



➢ The importance of temporal coding

✓ more than mean rates → ***temporal correlations*** among spikes



$\langle x_1(t) \rangle =$ ● 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

after von der Malsburg (1981) and Abeles (1982)

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

➢ zero-delays: synchrony
(1 and 2 more in sync than 1 and 3)

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

➢ nonzero delays: rhythms
(4, 5 and 6 correlated through delays)

Compositionality from Temporal Correlations

➢ 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*

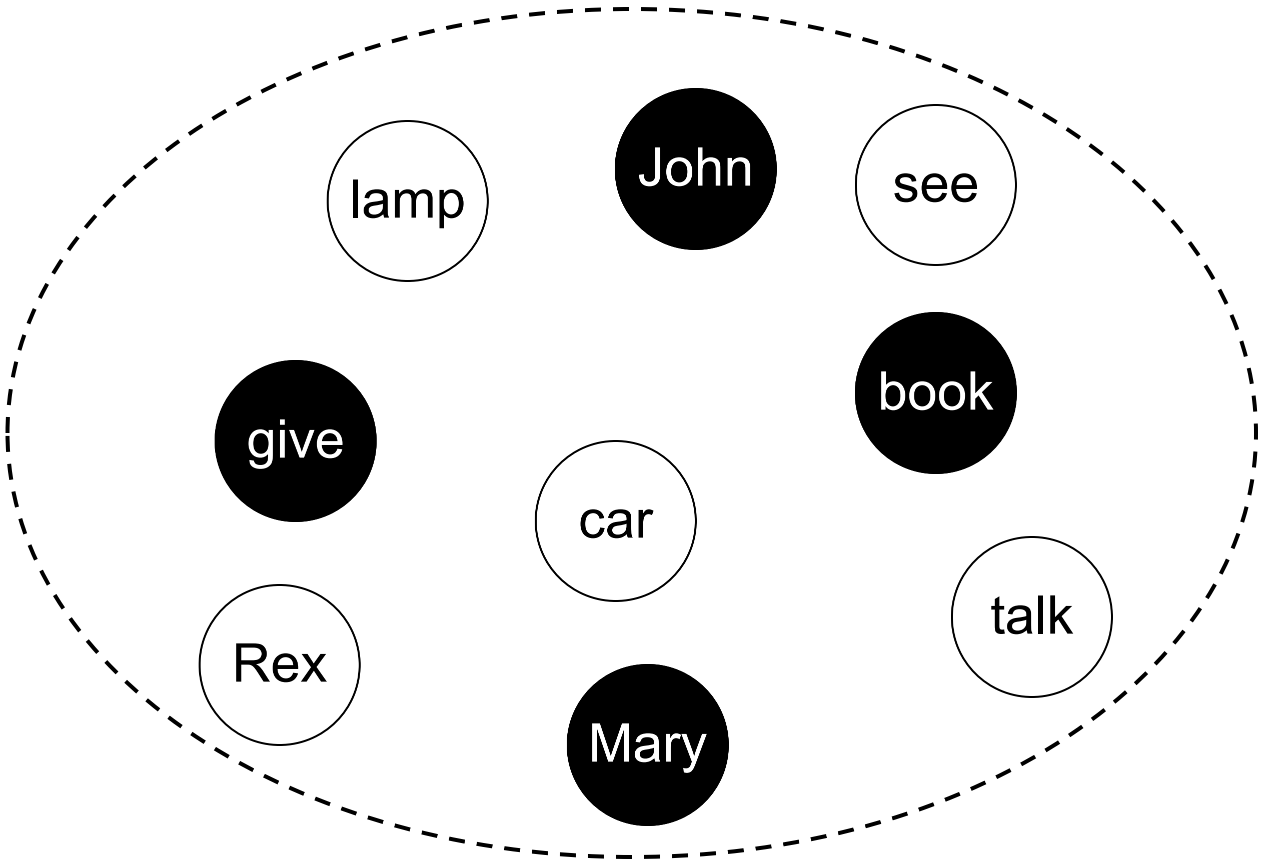
→ *rate coding is confirmed in sensory system and primary cortical areas, however increasingly considered insufficient for integrating the information*

➢ Temporal coding pioneers of the 1980-90's

- von der Malsburg (1981): *theoretical proposal to consider correlations*
- 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*

Compositionality from Temporal Correlations

➢ From feature co-activation to temporal binding



(a) John gives a book to Mary.

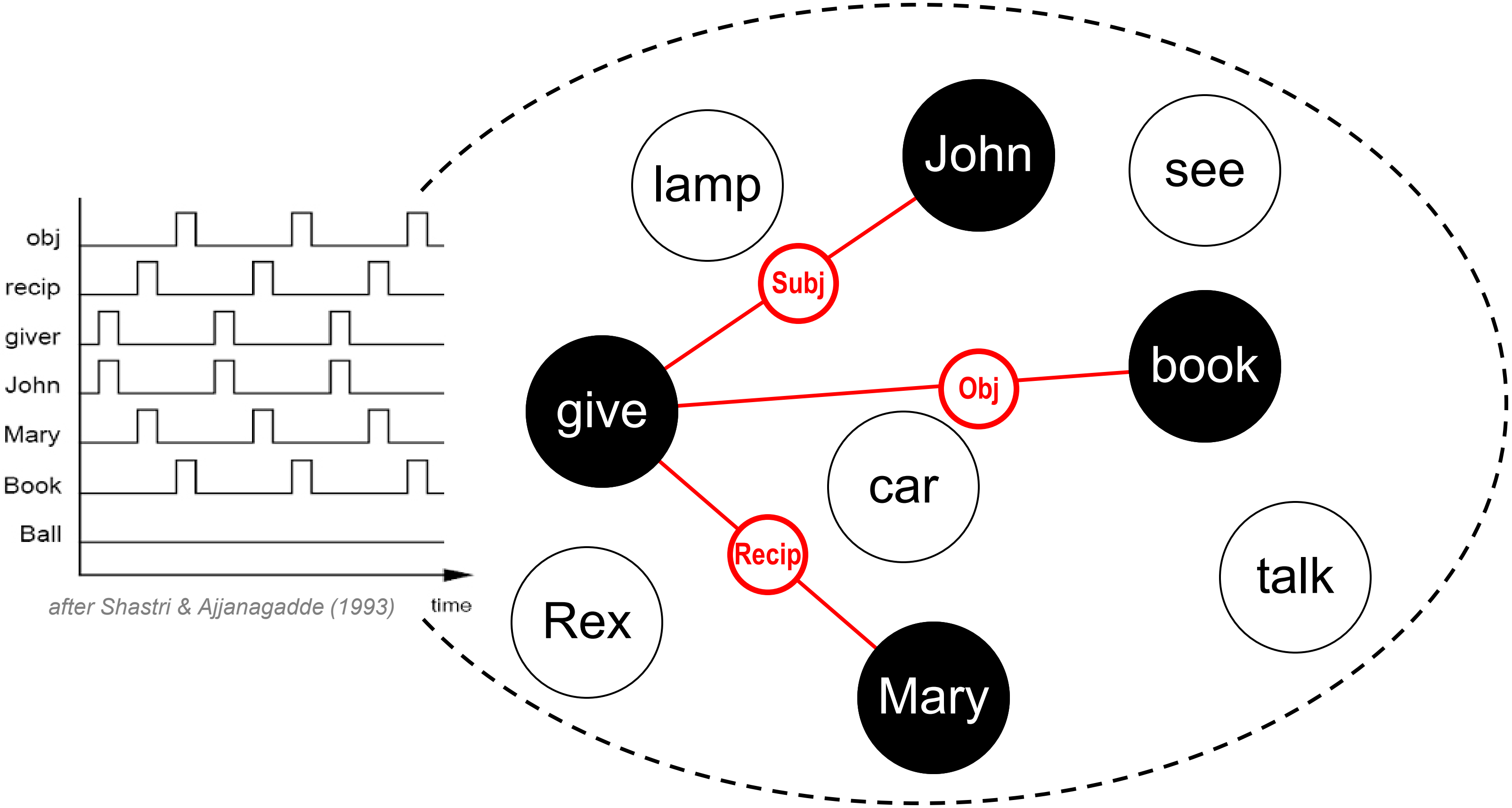
(b) Mary gives a book to John.

(c) Book John Mary give.*

“superposition catastrophe”

Compositionality from Temporal Correlations

➢ From feature co-activation to temporal binding



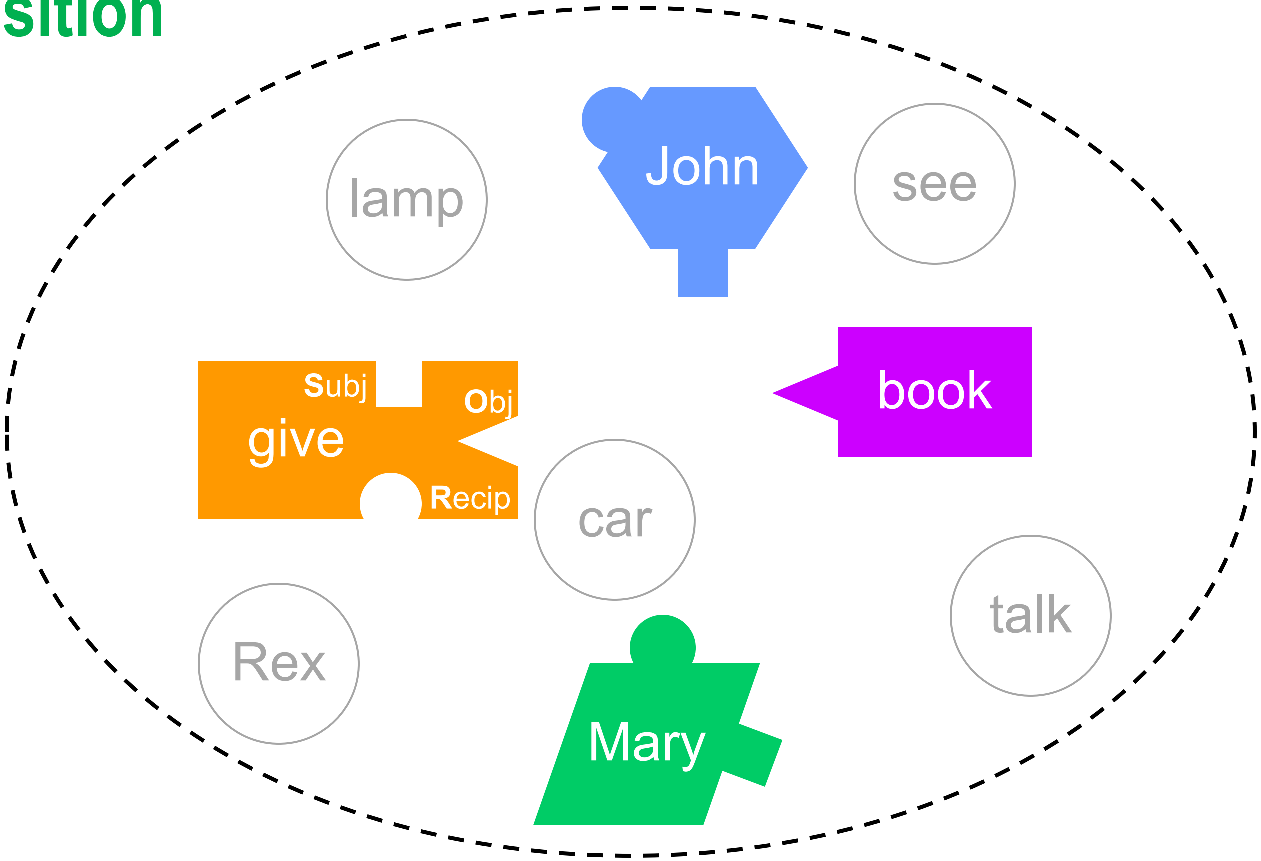
(a) John gives a book to Mary.

~~*(b) Mary gives a book to John.*~~

~~*(c)* Book John Mary give.*~~

Compositionality from Temporal Correlations

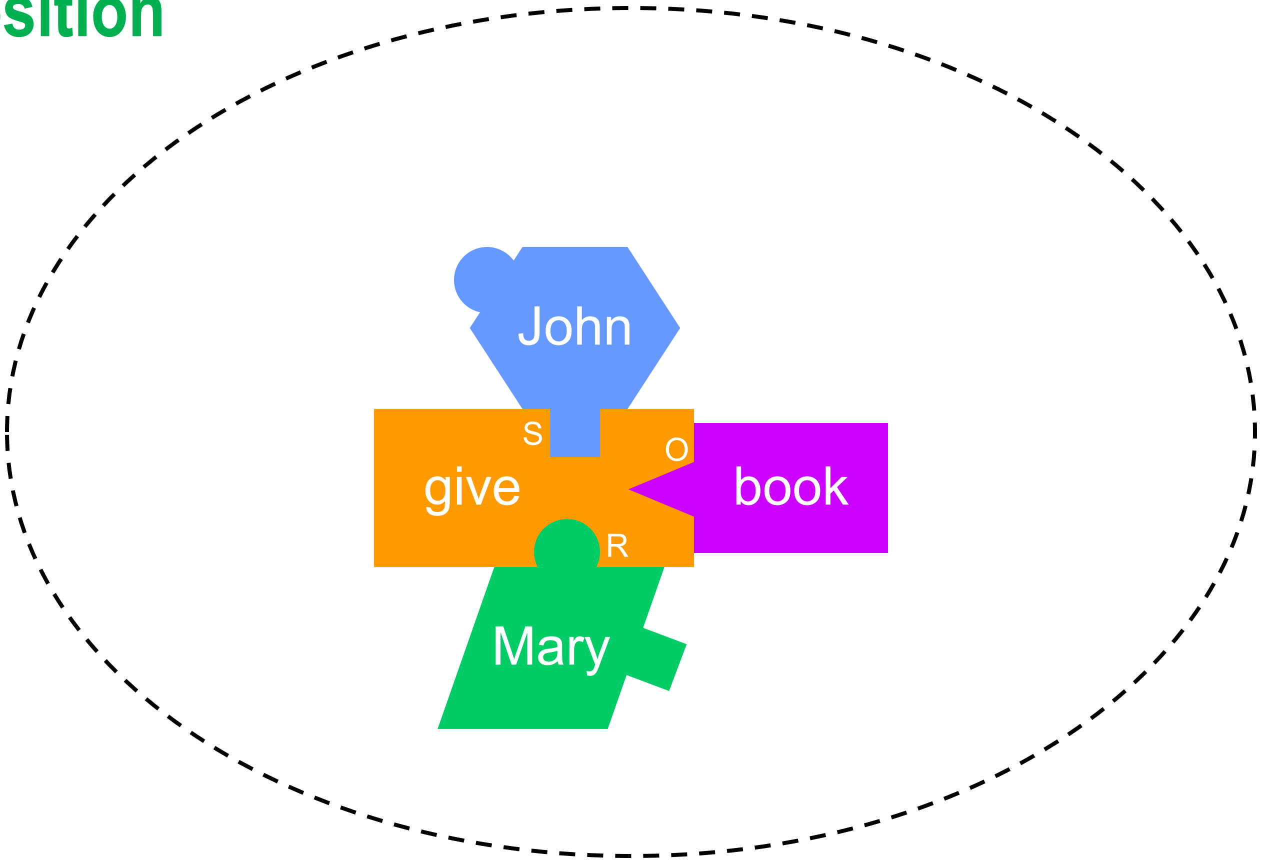
- ... further: from simple binding to full shape-based composition



- ✓ language as a construction game of “building blocks”

Compositionality from Temporal Correlations

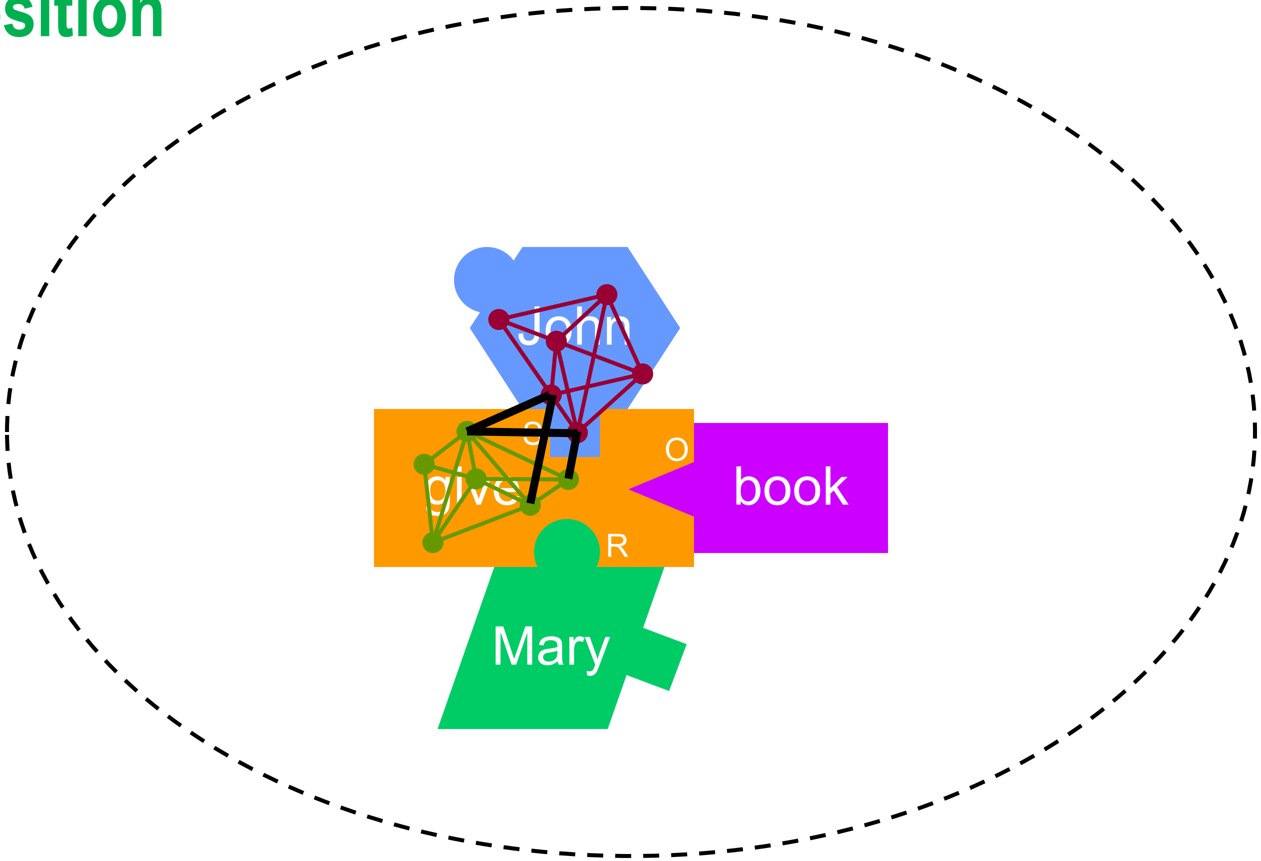
- ... further: from simple binding to full shape-based composition



✓ language as a construction game of "building blocks"

Compositionality from Temporal Correlations

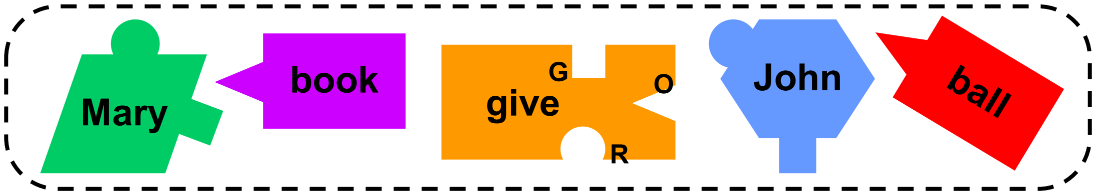
- ... further: from simple binding to full shape-based composition

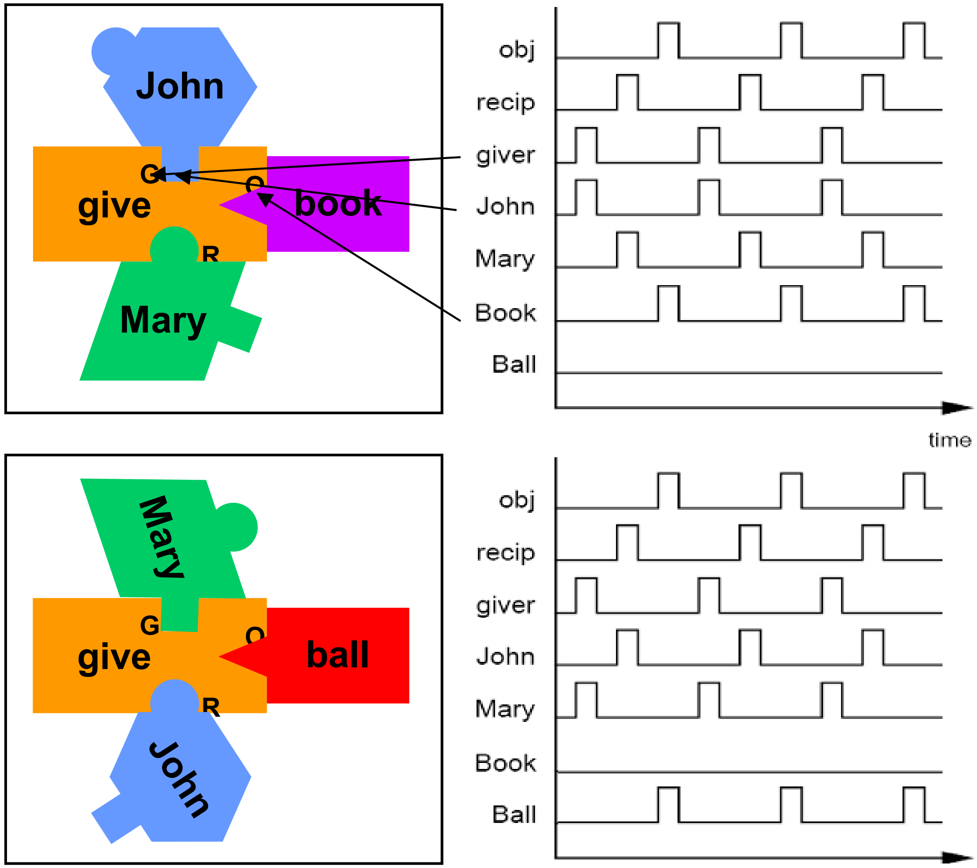


- ✓ language as a construction game of “building blocks”

Compositionality from Temporal Correlations

➢ Temp. binding is the "glue" of all shape-based composition





after Bienenstock (1995) *after Shastri & Ajjanagadde (1993)*

✓ language, perception, cognition are a game of ***building blocks***

✓ mental representations are internally ***structured***

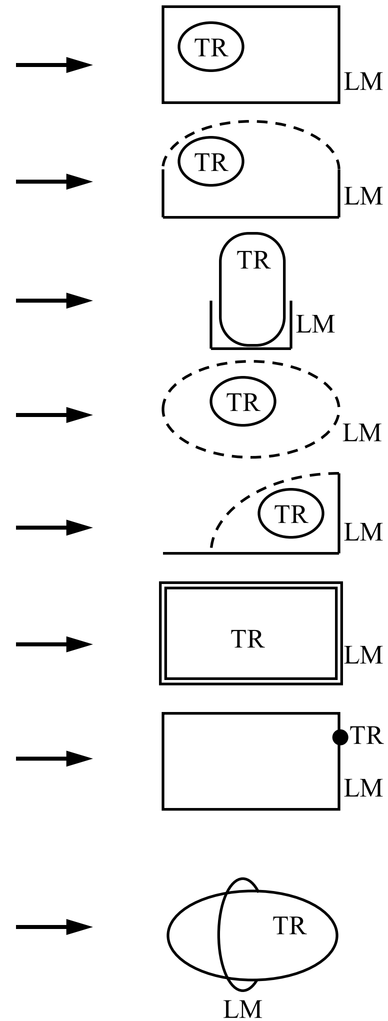
✓ elementary components ***assemble dynamically*** via temporal binding

Example 1: cognitive linguistics, iconic grammar

→ *Proposal: semantics is a **topological/geometric** affair (as opposed to a parse tree)*

IN

(1) (a) the cat **in** the house
(b) the bird **in** the garden
(c) the flowers **in** the vase
(d) the bird **in** the tree
(e) the chair **in** the corner
(f) the water **in** the vase
(g) the crack **in** the vase
(h) the foot **in** the stirrup
(i) ?the finger **in** the ring



prototype

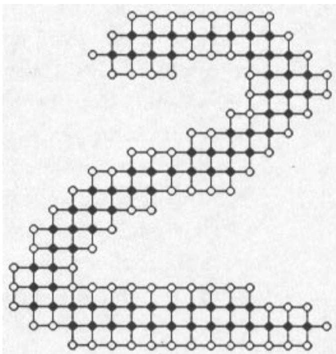
TR metonymy: flowers = stems

LM metonymy: vase = surface of vase

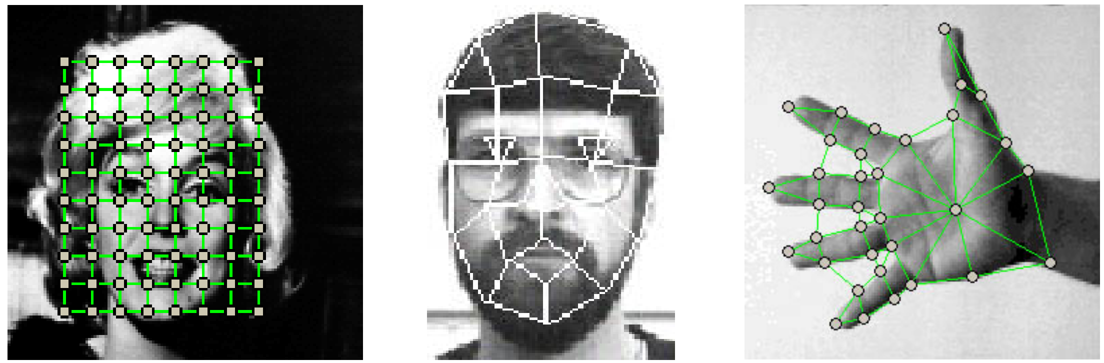
adapted from Herskovits (1986)

<u>Example 2</u>: graph representations in vision

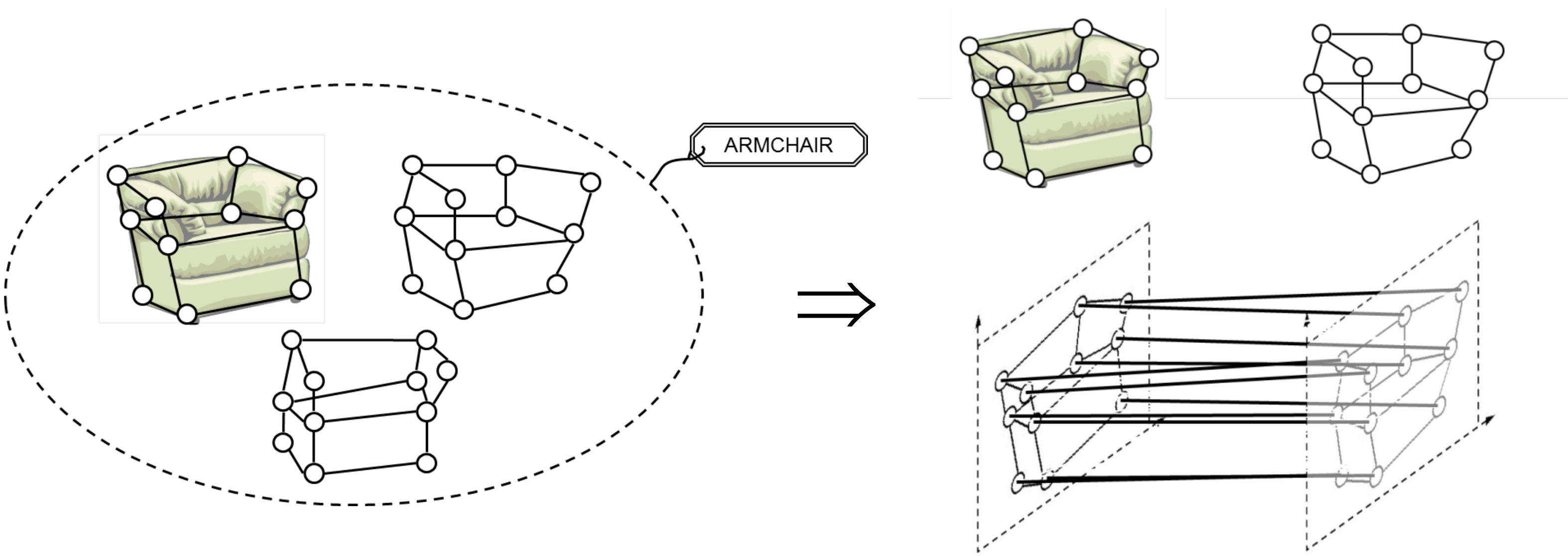
→ <u>*Proposal*</u>*:* ***graphs*** *representing the same object class are* ***structurally similar*** *and can be matched with each other*



Bienenstock & Doursat (1994)



Institut fuer Neuroinformatik, Bochum



Ok, so how could all this be done in spiking NNs?

(temporal coding is a good start but doesn't give us models)

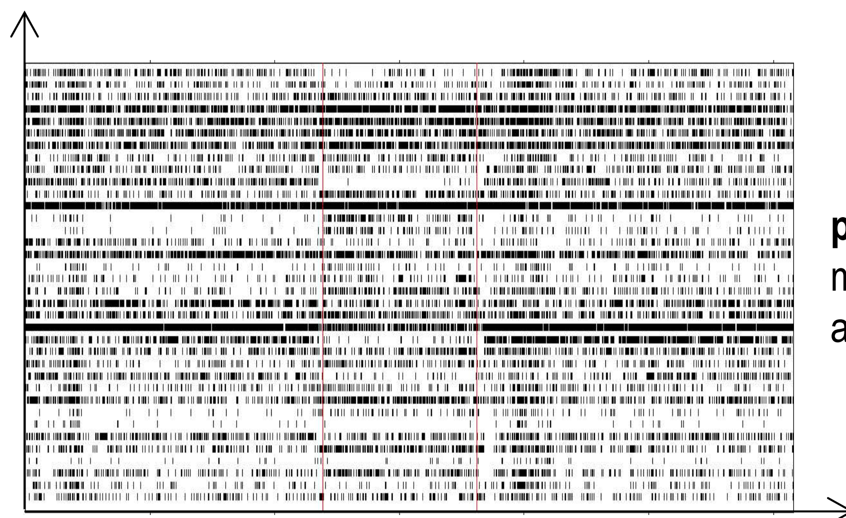
MORPHOGENETIC "NEURON-FLOCKING" (... WTH?)

MORPHOGENETIC "NEURON-FLOCKING"

phase space view:
complex spatiotemporal pattern =
mental shape

(dynamic) emergence?
structure?
properties?

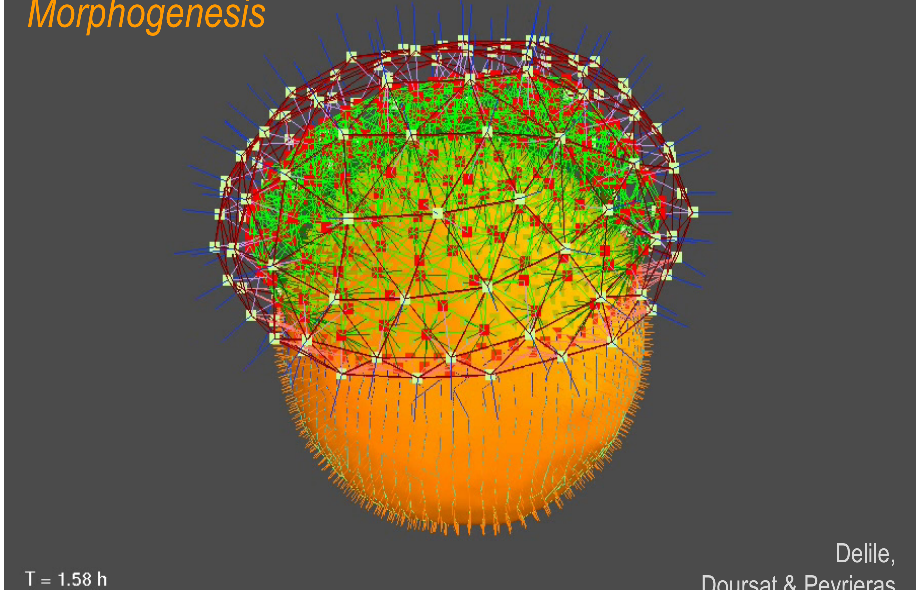
(long-term) persistence? learning? storage? compositionality?



physical space view:
mega-MEA raster plot =
activity of 10^6-10^8 neurons

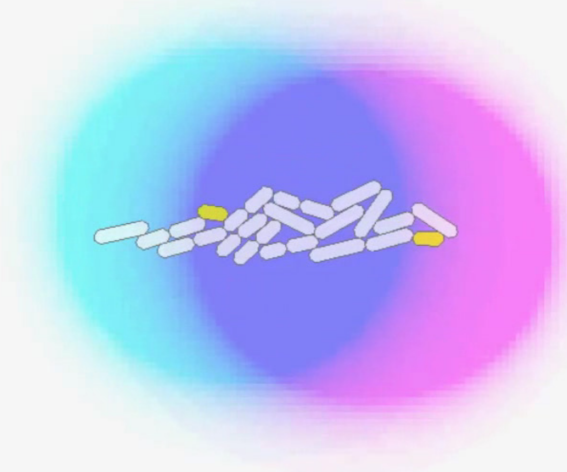
Morphogenetic Engineering → Devo-Inspired Alife

***MECAGEN** – Mechano-Genetic Model of Morphogenesis*



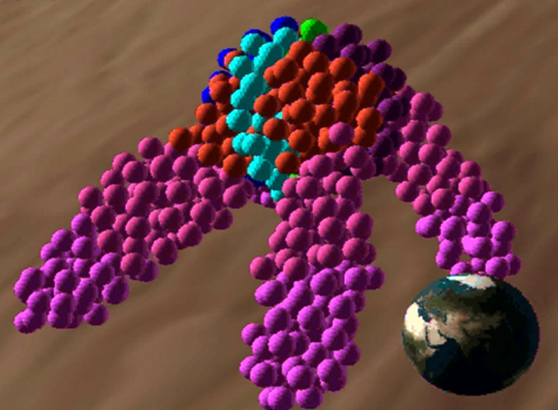
Delile, Doursat & Peyrieras

***SYNBIOTIC** – Synthetic Biology: From Design to Compilation*



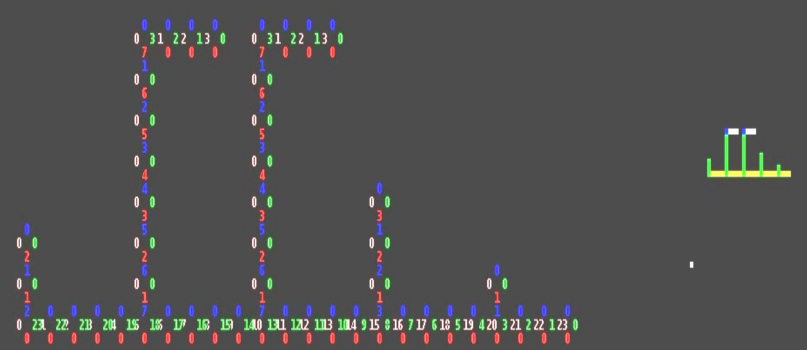
Kowaliw & Doursat

***MAPDEVO** – Modular Architecture by Programmable Development*



Doursat, Sanchez, Fernandez, Kowaliw & Vico

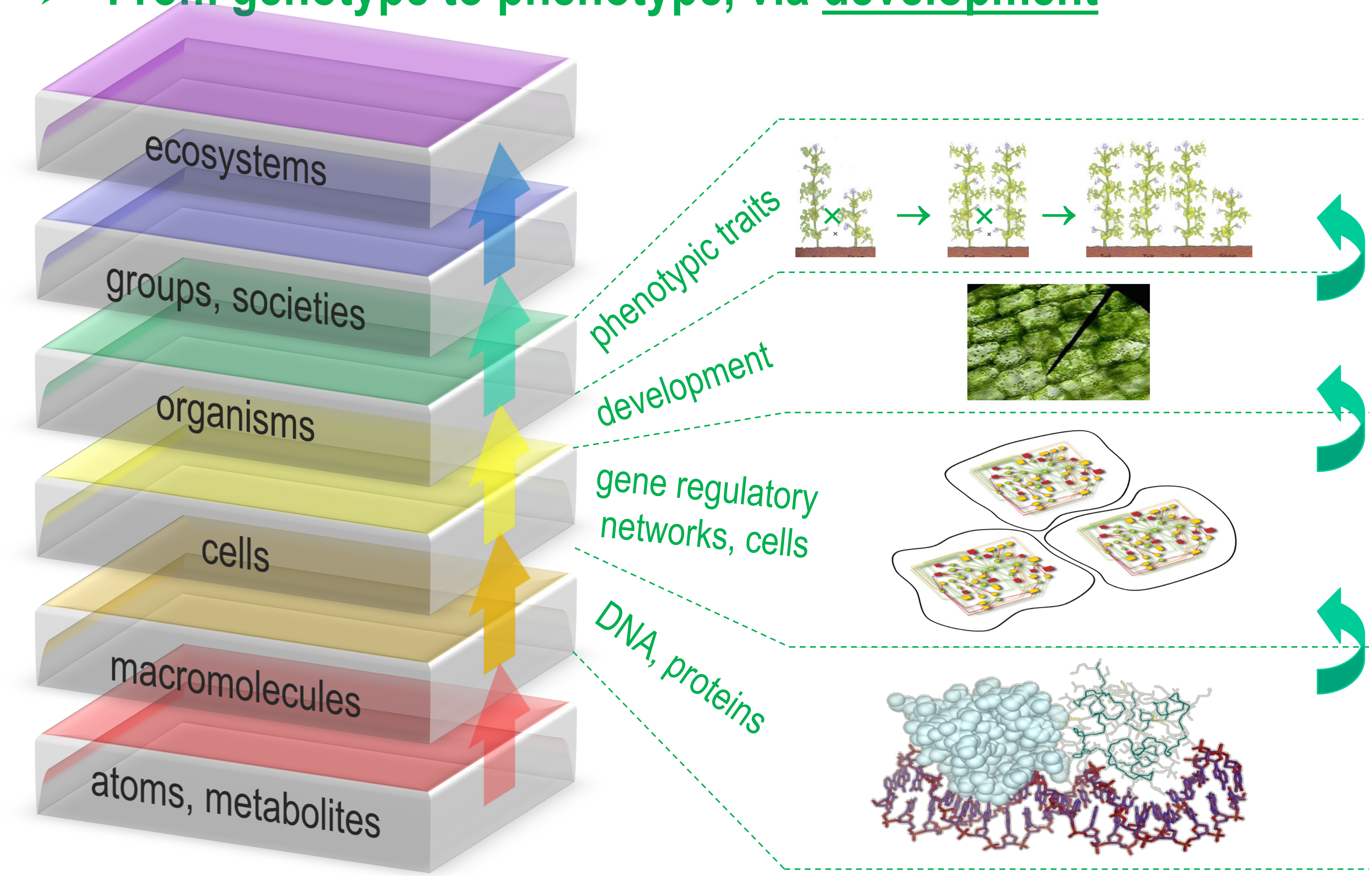
***PROGLIM** – Self-Constructed Network by Program-Limited Aggregation*



Doursat, Fourquet & Kowaliw

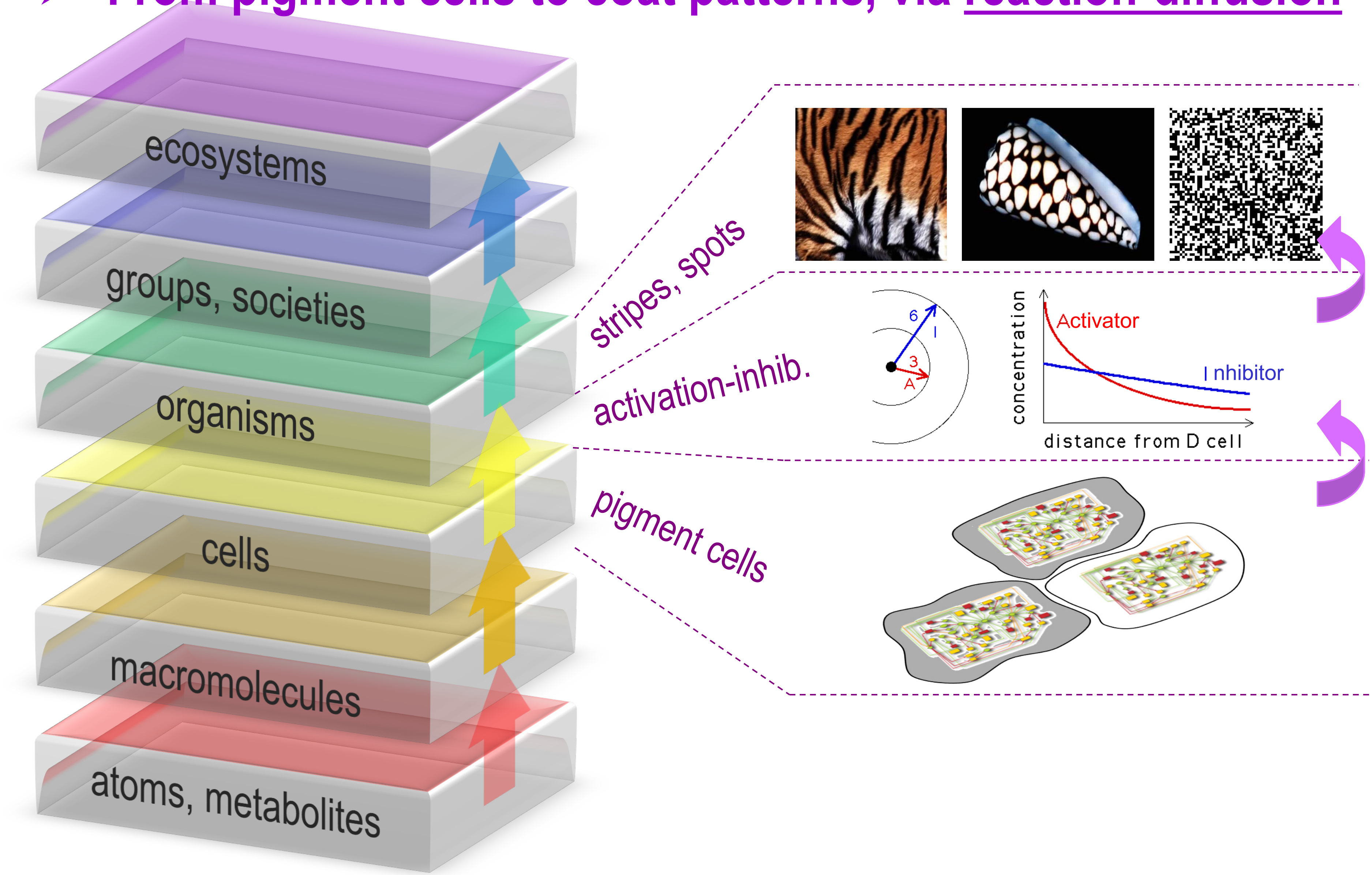
1. The Tower of Complex Systems

➢ From genotype to phenotype, via <u>development</u>



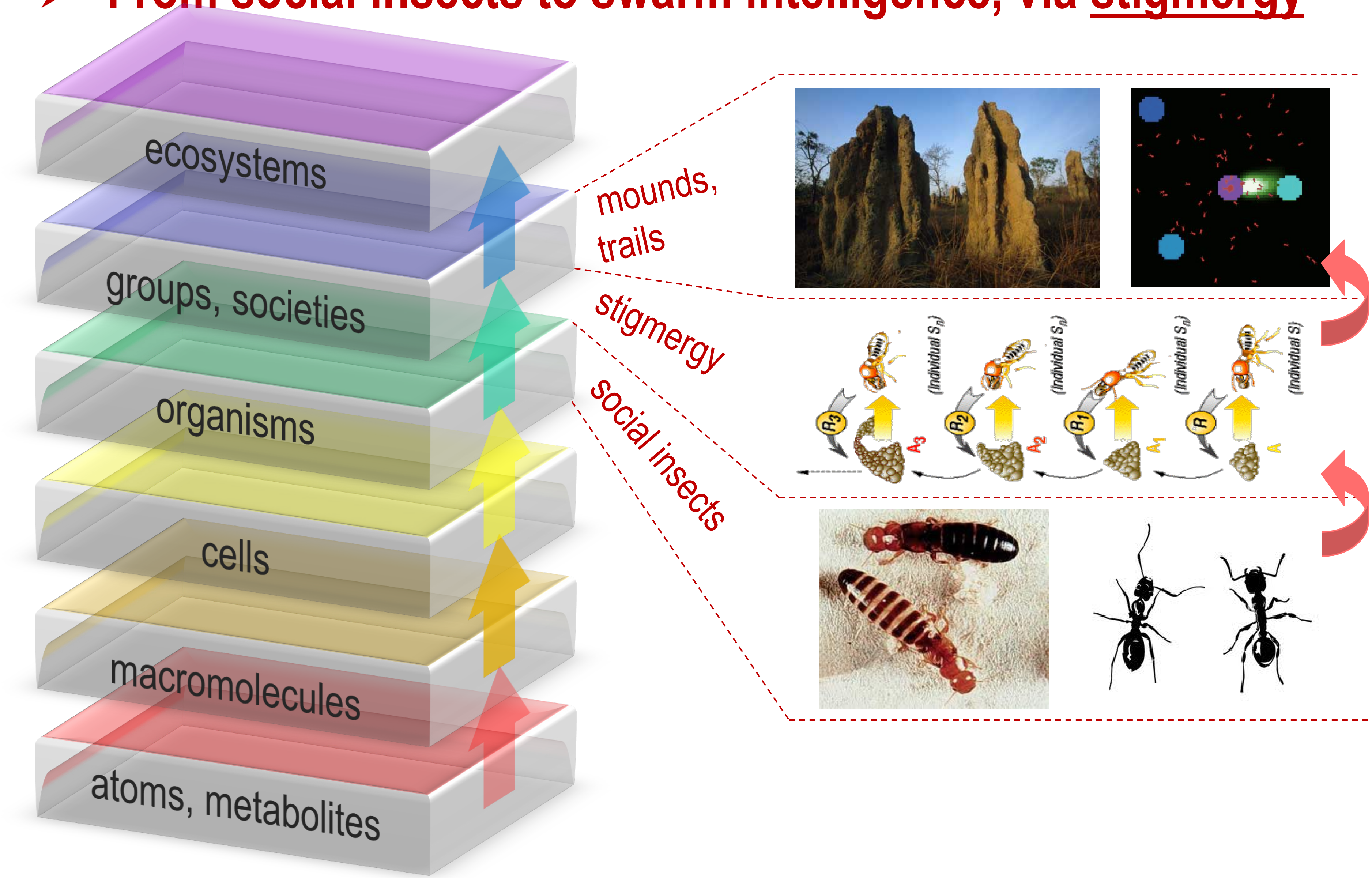
1. The Tower of Complex Systems

➢ **From pigment cells to coat patterns, via reaction-diffusion**



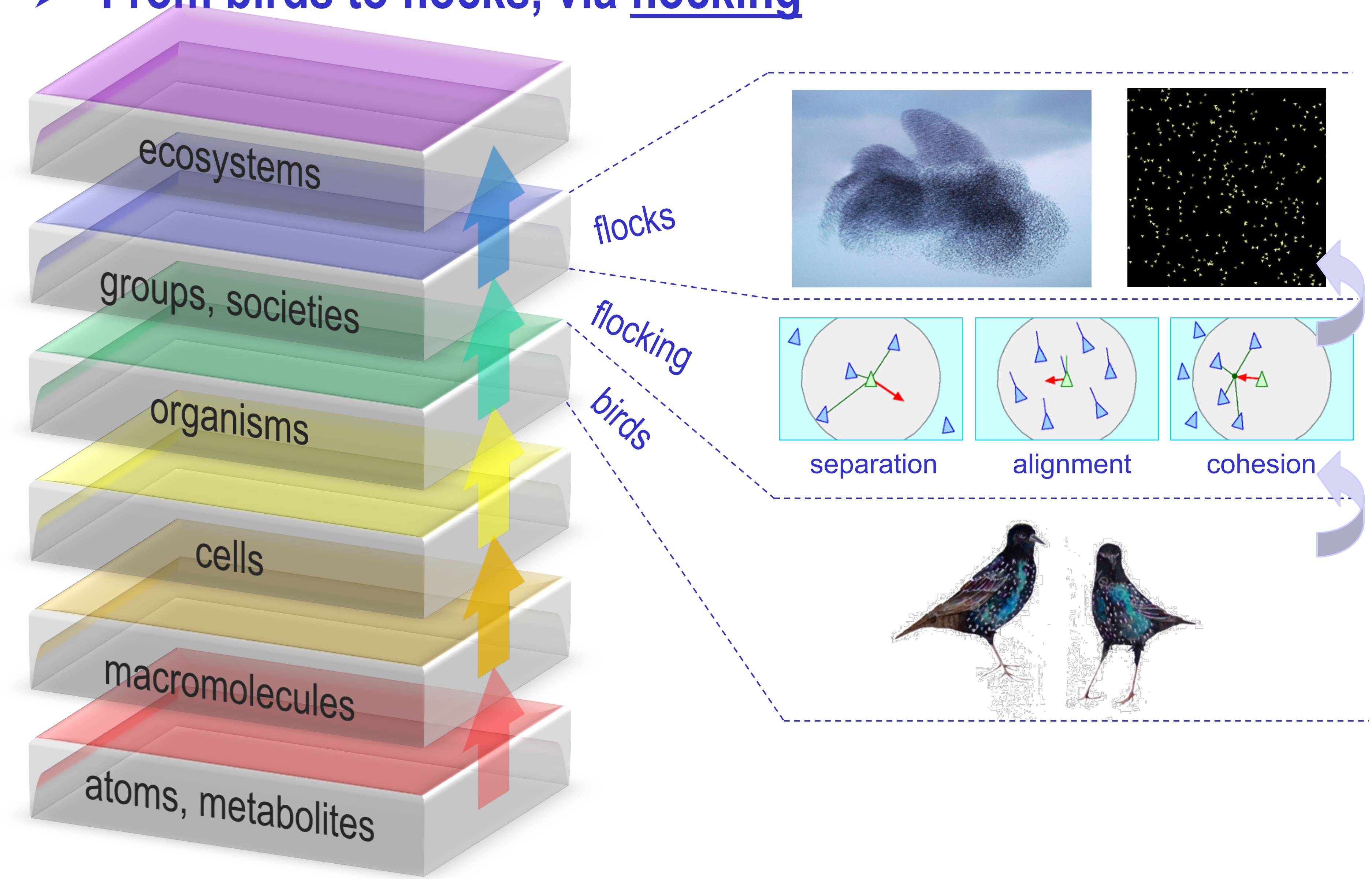
1. The Tower of Complex Systems

- From social insects to swarm intelligence, via <u>stigmergy</u>



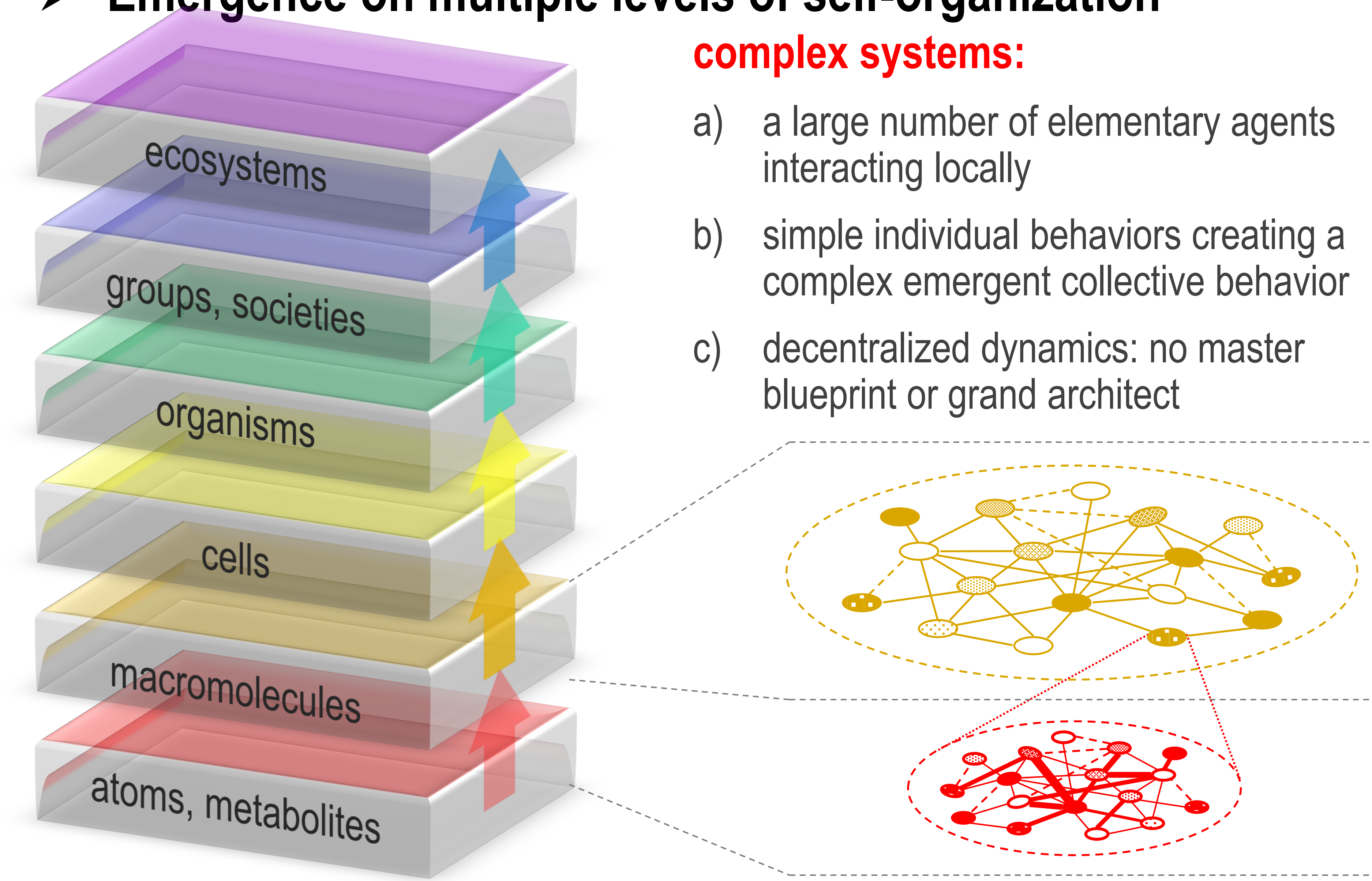
1. The Tower of Complex Systems

➢ From birds to flocks, via flocking



1. The Tower of Complex Systems

➢ **Emergence on multiple levels of self-organization**



complex systems:

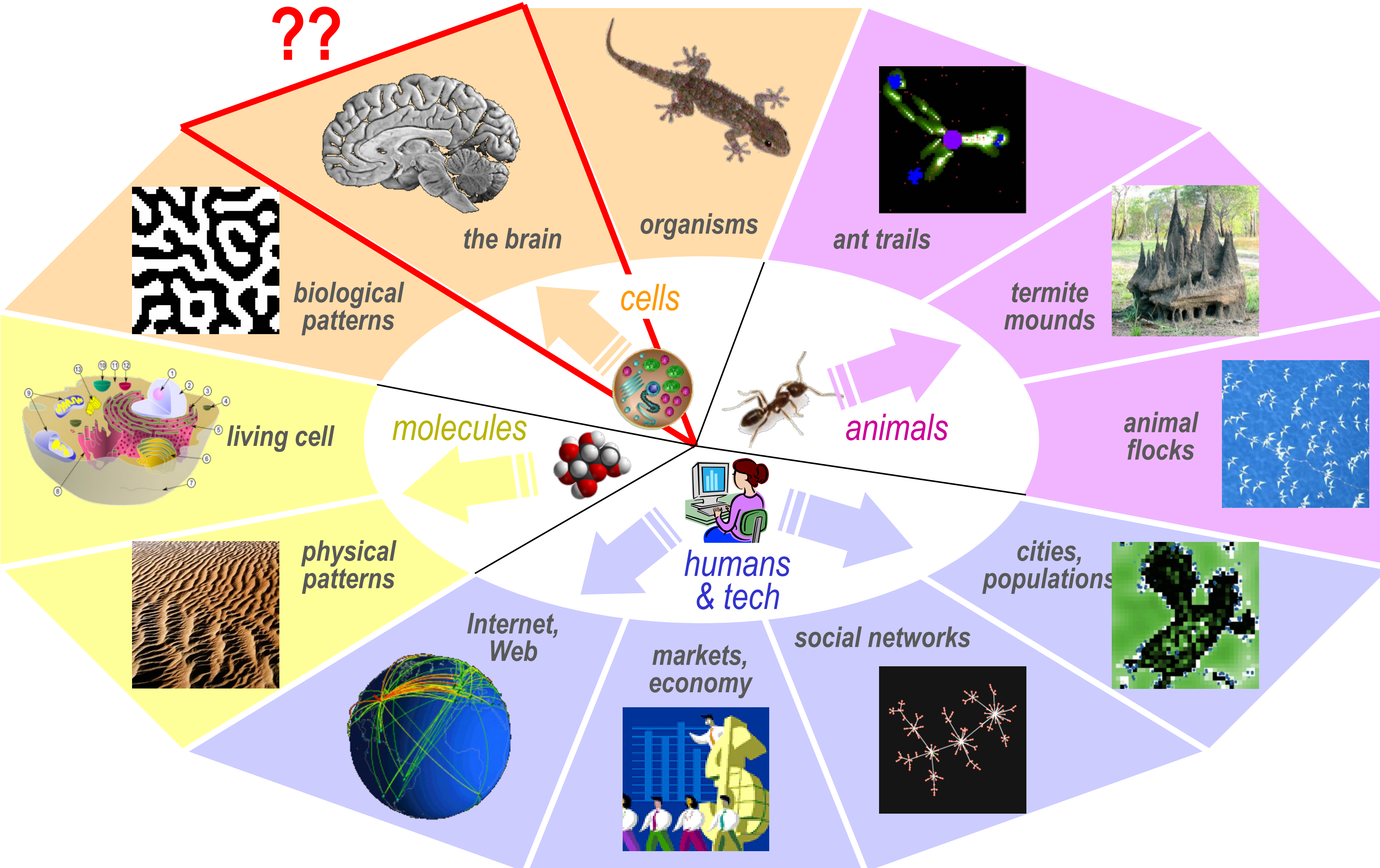
a) a large number of elementary agents interacting locally

b) simple individual behaviors creating a complex emergent collective behavior

c) decentralized dynamics: no master blueprint or grand architect

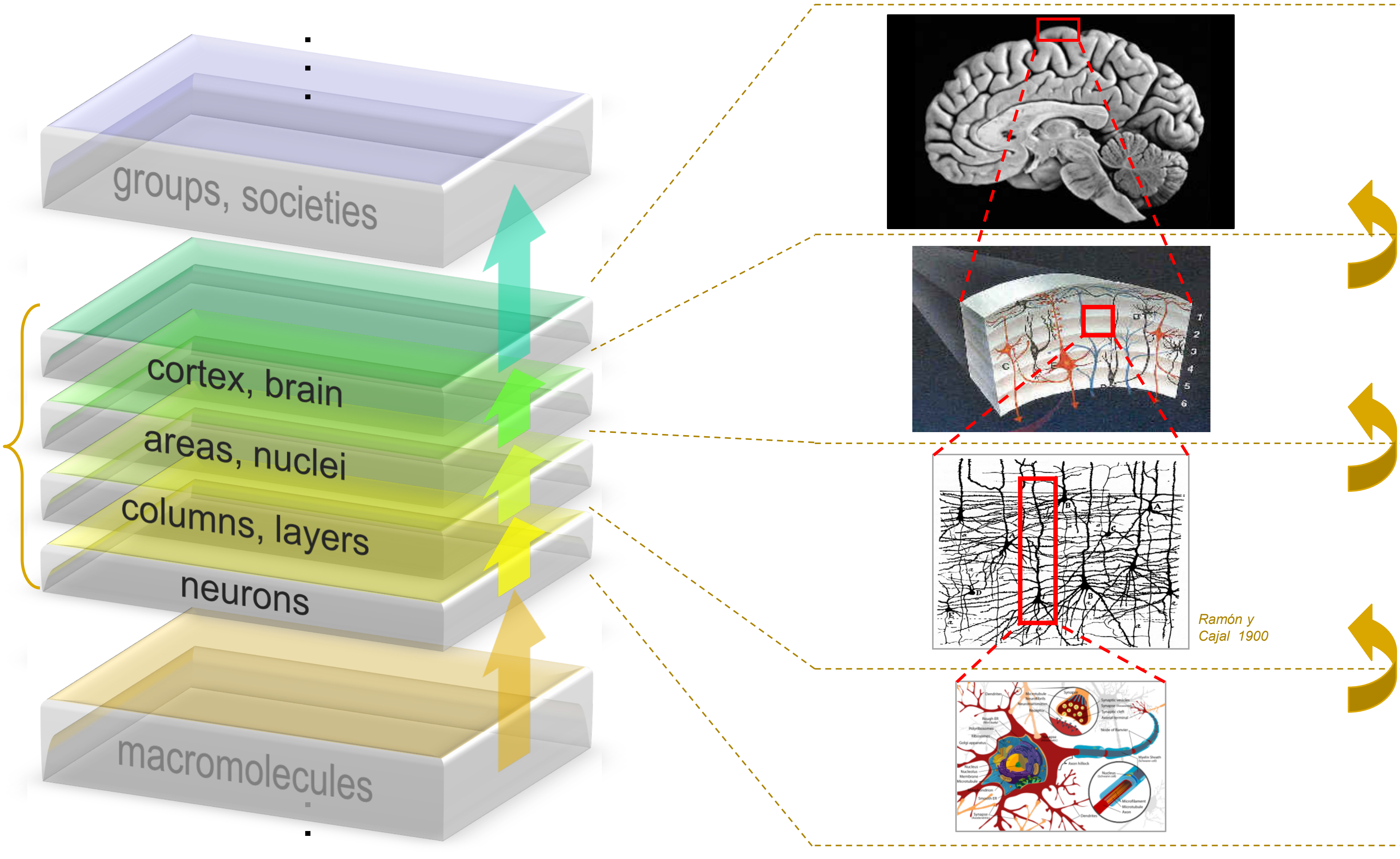
1. The Tower of Complex Systems

- All agent types: molecules, cells, animals, humans & tech

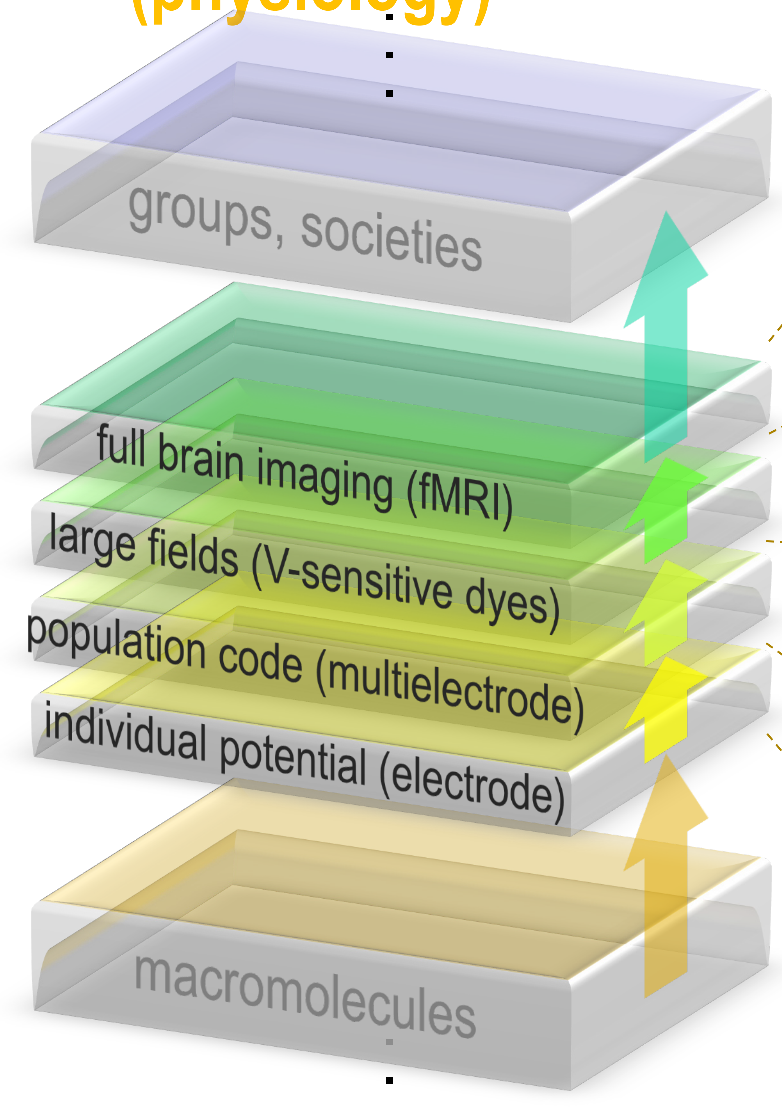


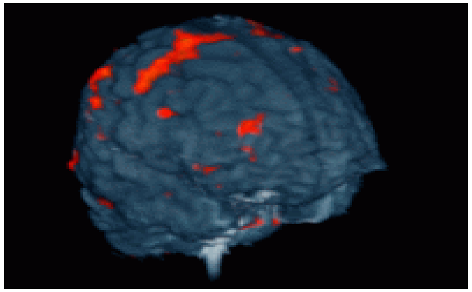
1. The Tower of Complex Systems

- From neurons to brain, via <u>neural development</u> (anatomy)

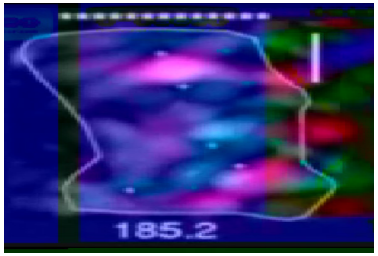


- **From potentials to fMRI, via synaptic transmission (physiology)**

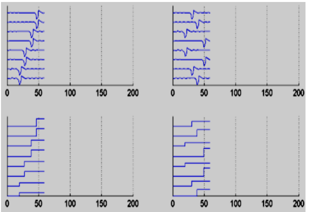




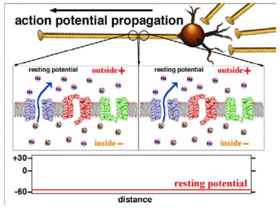
Animation of a functional MRI study (J. Ellermann, J. Strupp, K. Ugurbil, U Minnesota)



Dynamics of orientation tuning: polar movie
Sharon and Grinvald, Science 2002

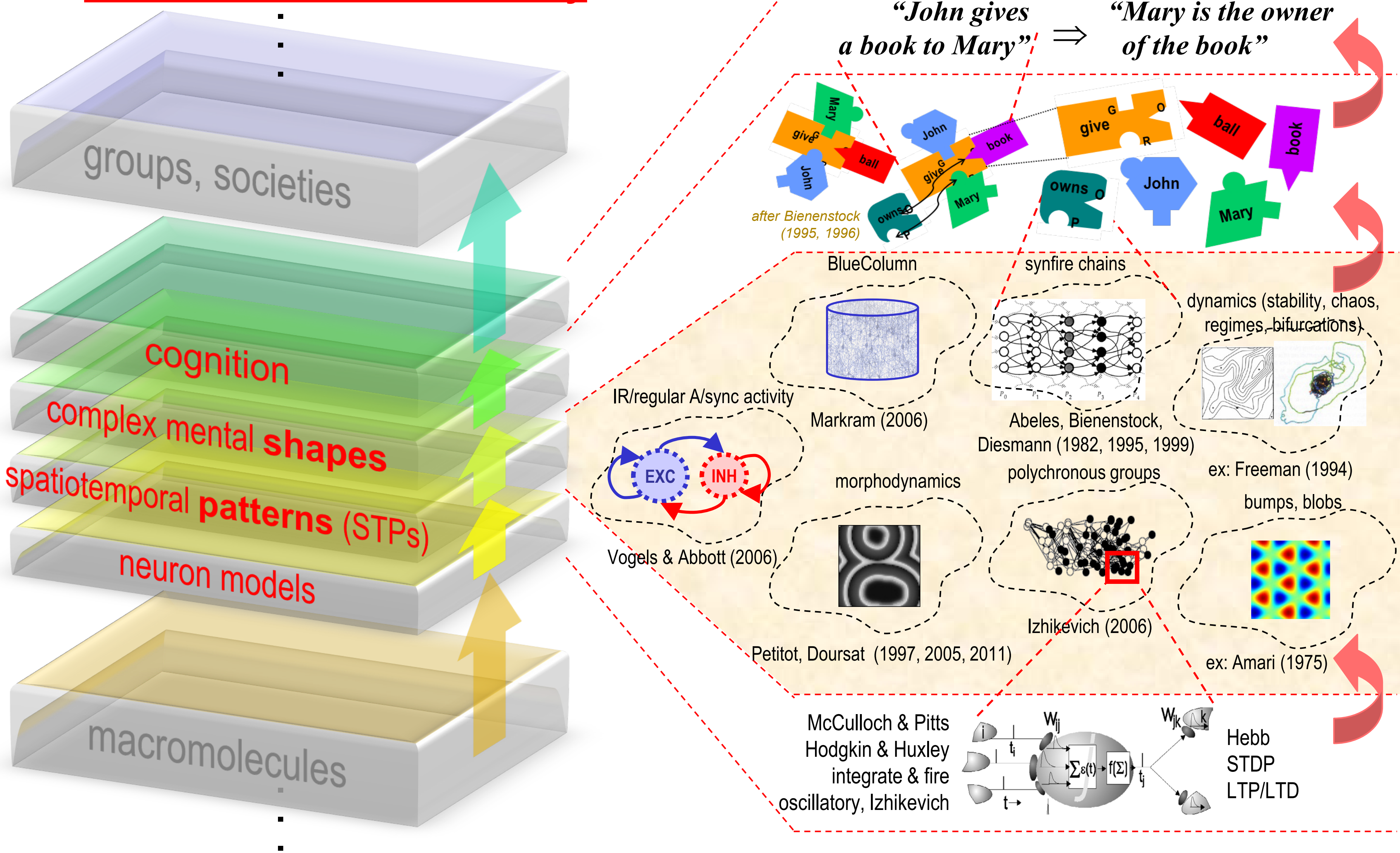


Raster plot of a simulated synfire braid, Doursat et al. 2012

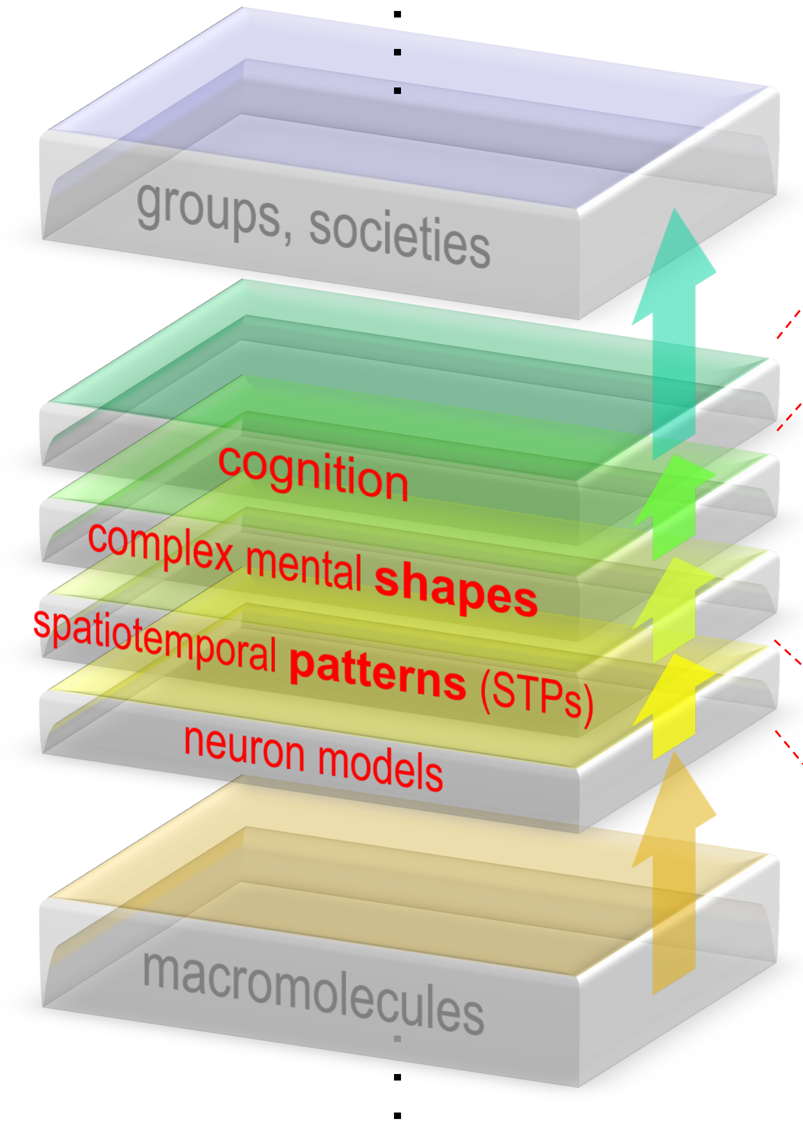


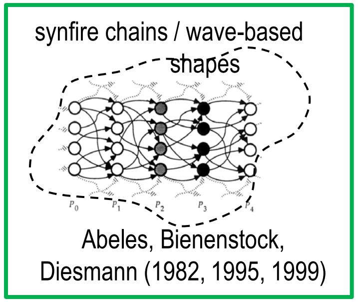
The Tower of Complex Systems

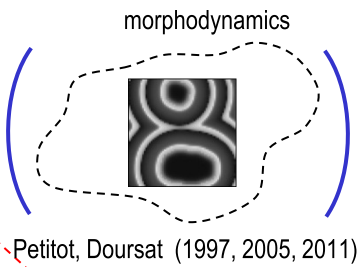
➢ ***Mind function*: from neurons to mind, via <u>self-organizing objects made of correlated activity</u>**



The Tower of Complex Systems

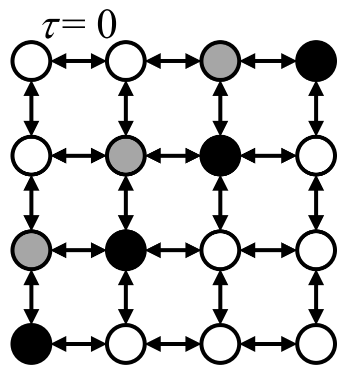




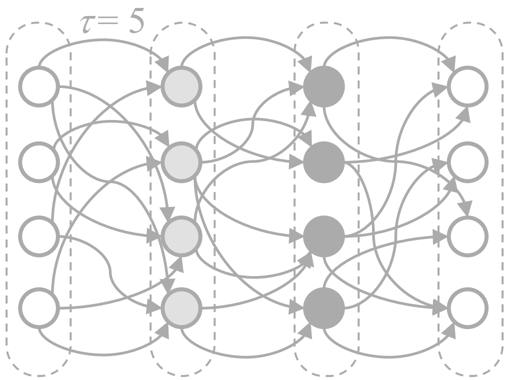


Wave-Based Shape-Matching

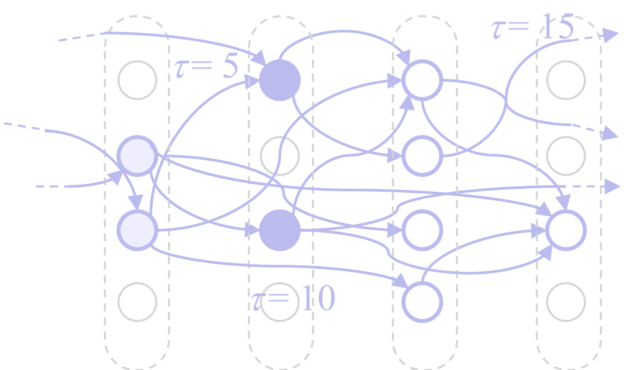
- **Wave-based pattern retrieval and matching**
  - ✓ **Lattices of coupled oscillators** (zero delays)
    - group synchronization
    - traveling waves
    - 2D wave shapes
    - shape metric deformation



  - ✓ **Synfire chains** (uniform delays)
    - wave propagation
    - chain growth
    - pattern storage and retrieval

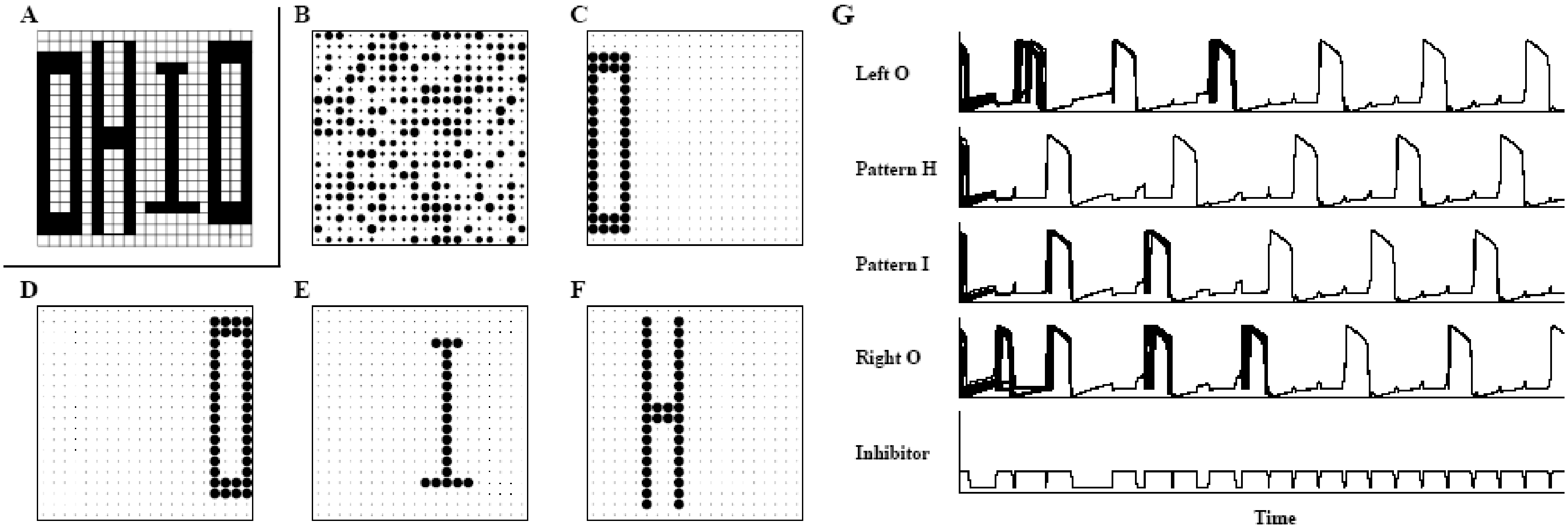


  - ✓ **Synfire braids** (transitive delays)
    - shape storage and retrieval
    - 2D wave-matching



3. Wave-Based Shape-Matching – Lattice

- **Lattice of coupled oscillators** ***– group sync, phase-tagging***
  - ✓ the base of many perceptual segmentation models in the 1990's
    - auditory: von der Malsburg & Schneider (1986), "cocktail party" processor
    - visual, after Gray & Singer (1989): Kurrer & Schulten (1990), König & Schillen (1991), DL Wang & Terman (1995), Campbell & DL Wang (1996), etc.
      - **oscillatory or excitable units** as an abstraction of excit↔inhib columnar activity
      - **2D lattice coupling** as an abstraction of topographically organized visual cortex



(w/ relaxation oscillators similar to FitzHugh-Nagumo/Morris-Lecar + global inhibition)

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

3. Wave-Based Shape-Matching

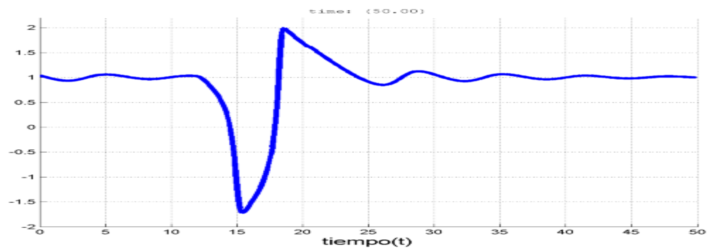
- **Stochastic excitable units**
  - ✓ ex: Bonhoeffer-van der Pol (BvP) oscillator's two main regimes:

$$\left\{ \begin{aligned} \frac{du_i}{dt} &= c\left(u_i - \frac{u_i^3}{3} + v_i + z\right) + \eta \\ \frac{dv_i}{dt} &= \frac{1}{c}(a - u_i - bv_i) + \eta \end{aligned} \right.$$

$z > z_c$ a) sparse, stochastic → ***excitable***

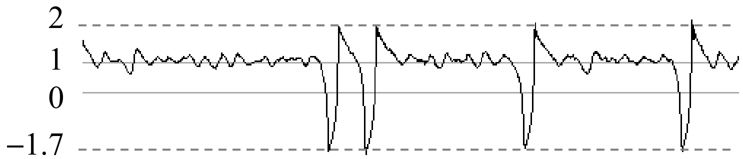
$z_c = -0.3465$

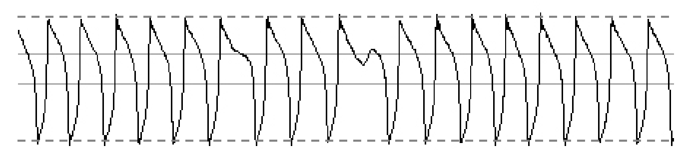
$z < z_c$ b) quasi-periodic → ***oscillatory***



$a = 0.7$
$b = 0.8$
$c = 3$

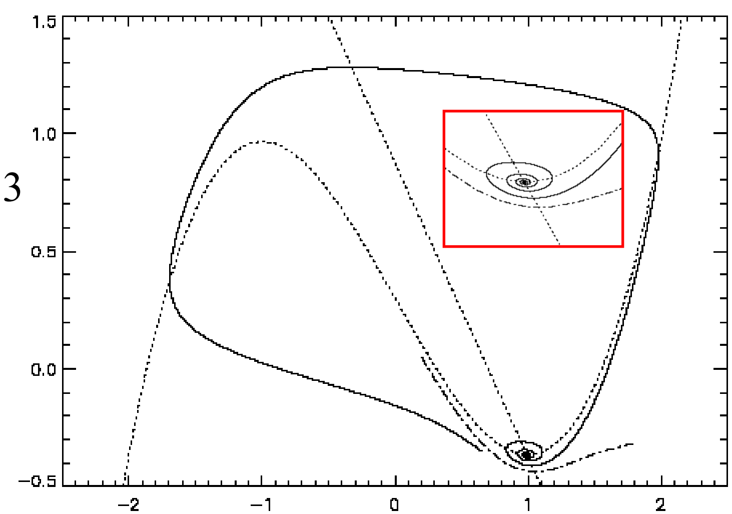
(a)

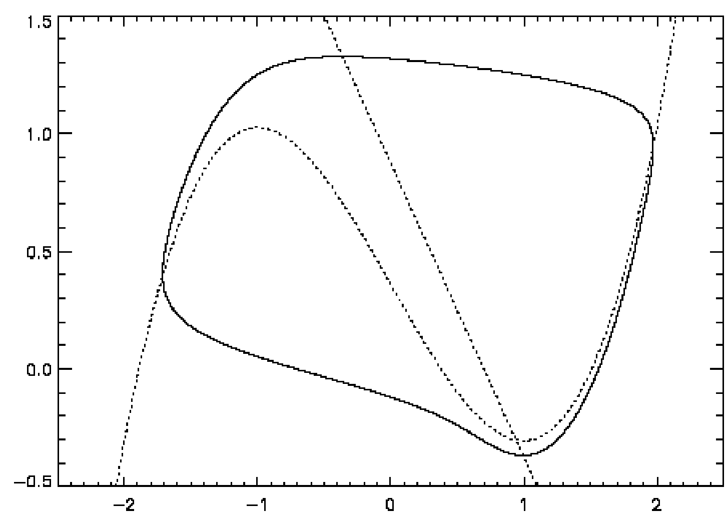




(b)

$z = -0.3$





$z = -0.36$

Wave-Based Shape-Matching – Lattice

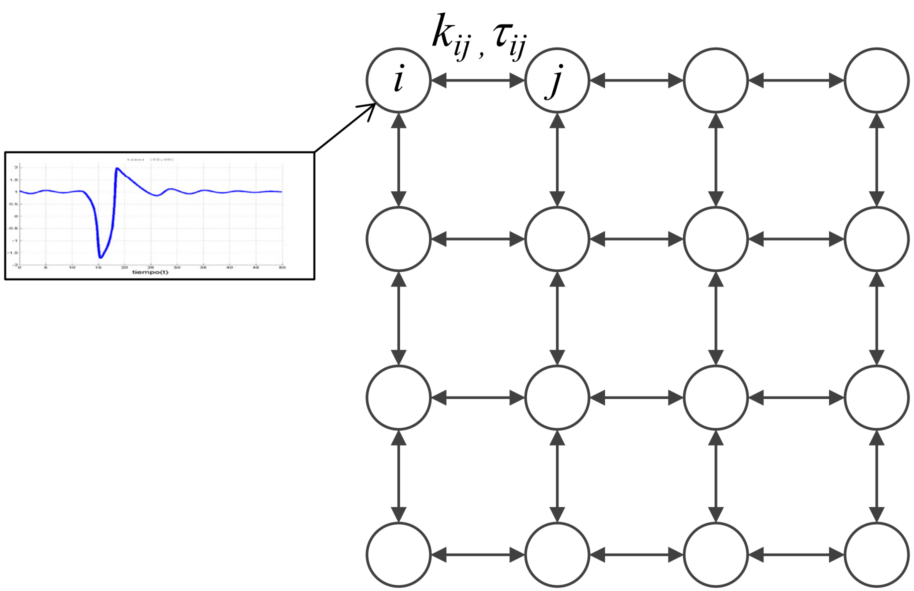
- **Lattice of coupled oscillators**
  - ✓ $i \leftarrow j$ coupling features
    - isotropic
    - proportional to the u signal difference
      - only in spiking domain $u < 0$
    - positive connection weight k_{ij}
    - possible transmission delay τ_{ij}
      - here zero delays $\tau_{ij} = 0$

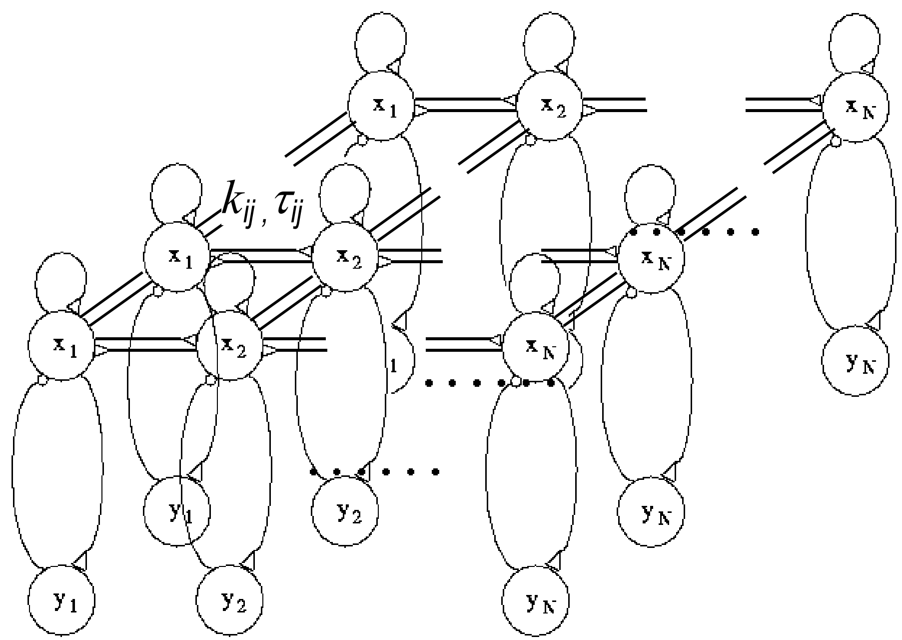
$$\begin{cases} \dfrac{du_i}{dt} = c\left(u_i - \dfrac{u_i^3}{3} + v_i + z\right) + \eta + K_i + I_i \\ \dfrac{dv_i}{dt} = \dfrac{1}{c}(a - u_i - bv_i) + \eta \end{cases}$$

coupling term

input term

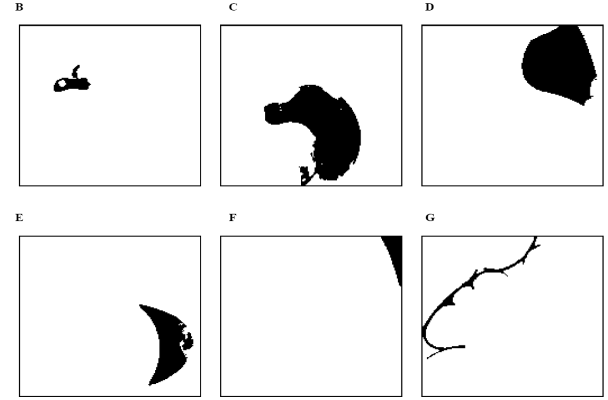
$$\boxed{K_i(t) = \sum_{\substack{j=1 \\ u_j(t-\tau_{ij})<0}}^{N} k_{ij}\Big(u_j(t-\tau_{ij}) - u_i(t)\Big)}$$

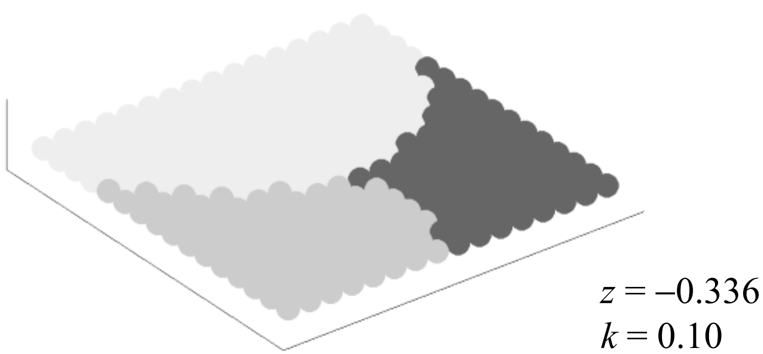




3. Wave-Based Shape-Matching – Lattice

➢ **Lattice of coupled oscillators** – *group sync, phase-tagging*



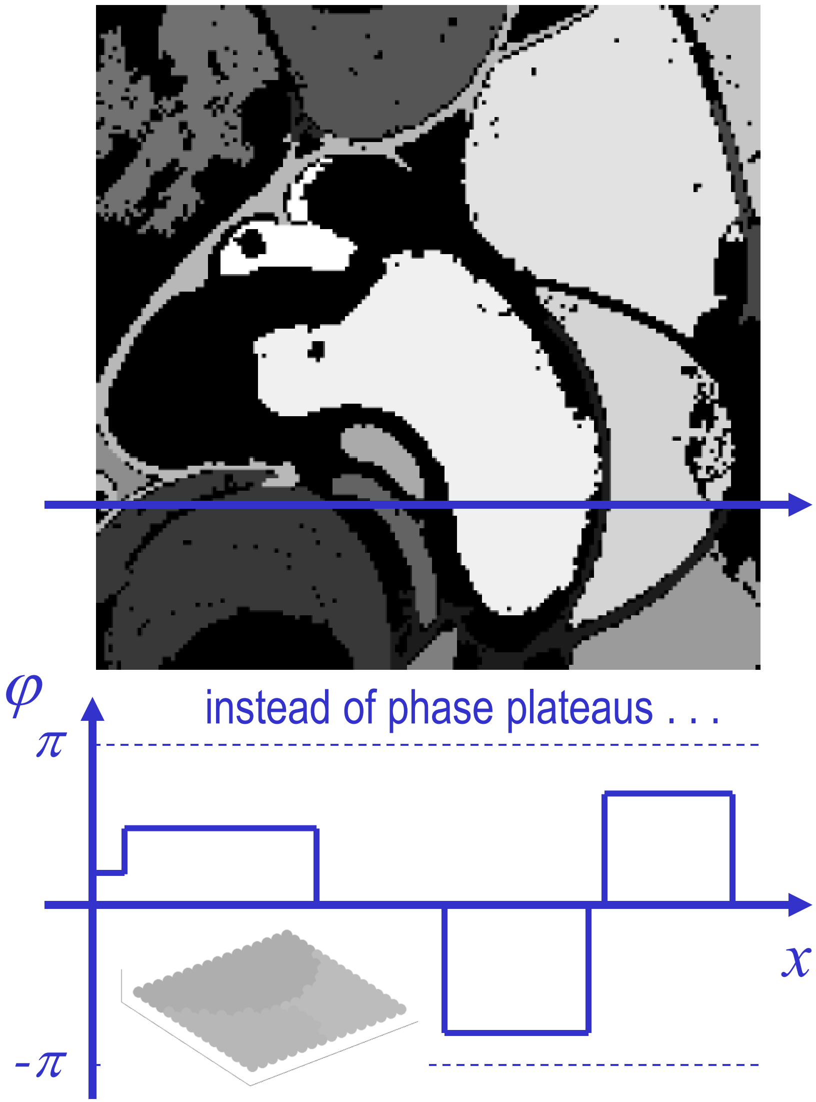


(illustration by Doursat & Sanchez 2012)

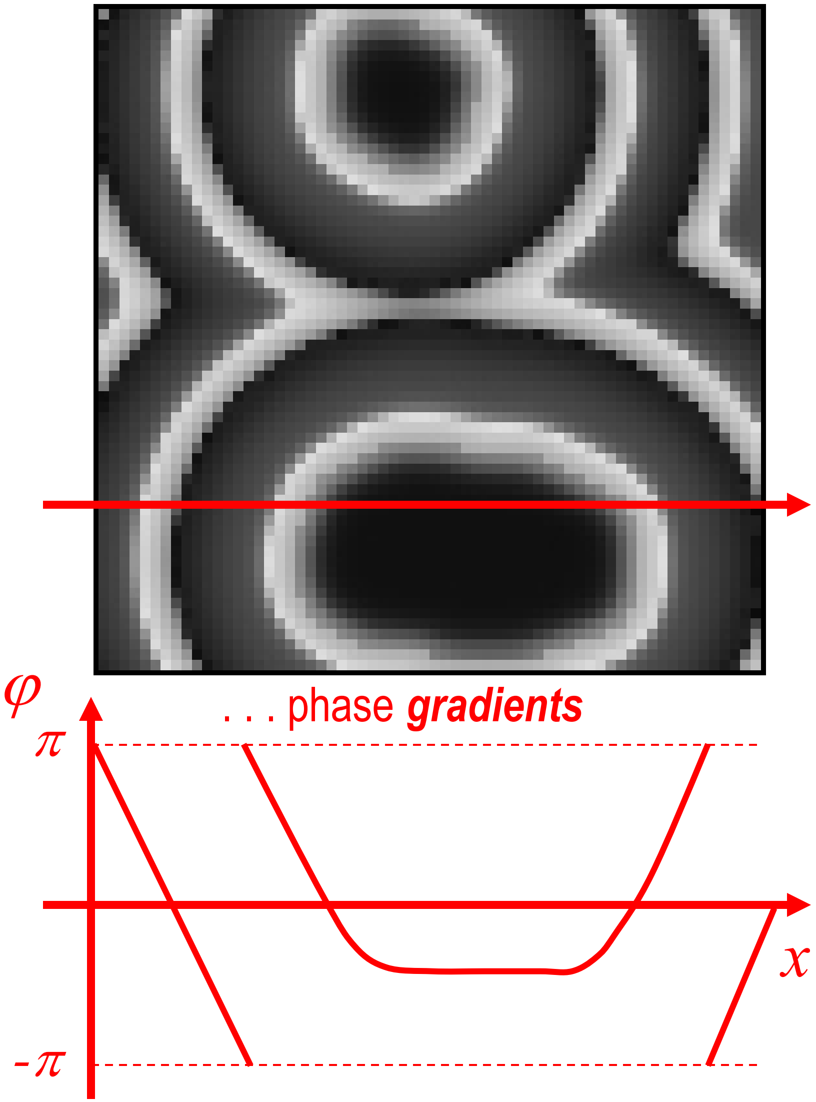
Wang D.L. and Terman D. (1997): Image segmentation based on oscillatory correlation. *Neural Computation*, vol. 9, 805-836

Wave-Based Shape-Matching – Lattice

- Lattice of coupled oscillators – *traveling waves*



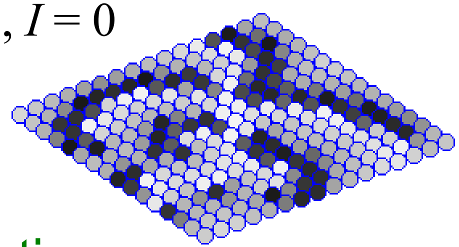
Wang D.L. and Terman D. (1997): Image segmentation based on oscillatory correlation. *Neural Computation*, vol. 9, 805-836



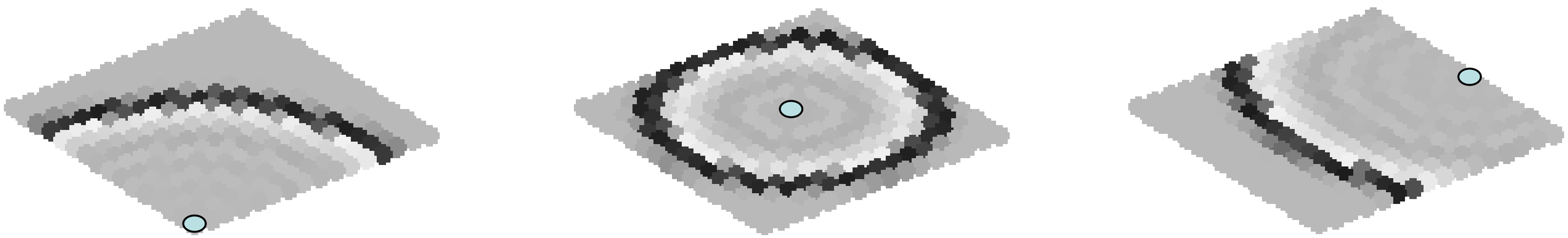
Doursat,, R. & Petitot, J. (2005) Dynamical systems and cognitive linguistics: Toward an active morphodynamical semantics. *Neural Networks* **18**: 628-638.

Wave-Based Shape-Matching – Lattice

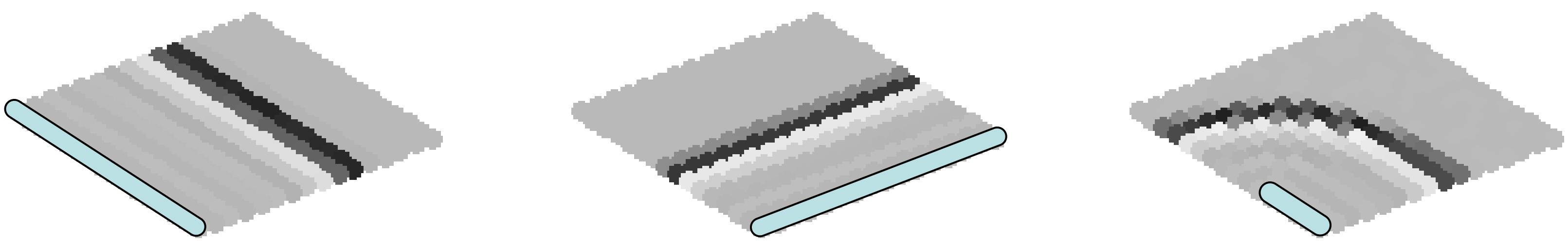
- **Lattice of coupled oscillators** – ***traveling waves***
  - ✓ Random propagation
    - $z = -0.346$, $k = 0.04$, $I = 0$



  - ✓ Circular wave generation
    - $z = -0.29$, $k = 0.10$, $I = -0.44$ (point stimulus)



  - ✓ Planar & mixed wave generation
    - $z = -0.29$, $k = 0.10$, $I = -0.44$ (bar stimulus)



3. Wave-Based Shape-Matching – Lattice

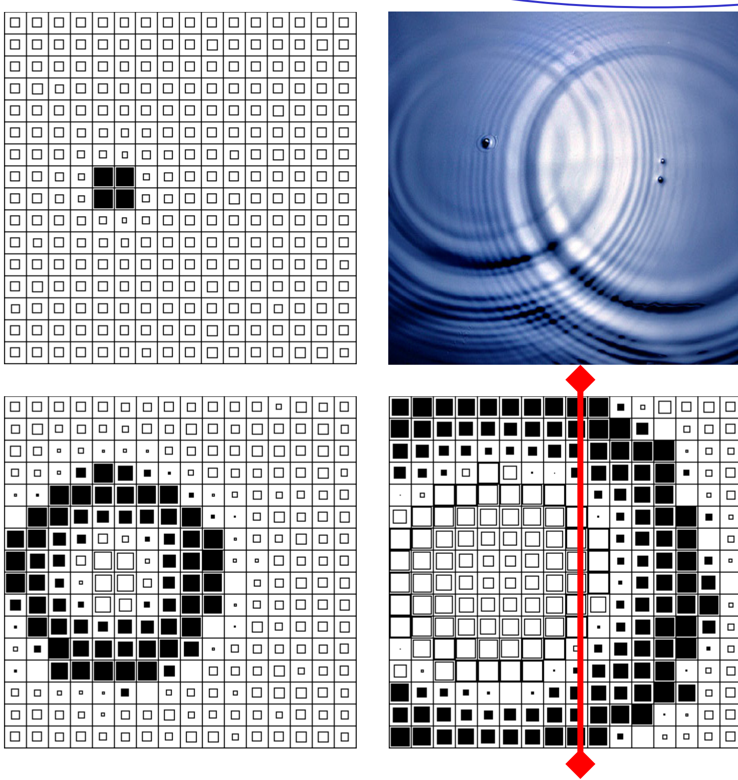
➢ The “morphodynamic pond”: a neural medium at criticality

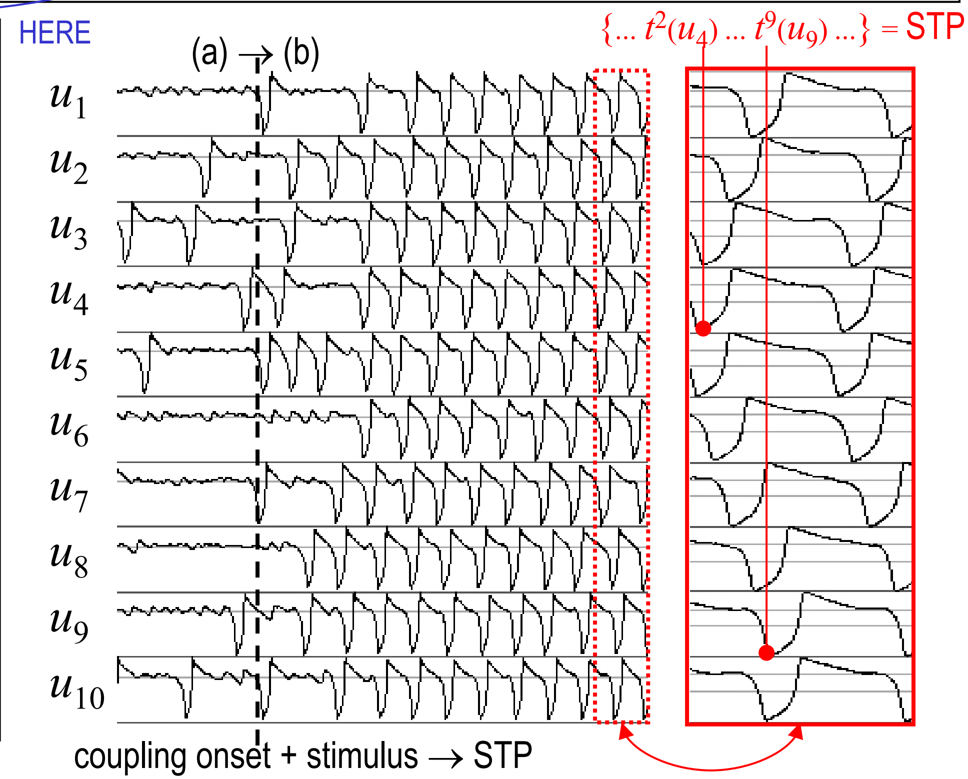
✓ upon coupling onset and/or stimulation → emergence of a wave

- quick transition to ordered regime (STP): reproducible succession of spike events ($t^1, t^2, \ldots$)

✓ the structure of the STP is a trade-off between

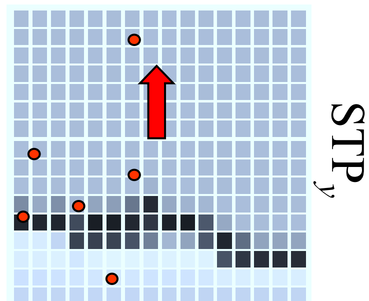
- **endogenous factors:** *connectivity* (structural bias), *attractors* (preferred activation modes)
- **exogenous factors:** *stimulus* (perturbation), *binding* (composition with other STPs)

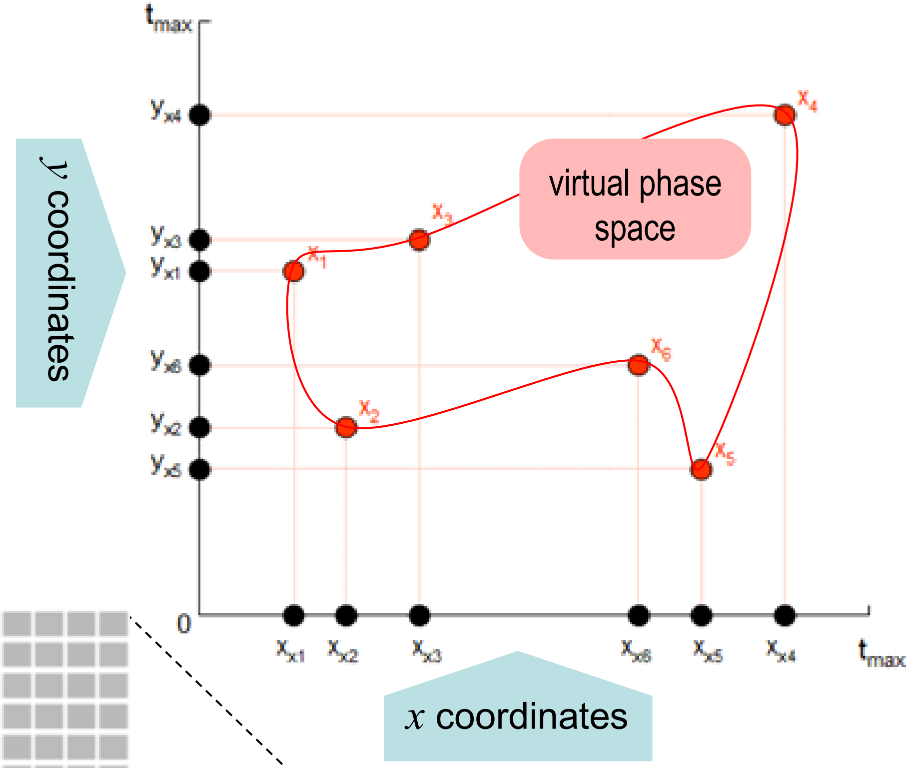




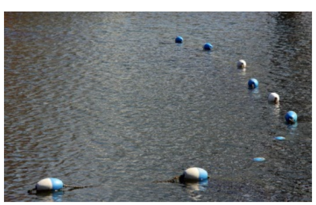
Wave-Based Shape-Matching – Lattice

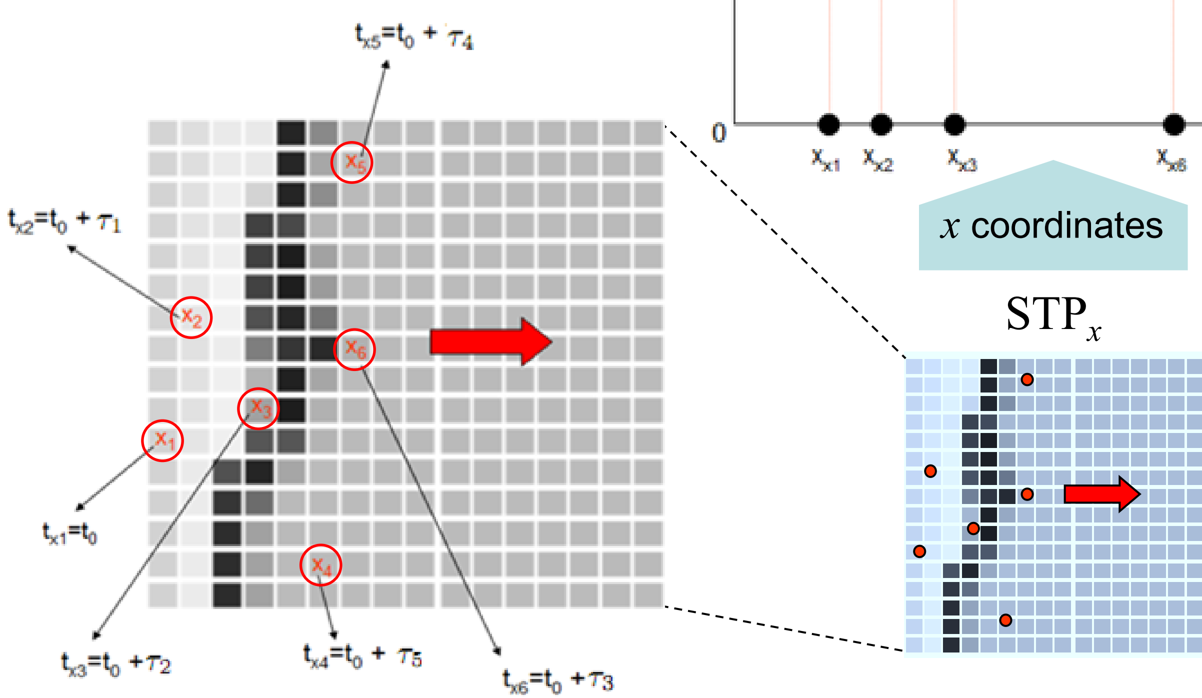
- **Lattice of coupled oscillators** *– 2D wave shapes*
  - ✓ coding coordinates with phases





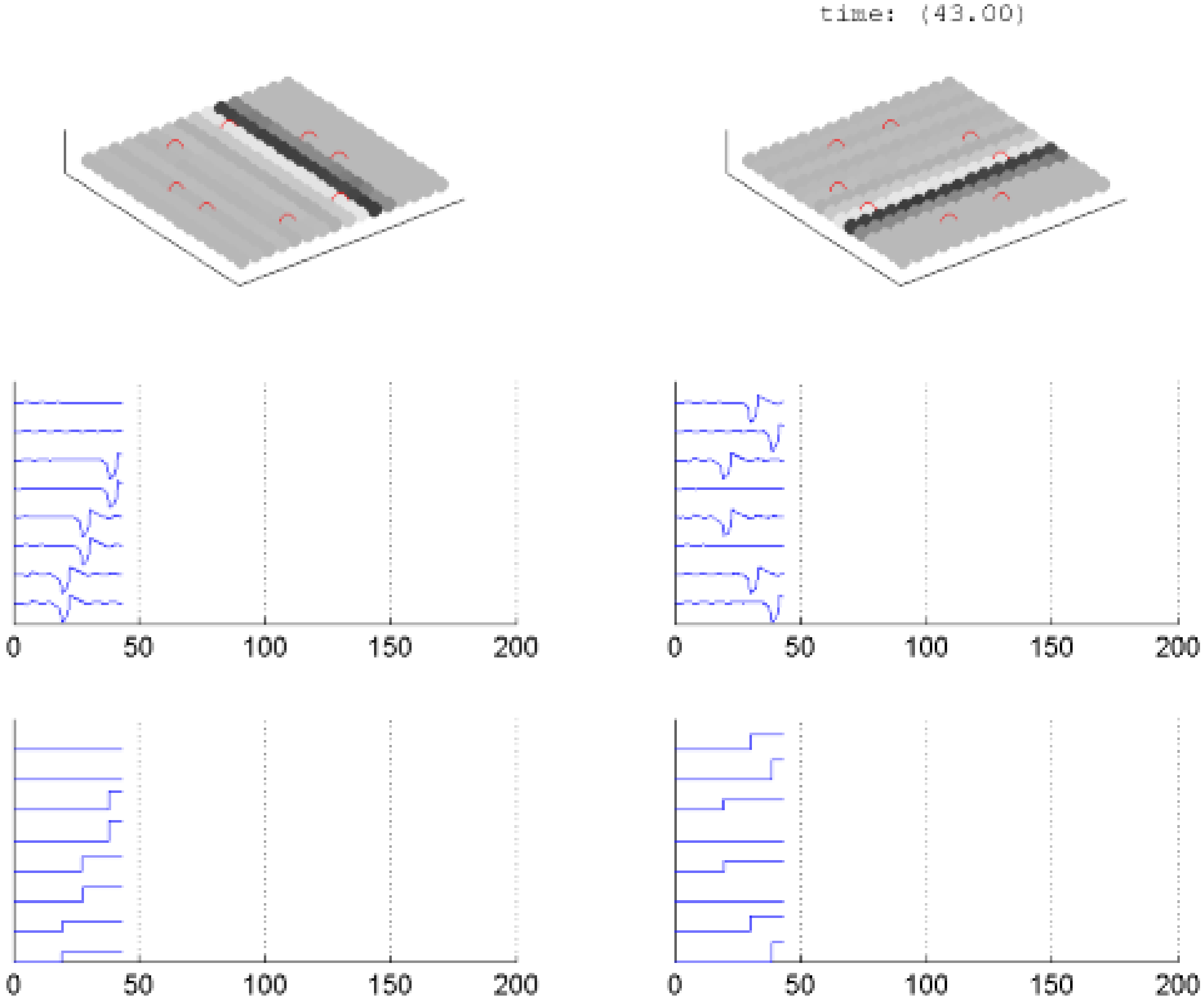
- similar to buoys floating on water





Wave-Based Shape-Matching – Lattice

- **Lattice of coupled oscillators** *– 2D wave shapes*
  - ✓ coding coordinates with phases

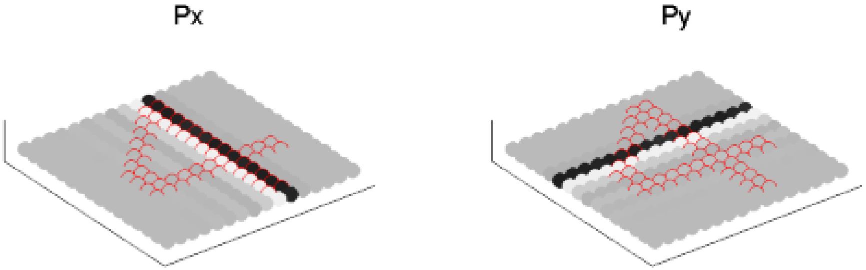


- similar to buoys floating on water

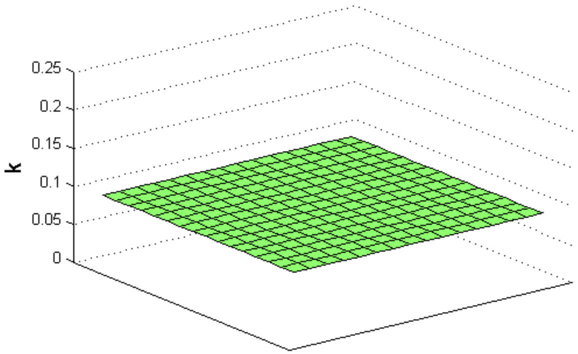
Wave-Based Shape-Matching – Lattice

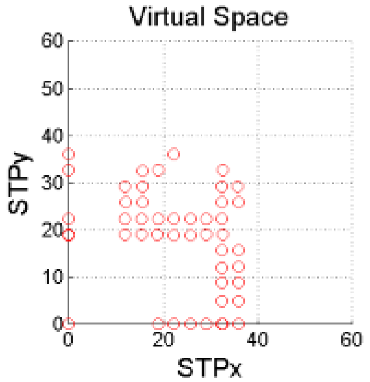
- **Lattice of coupled oscillators** *– 2D wave shapes*
  - ✓ the final shape in virtual phase space depends on
    - the physical position of the feature units on the lattice
    - the form and direction of the two waves, itself depending on:
      - endogenous factors: connectivity and weight distribution
      - exogenous factors: stimulus domains
  - ✓ ex: no deformation
    - planar & orthogonal waves
      - uniform weights on P_X and P_Y
      - orthogonal full-bar stimuli

    $\rightarrow$ *shape* $=$ *physical positions*

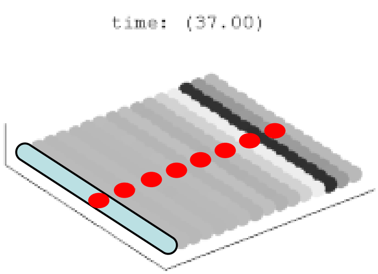


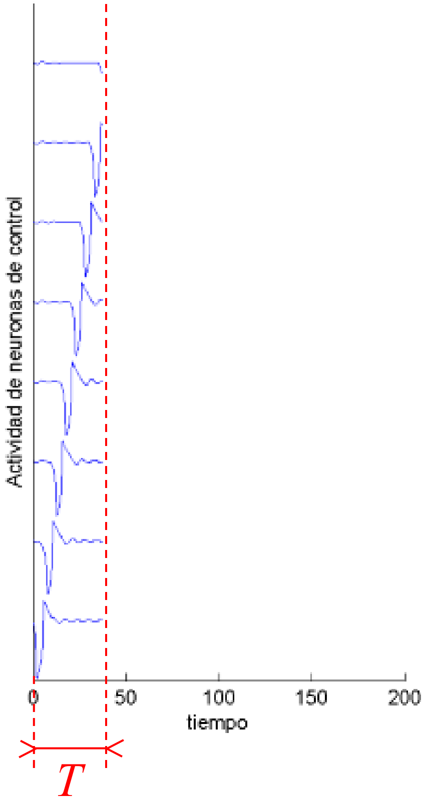
uniform weight distribution: $k = 0.09$

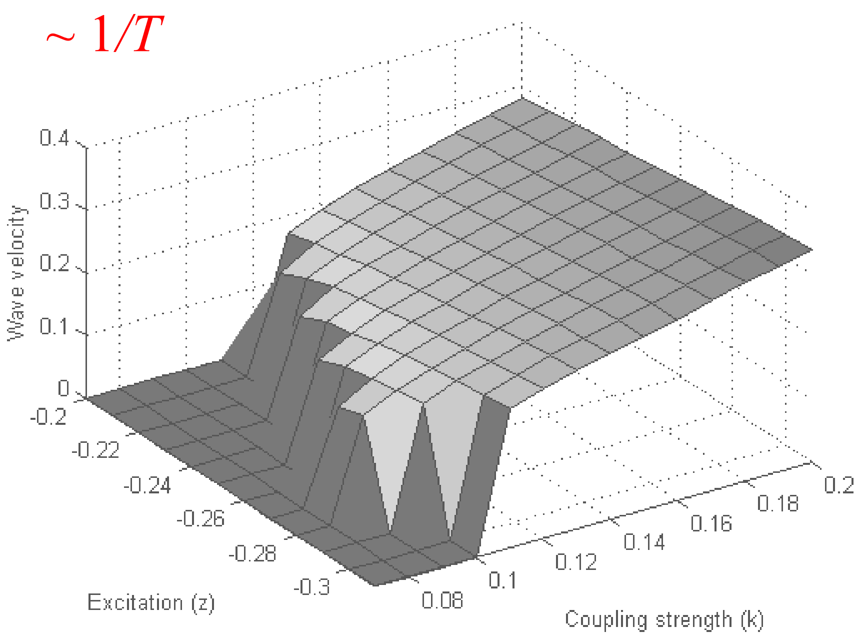




- **Lattice of coupled oscillators** – *shape metric deformation*
  - ✓ wave detection and velocity measure based on control units
    - the probability of wave generation increases with $z \searrow$ and $k \nearrow$
    - the velocity of the generated wave increases with $z \searrow$ and $k \nearrow$

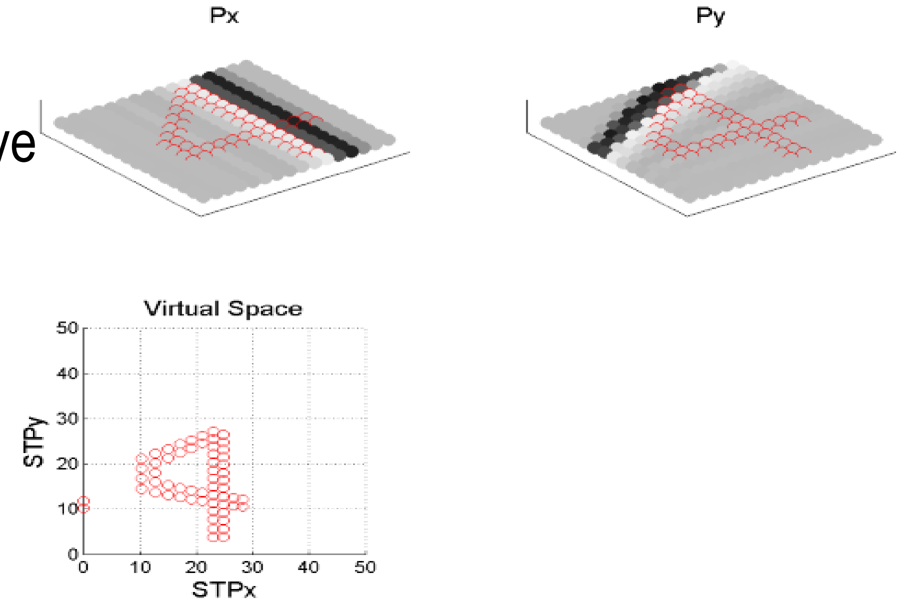




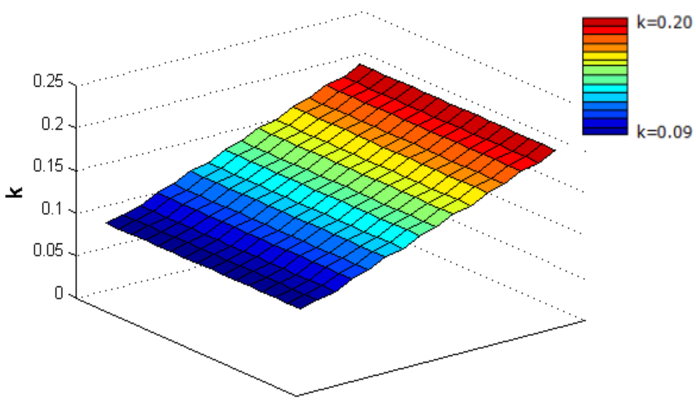


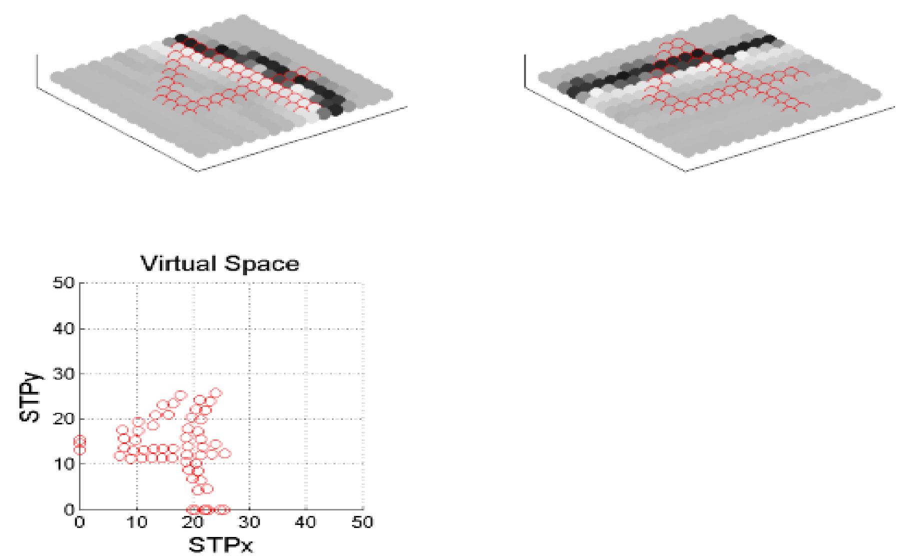
Wave-Based Shape-Matching – Lattice

- **Lattice of coupled oscillators** *– shape metric deformation*
  - ✓ ex: “shear stress” deformation
    - ▪ vertical wave + horizontal wave
      - ○ Y-gradient of weights on P_Y
      - ○ orthogonal full-bar stimuli



gradient weight landscape:
$k \in [0.09, 0.20]$

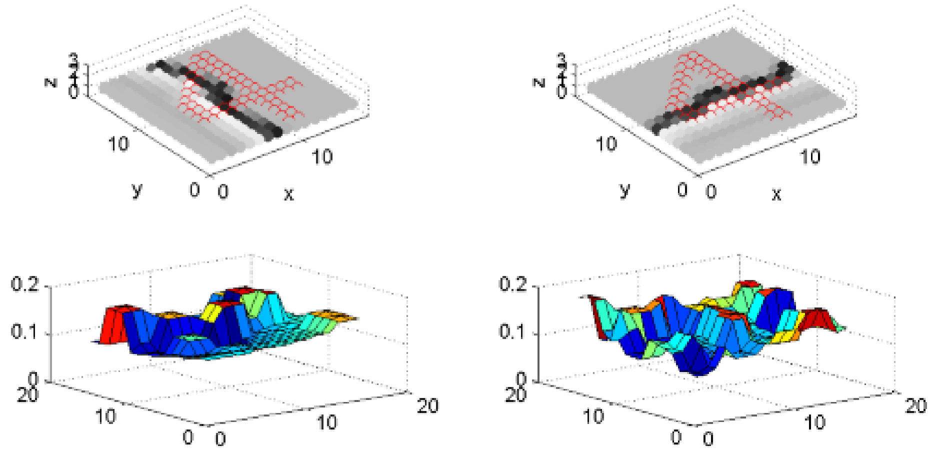


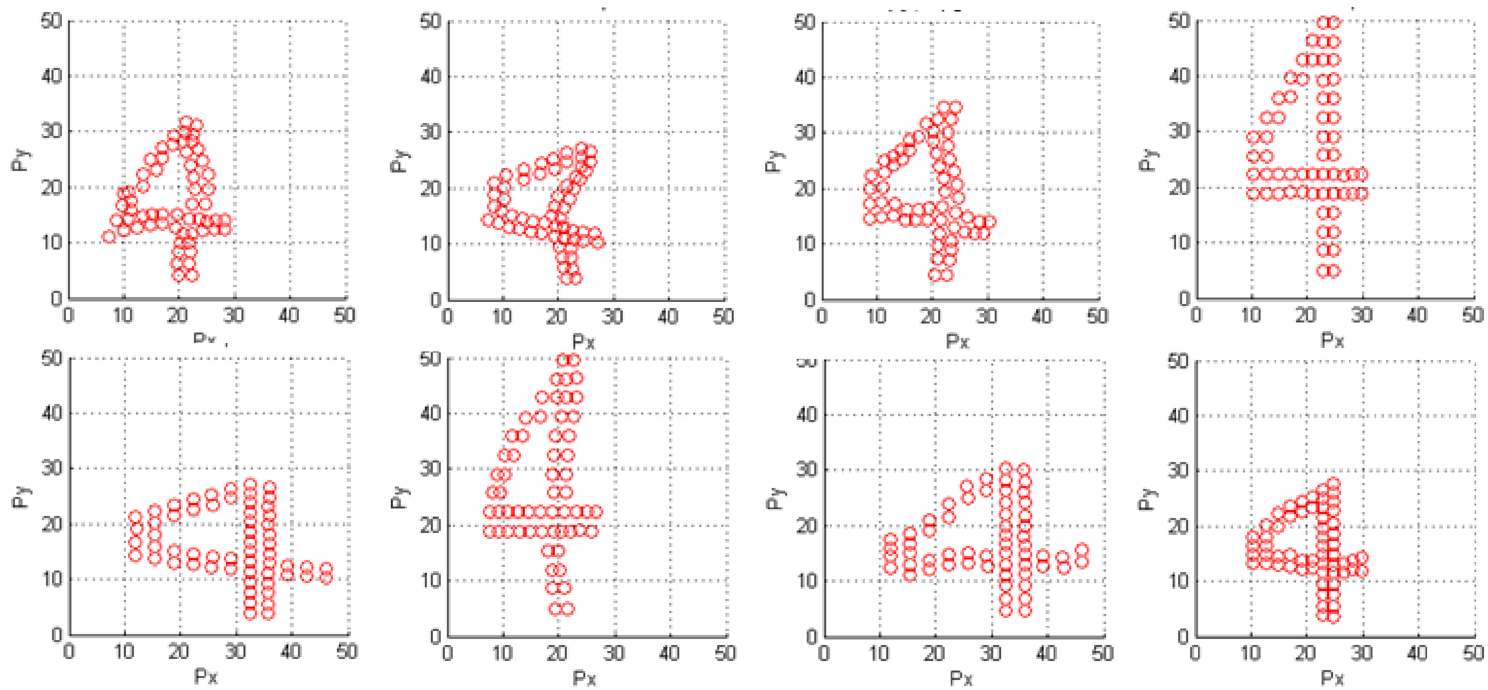


  - ✓ ex: “laminar flow” deformation
    - ▪ laminar wave + vertical wave
      - ○ Y-gradient of weights on P_X
      - ○ orthogonal full-bar stimuli

Wave-Based Shape-Matching – Lattice

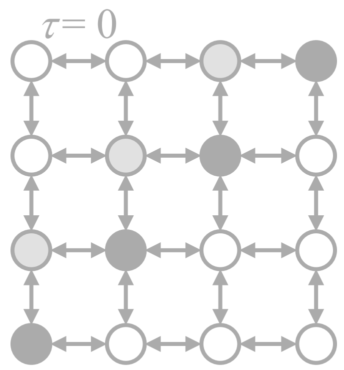
- **Lattice of coupled oscillators** *– shape metric deformation*
  - ✓ ex: irregular deformation
    - heterogeneous waves
      - random weight distribution (bumps & dips) on P_X and P_Y
      - orthogonal full-bar stimuli
  - ✓ various weight combinations

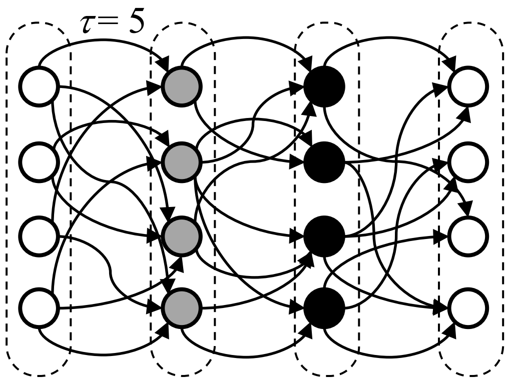


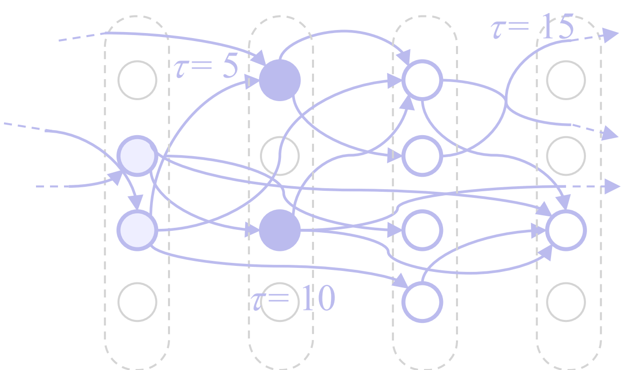


Wave-Based Shape-Matching

- **Wave-based pattern retrieval and matching**
  - ✓ **Lattices of coupled oscillators** (zero delays)
    - group synchronization
    - traveling waves
    - 2D wave shapes
    - shape metric deformation
  - ✓ **Synfire chains** (uniform delays)
    - wave propagation
    - chain growth
    - pattern storage and retrieval
  - ✓ **Synfire braids** (transitive delays)
    - shape storage and retrieval
    - 2D wave-matching



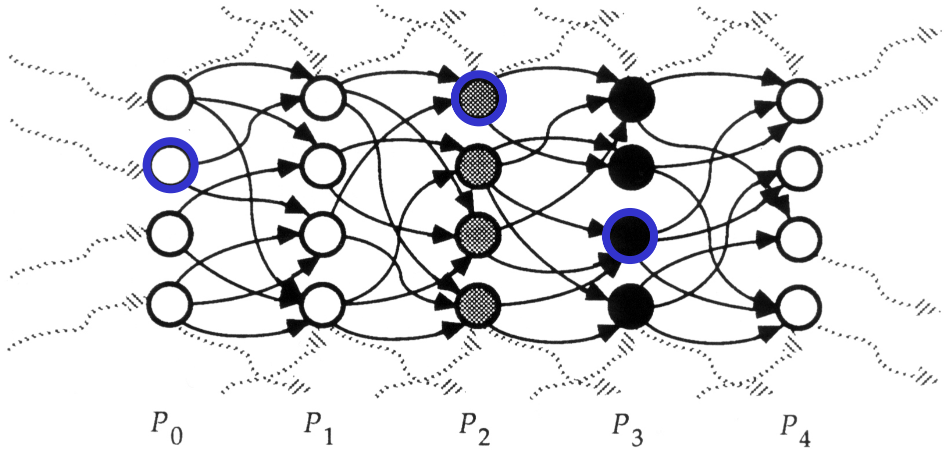


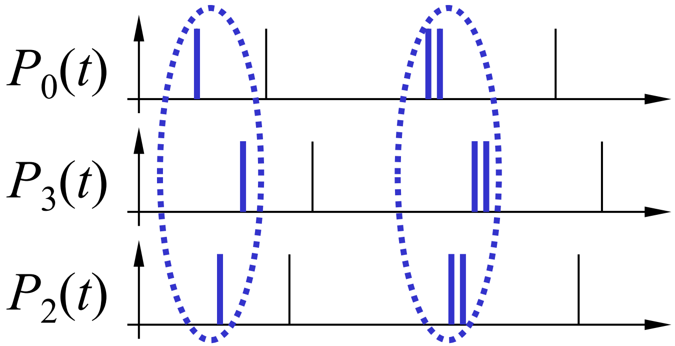


3. Wave-Based Shape-Matching – Chains

➢ Synfire chains – *definition*

- ✓ a synfire chain (Abeles 1982) is a sequence of synchronous neuron groups $P_0 \rightarrow P_1 \rightarrow P_2$ ... linked by feedfoward connections that can support the propagation of waves of activity (action potentials)

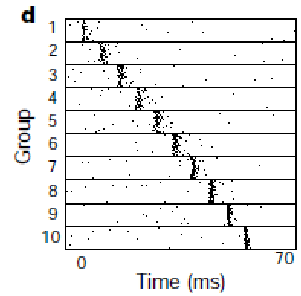




- ✓ synfire chains have been hypothesized to explain neurophysiological recordings containing statistically significant delayed correlations
- ✓ the redundant divergent/convergent connectivity of synfire chains can preserve accurately synchronized action potentials, even under noise

Wave-Based Shape-Matching – Chains

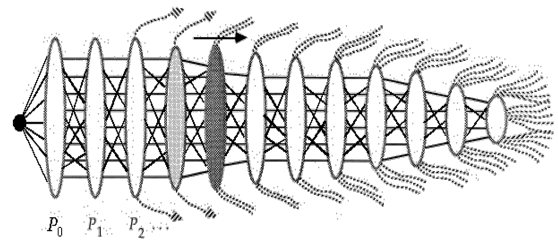
➢ Synfire chains – *typical example studies*



✓ 1-chain propagation viability

mental shape **stability**

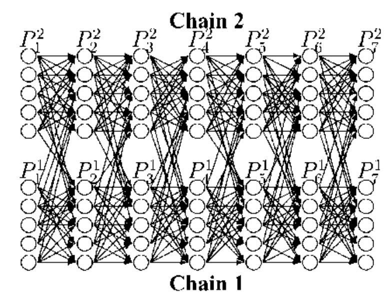
- Diesmann, Gewaltig & Aertsen (1999) *Stable propagation of synchronous spiking in cortical neural networks*



✓ 1-chain self-organized growth

mental shape **learning**

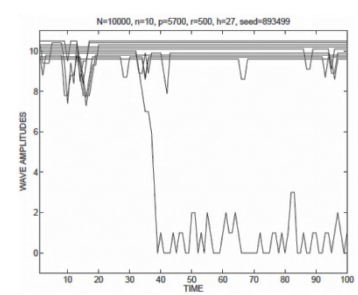
- Doursat & Bienenstock (1991, 2006) *Neocortical self-structuration as a basis for learning*



✓ 2-chain binding

mental shape **composition**

- Abeles, Hayon & Lehmann (2004) *Modeling Compositionality by Dynamic Binding of Synfire Chains*



✓ N-chain storage capacity

mental shape **memory**

- Bienenstock (1995) *A model of neocortex*
- Trengove (2007) *Storage capacity of a superposition of synfire chains using conductance-based I&F neurons*

synfire chains potential fill all the requirements for a mesoscopic world of mental shapes

Wave-Based Shape-Matching – Chains

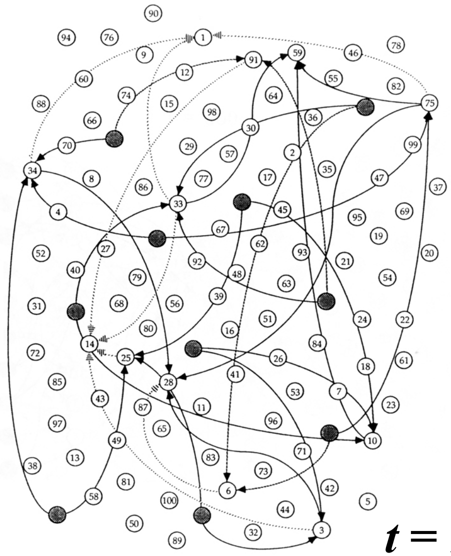
➢ **Synfire chains** – *self-organized growth*

1. Hebbian rule

$$\Delta W_{ij} \sim x_i x_j$$

$$\sum \Delta W_{ij} \sim 0$$

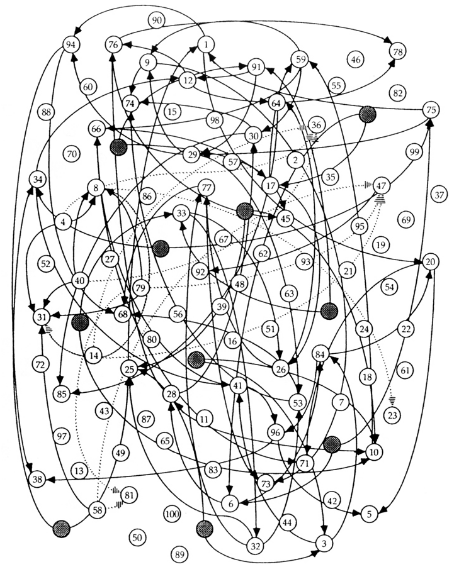
2. sum rule



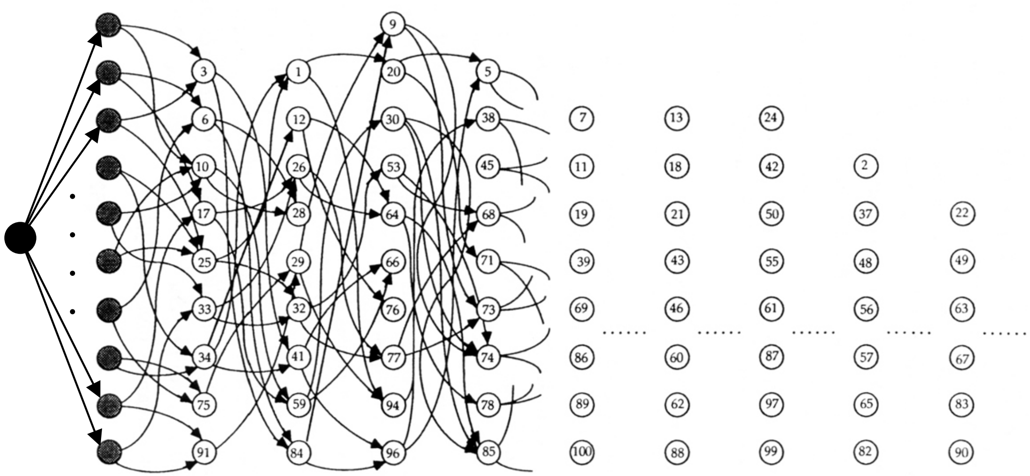
$t = 200$

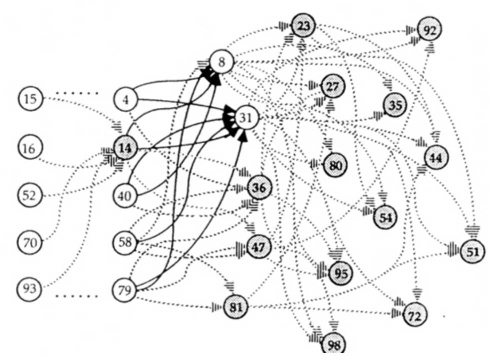
network **structuration** by accretive synfire growth

$t = 4000$



spatially rearranged view



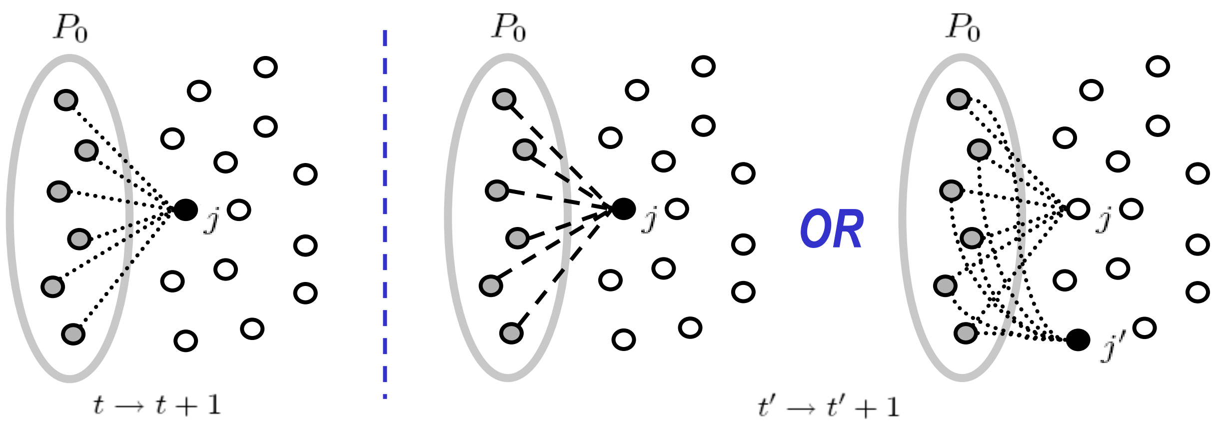


Doursat, R. (1991), Doursat & Bienenstock, E. (2006) Neocortical self-structuration as a basis for learning. *5th International Conference on Development and Learning (ICDL 2006)*, May 31-June 3, 2006, Indiana University, Bloomington, IN. IU, ISBN 0-9786456-0-X.

3. Wave-Based Shape-Matching – Chains

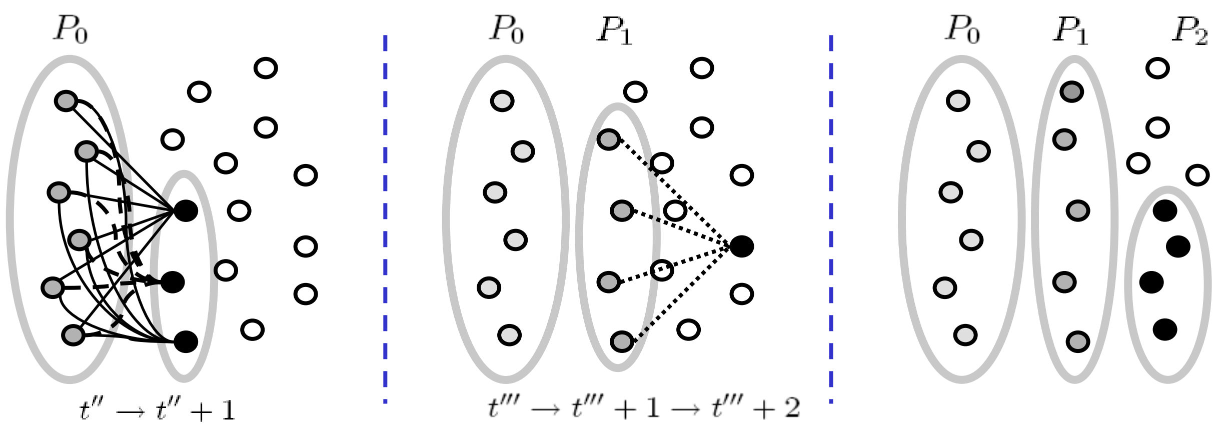
- **Synfire chains** – ***self-organized growth***
  - ✓ a special group of n_0 synchronous cells, P_0, is repeatedly (not necessarily periodically) activated and recruits neurons "downstream"

if j fires once after P_0, its weights increase and give it a 12% chance of doing so again (vs. 1.8% for the others)

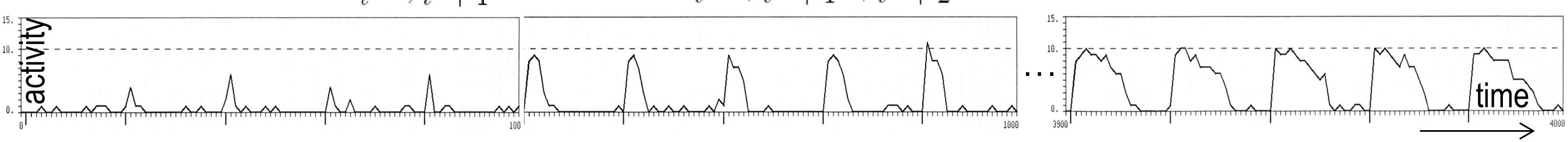


if j fires a 2[nd] time after P_0, j has now 50% chance of doing so a 3[rd] time; else it stays at 12% while another cell, j' reaches 12%

the number of post-P_0 cells (cells with larger weights from P_0) increases and forms the next group P_1



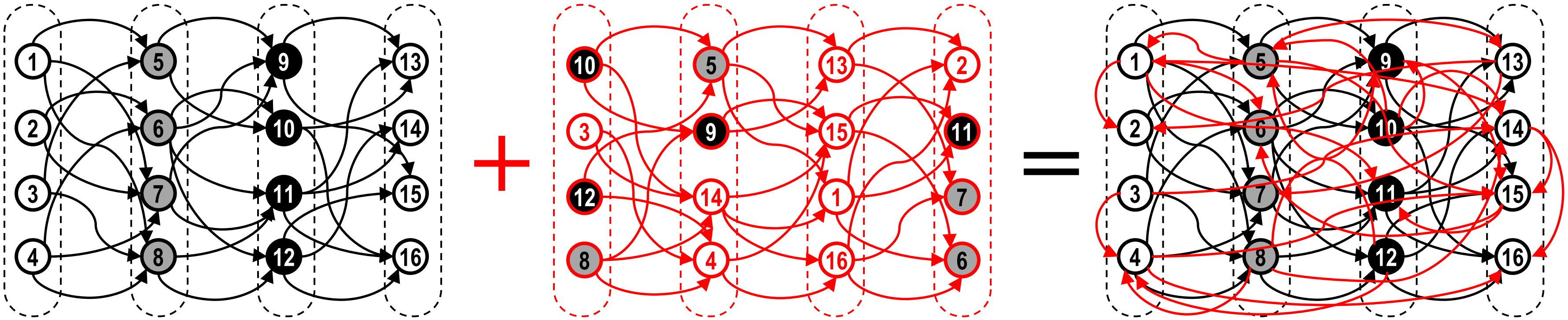
once it reaches a critical mass, P_1 also starts recruiting and forming a new group P_2, etc.



Wave-Based Shape-Matching – Chains

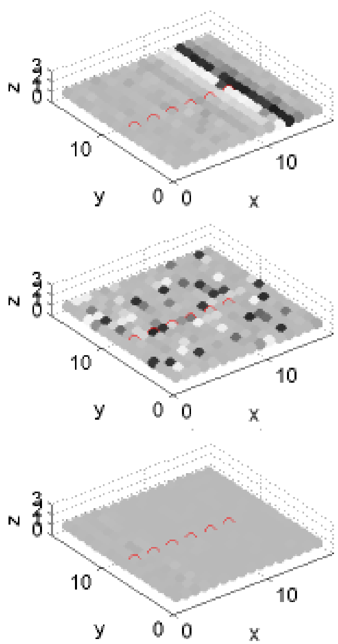
➢ Synfire chains – *pattern mix and selective retrieval*

✓ random renumbering and uniform rewiring (column→column probability p)



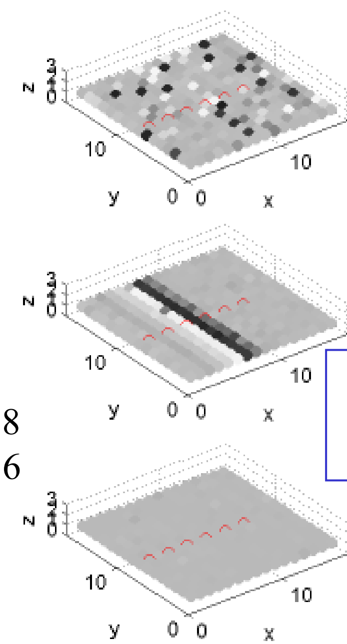
layout A w/ weights A | layout B w/ weights B | layout A w/ mixed weights A + weights B

layout A
$N_A = 13$



mixed weights

$p = 0.5$
$z = -0.28$
$k = 0.016$



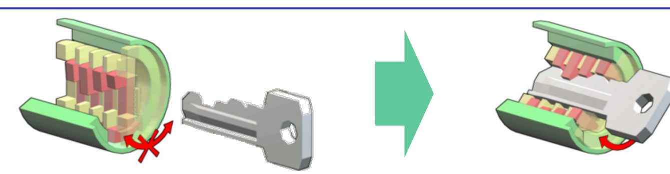
layout B
$N_B = 13$

layout A
$N_A = 8$
→ no wave

✓ high specificity of synfire stimulus

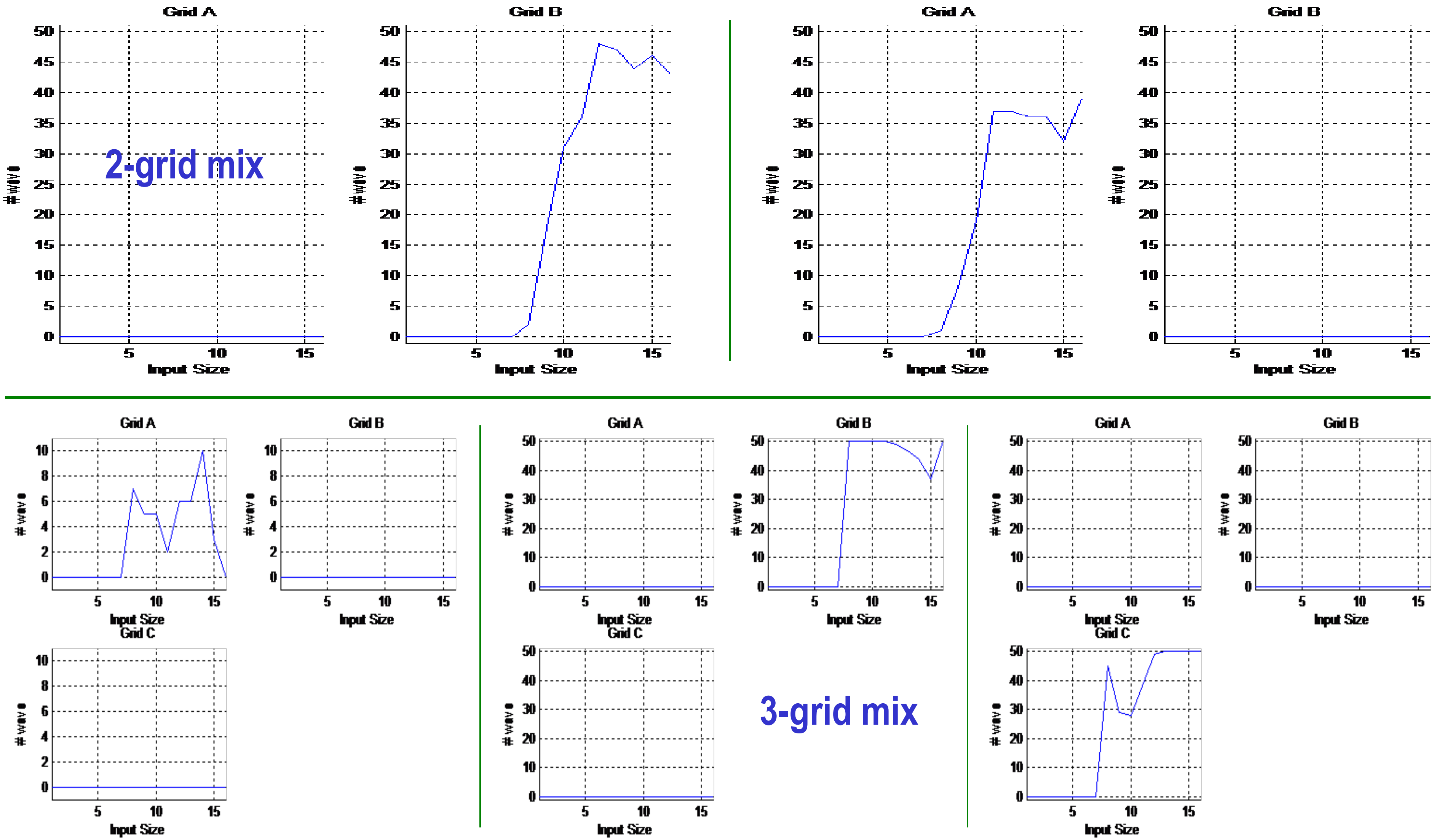
- unlike the "sensitive" isotropic lattice, not any input pattern will trigger a wave
- a synfire chain needs a "critical seed" of N stimulated neurons at the right place

- **endo:** *connectivity*, *attractors* HERE
- **exo:** *stimulus*, *binding*



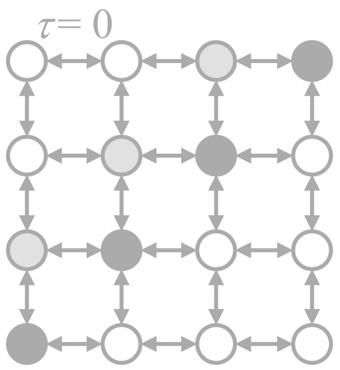
Wave-Based Shape-Matching – Chains

- **Synfire chains** – *pattern mix and selective retrieval*
  - ✓ statistics of selective retrieval depending on input size (in first pool)

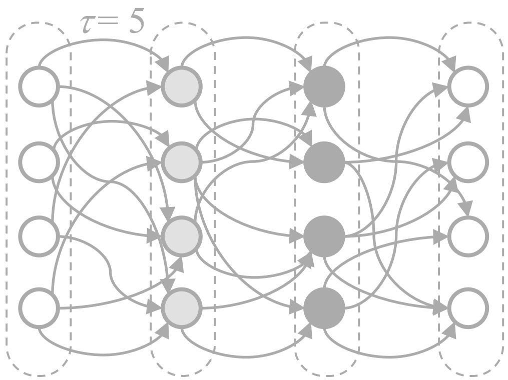


Wave-Based Shape-Matching

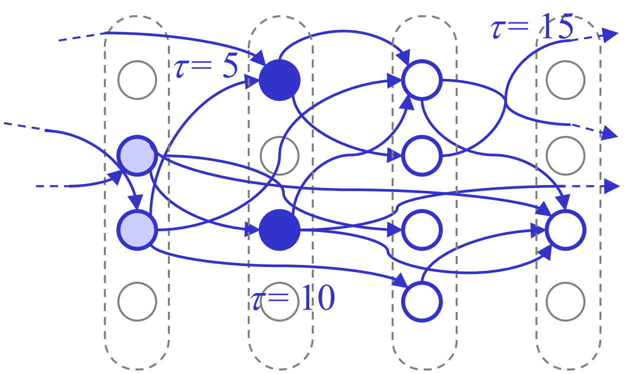
- **Wave-based pattern retrieval and matching**
  - ✓ **Lattices of coupled oscillators** (zero delays)
    - group synchronization
    - traveling waves
    - 2D wave shapes
    - shape metric deformation



  - ✓ **Synfire chains** (uniform delays)
    - wave propagation
    - chain growth
    - pattern storage and retrieval



  - ✓ **Synfire braids** (transitive delays)
    - shape storage and retrieval
    - 2D wave-matching

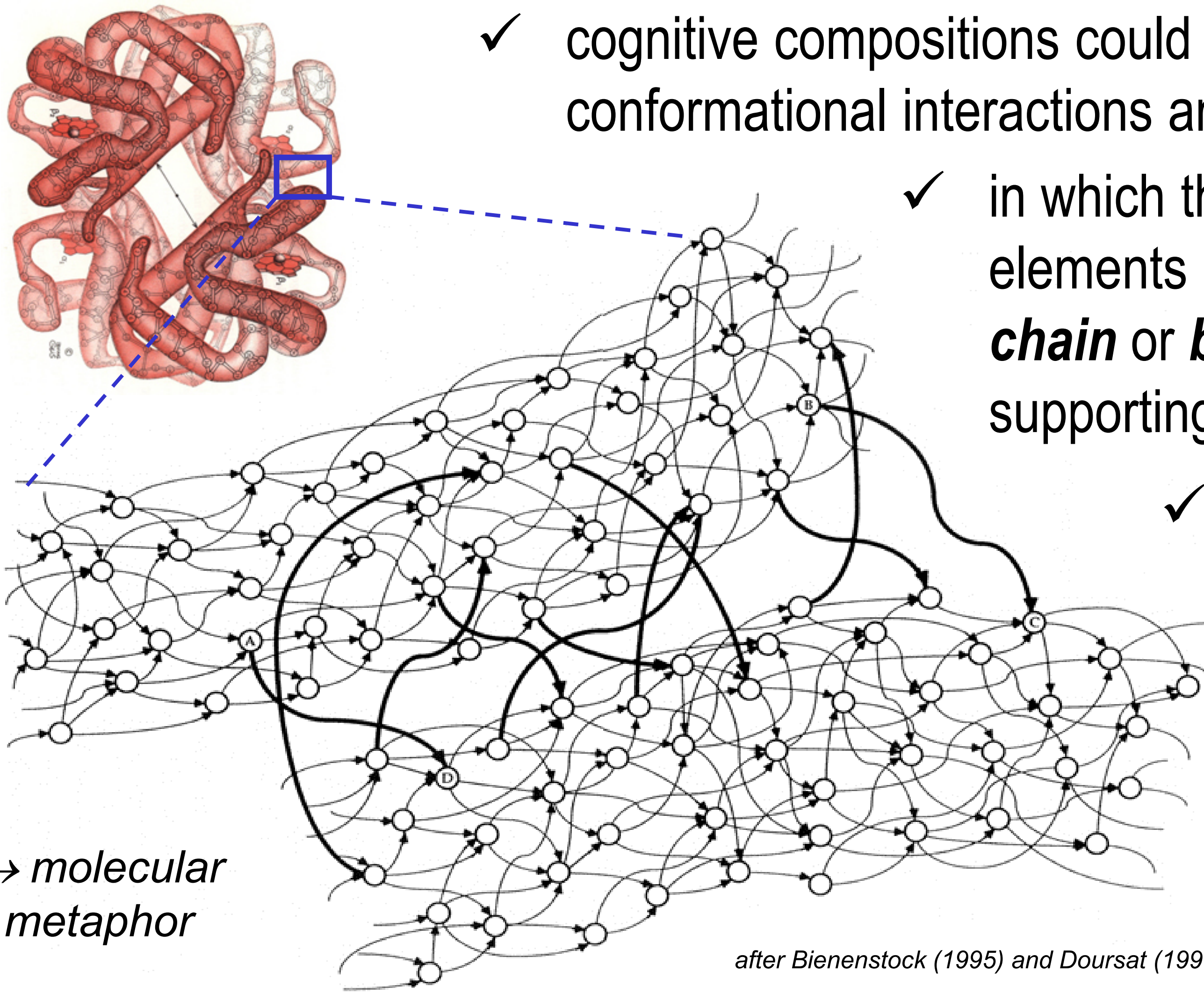


Wave-Based Compositionality – Braids

➢ Ex: synfire patterns can *bind*, i.e. support compositionality

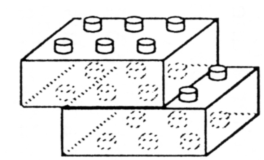
- ✓ cognitive compositions could be analogous to conformational interactions among proteins...
  - ✓ in which the basic “peptidic” elements could be ***synfire chain*** or ***braid*** structures supporting traveling waves
    - ✓ two synfires can bind by synchronization through ***coupling links***

hemoglobin



after Bienenstock (1995) and Doursat (1991)

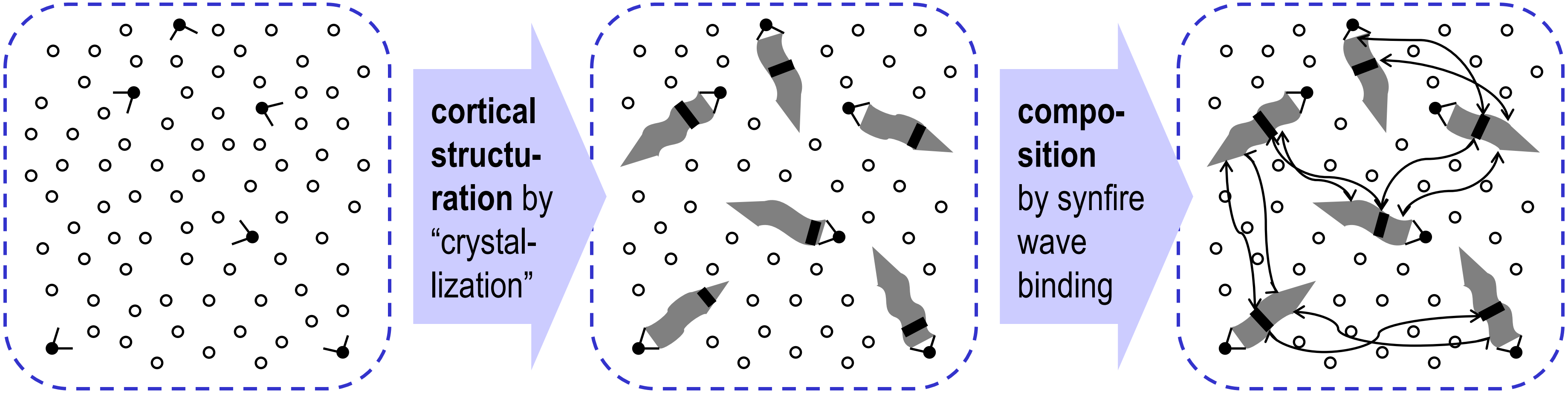
→ *molecular metaphor*



Wave-Based Compositionality – Braids

➢ Sync & coalescence in a "self-woven tapestry" of chains

- ✓ multiple chains can "crystallize" from intrinsic "inhomogeneities" in the form of "seed" groups of synchronized neurons



see Bienenstock (1995), Abeles, Hayon & Lehmann (2004), Trengrove (2005)

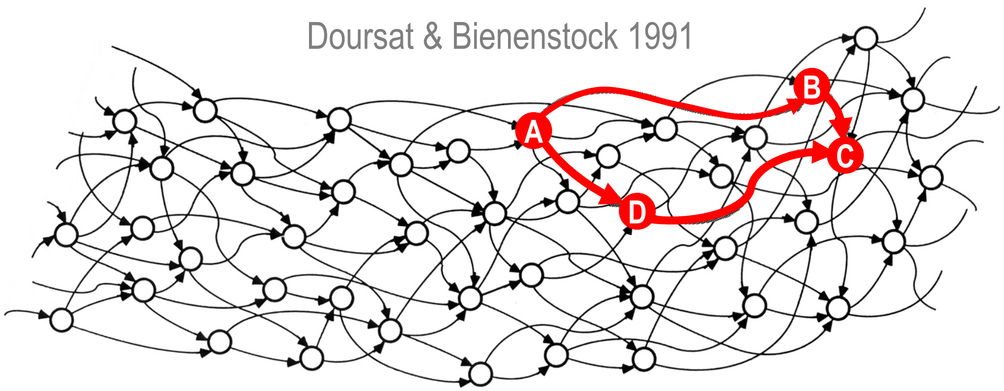
- ✓ concurrent chain development defines a ***mesoscopic scale of neural organization***, at a finer granularity than macroscopic AI symbols but higher complexity than microscopic neural potentials
- ✓ on this substrate, the dynamical binding & coalescence of multiple synfire waves provides the basis for compositionality and learning

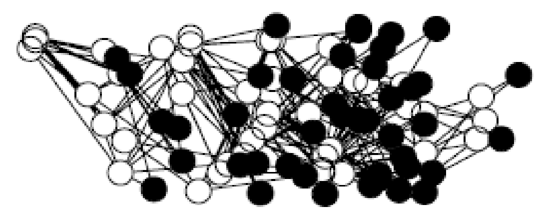
Wave-Based Shape-Matching – Braids

➢ Synfire braids – *definition*

- ✓ synfire braids (Bienenstock 1991, 1995) are generalized STPs with longer delays among nonconsecutive neurons, without distinct synchronous groups
- ✓ they were rediscovered later as "polychronous groups" (Izhikevich 2006)

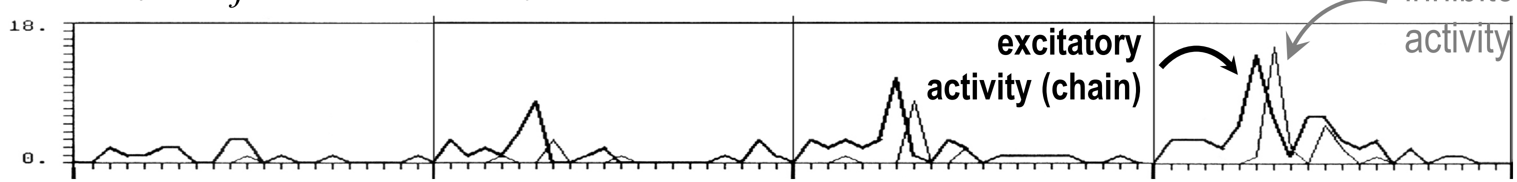
Doursat & Bienenstock 1991





Izhikevich 2006

- ✓ in a synfire braid, delay transitivity $\tau_{AB} + \tau_{BC} = \tau_{AD} + \tau_{DC}$ supports incoming spike coincidences, hence stable propagation of activity
- ✓ synfire braids can also grow in a network with nonuniform integer-valued delays τ_{ij} and inhibitory neurons

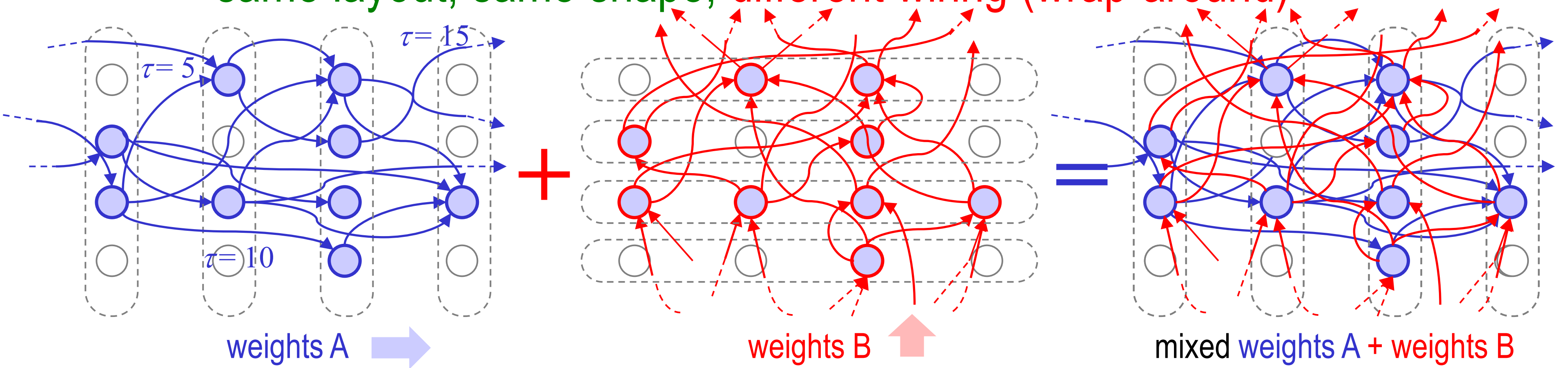


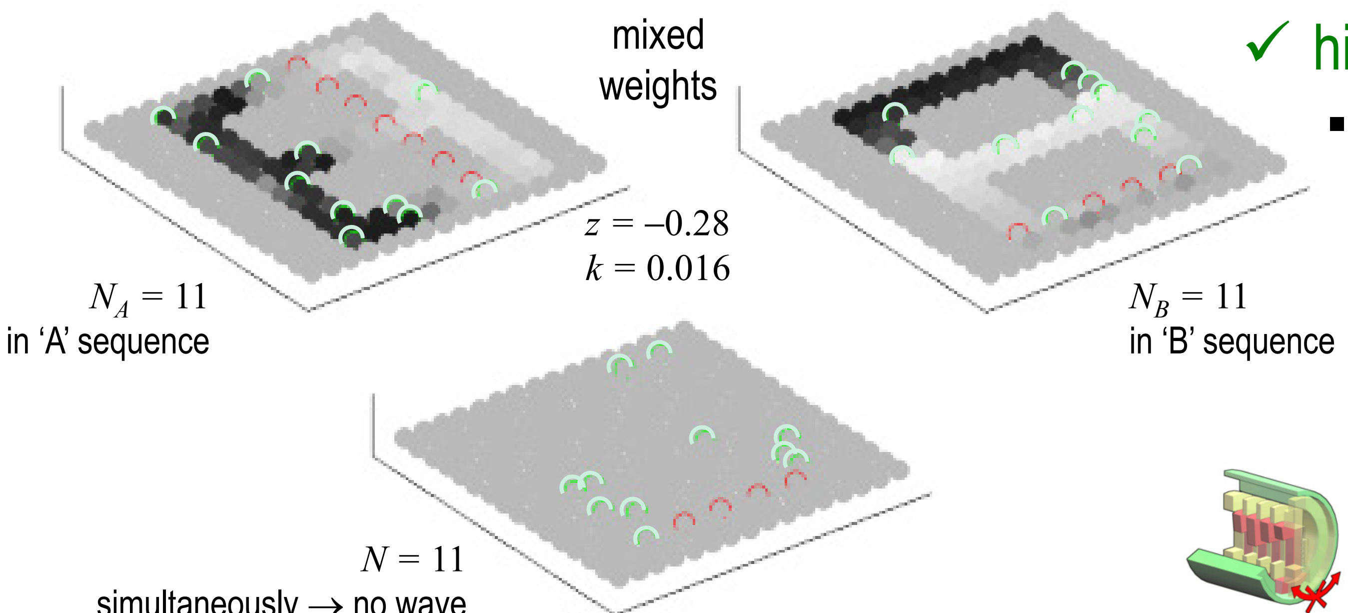
Doursat & Bienenstock 1991

Wave-Based Shape-Matching – Braids

➢ **Synfire braids** – ***pattern mix and selective retrieval***

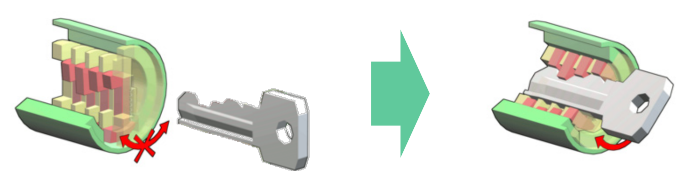
✓ same layout, same shape, different wiring (wrap-around)





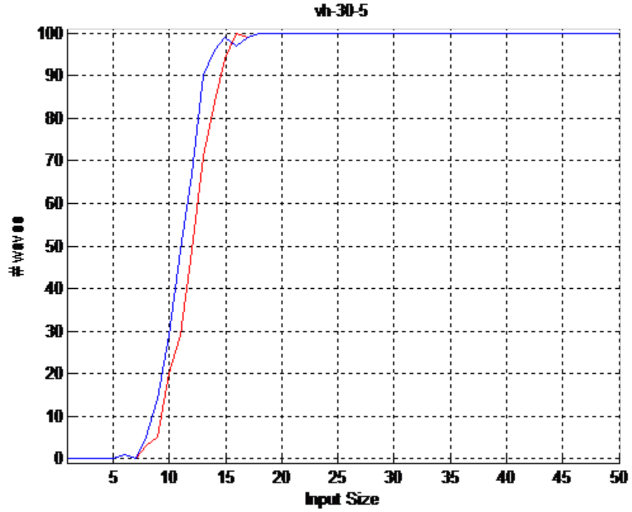
✓ high stimulus specificity

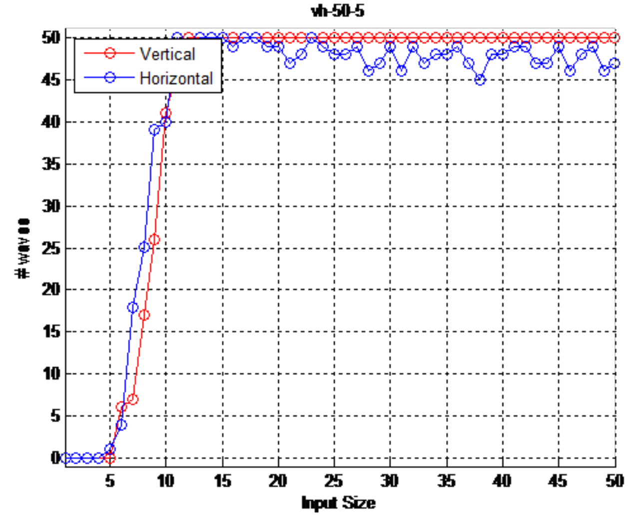
- to generate a wave, a synfire braid needs a minimum of N neurons stimulated in a *sequence ("sub-STP") compatible with the delays*



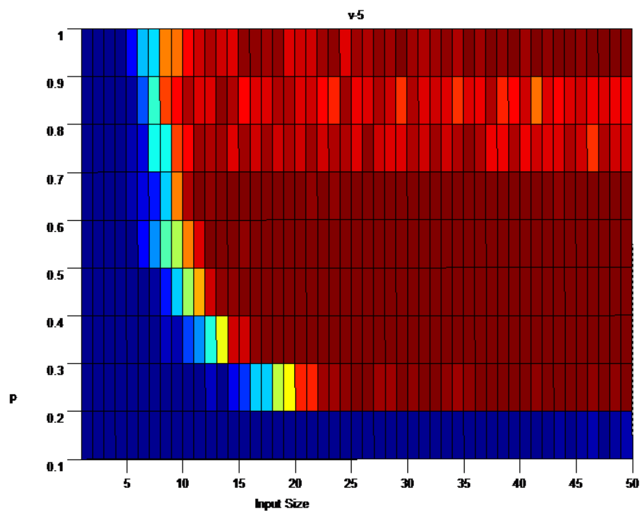
Wave-Based Shape-Matching – Braids

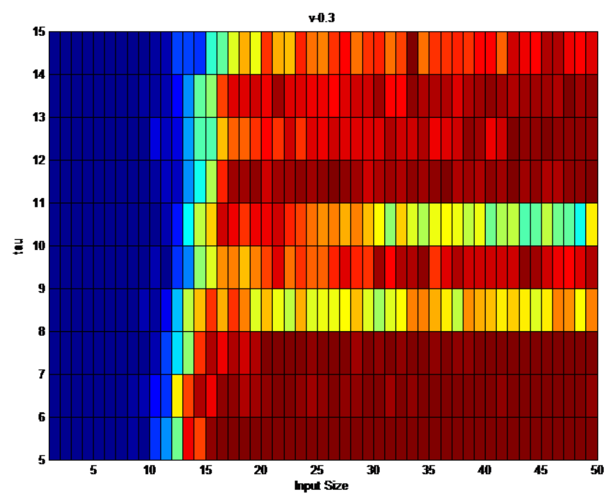
- **Synfire braids** – *pattern mix and selective retrieval*
  - ✓ statistics of selective retrieval depending on input size (in sequence)





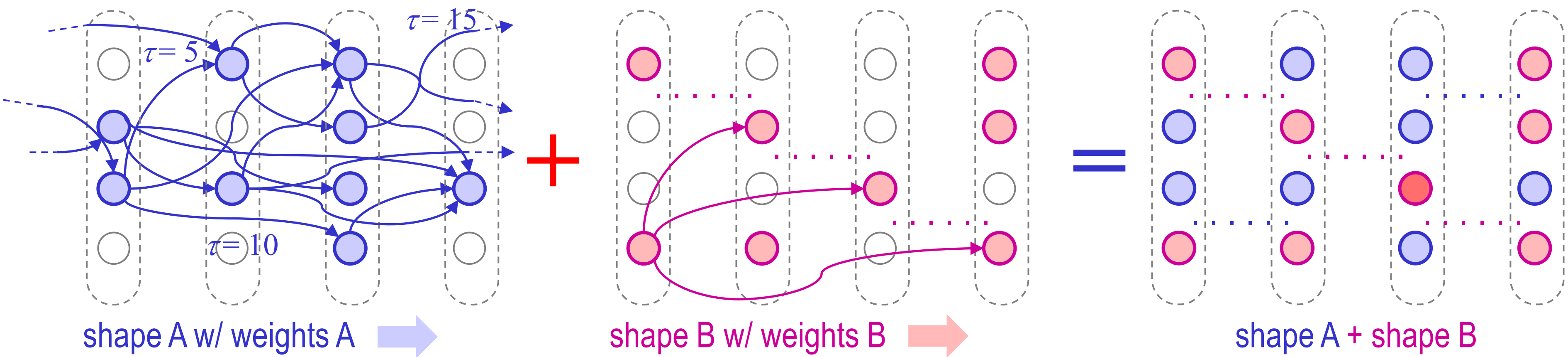
  - ✓ statistics of selective retrieval depending on input size and p or τ

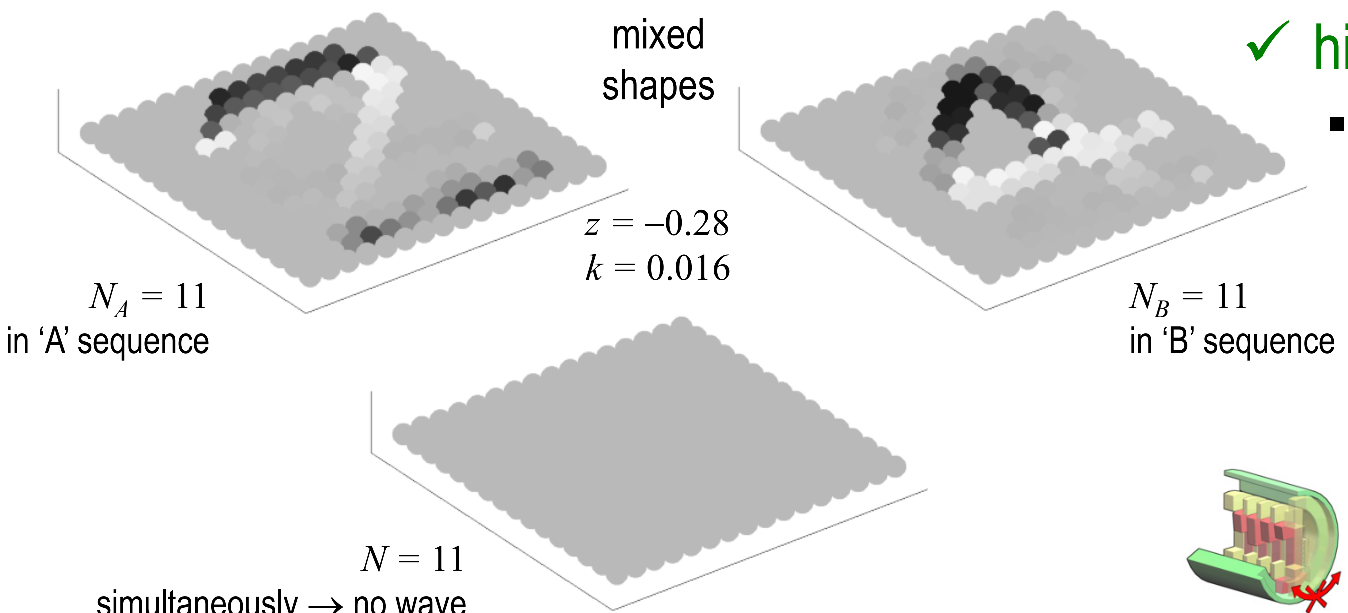




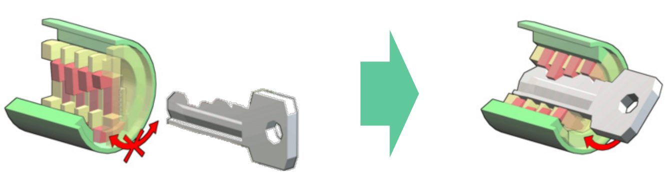
3. Wave-Based Shape-Matching – Braids

- **Synfire braids** – ***shape mix and selective retrieval***
  - ✓ same layout, different shape





- ✓ high stimulus specificity
  - to generate a wave, a synfire braid needs a minimum of N neurons stimulated in a *sequence ("sub-STP") compatible with the delays*

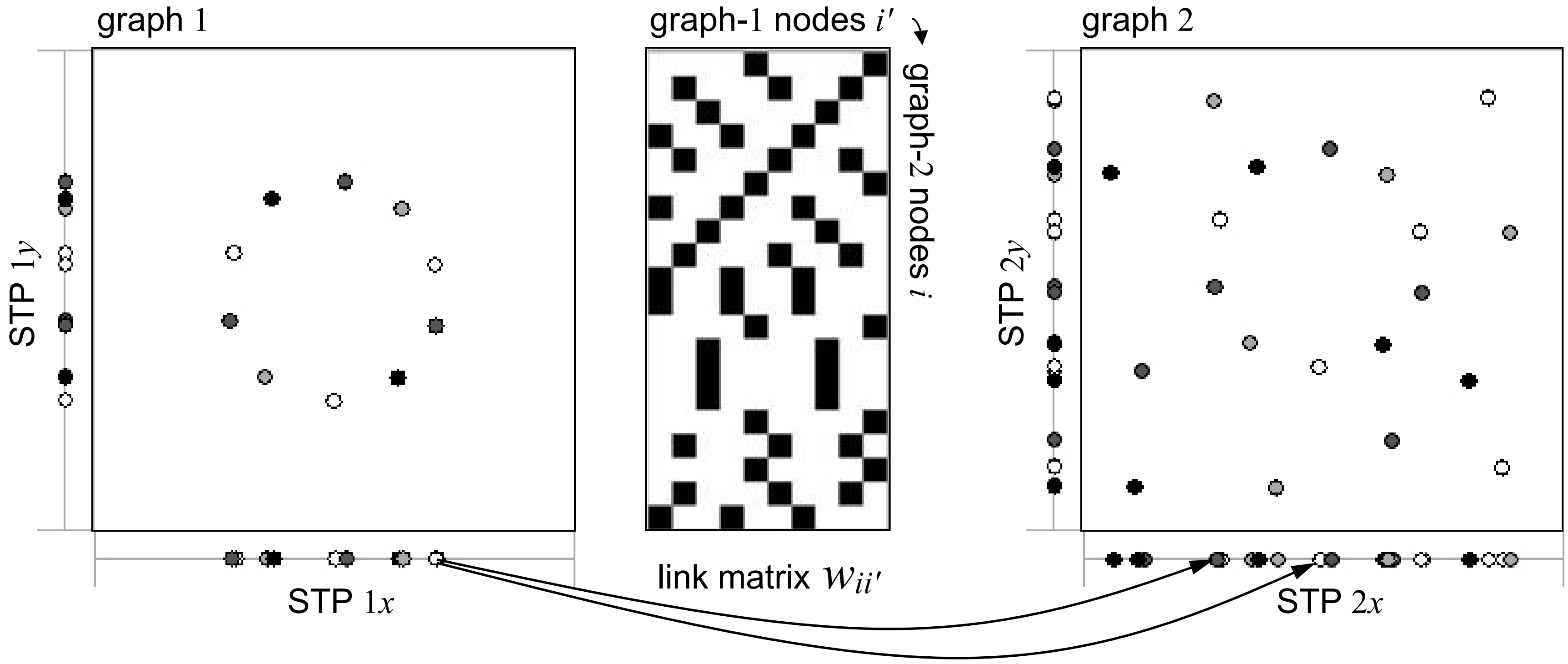


3. Wave-Based Shape-Matching – Braids

- **Synfire braids** – ***wave-matching***
  - ✓ graph-matching implemented as dynamical link matching between two pairs of STPs

$$\begin{cases} \dfrac{du_i}{dt} = c\left(u_i - \dfrac{u_i^3}{3} + v_i + z\right) + \eta + K_i + W_i \\ \dfrac{dv_i}{dt} = \dfrac{1}{c}(a - u_i - bv_i) + \eta \end{cases}$$

$$\boxed{W_i = \sum w_{ii'}(u_{i'} - u_i)}$$



3. Wave-Based Shape-Matching – Braids

➢ Synfire braids – *wave-matching*

✓ additional coupling term: $$W_i^{Xx}(t) = \sum_{\substack{j=1 \\ u_{i'}^x(t)<0}}^{N} w_{ii'}(t)\Big(u_{i'}^x(t) - u_i^X(t)\Big)$$

✓ where $w_{ii'}$ varies according to

1. Hebbian-type synaptic plasticity based on temporal correlations

$$\Delta w_{ii'}(t) = \alpha\Big(-w_{ii'}(t) + w_0 f(s_{ii'}^{Xx}(0))\Big) \quad \text{with}$$

$$s_{ii'}^{Xx}(0) = \langle u_i^X(t')\ u_{i'}^x(t')\rangle_{t-T_s}^{t} \quad \text{and} \quad f(s) = (1 + e^{-\lambda(s-s_0)})^{-1}$$

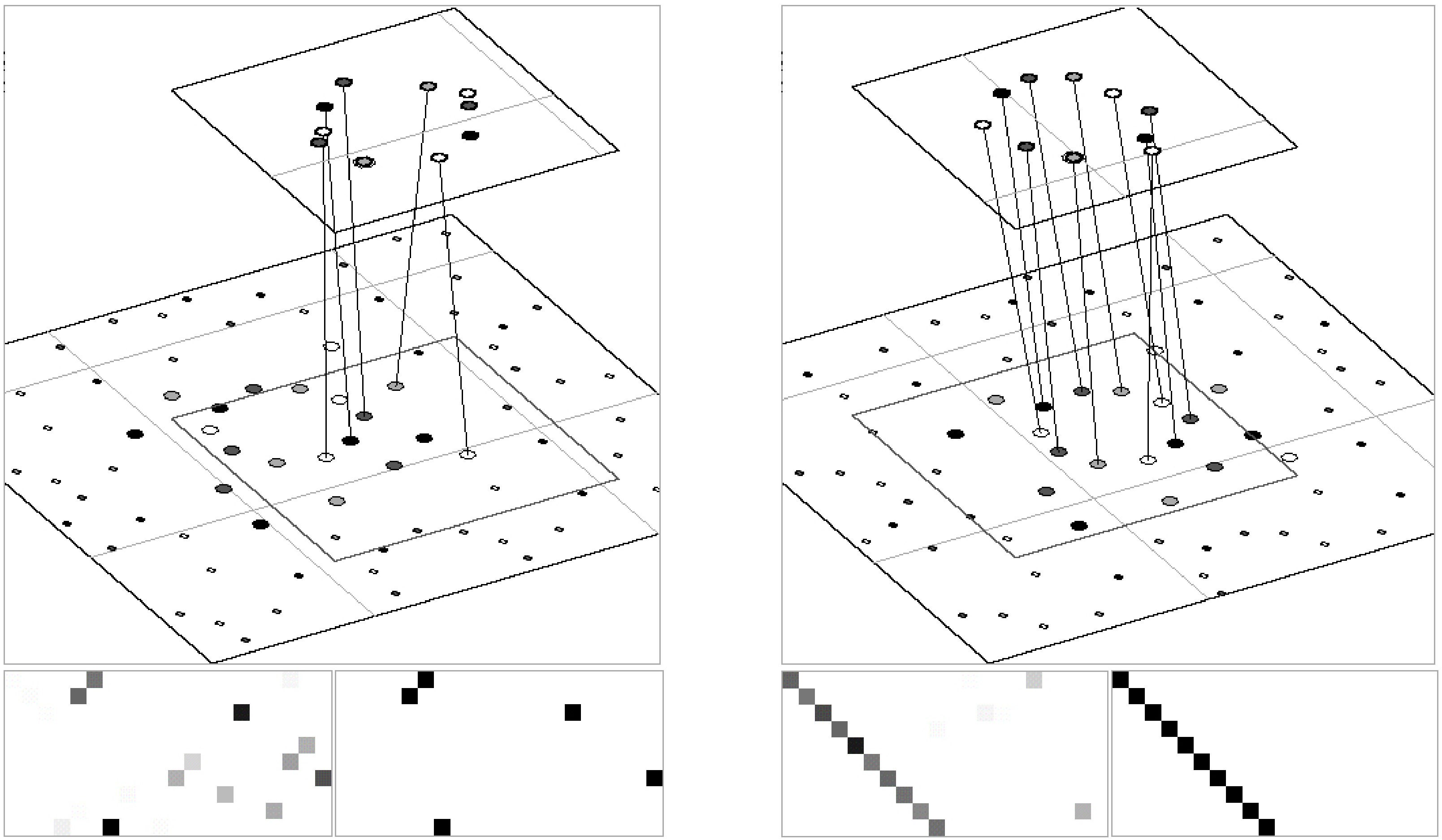
2. competition: renormalize efferent links

$$w_{ii'} \to w_{ii'} / \textstyle\sum_j w_{ji'}$$

3. label-matching constraint

Wave-Based Shape-Matching – Braids

- **Synfire braids** – ***2D wave-matching***
  - ✓ Hebbian rule in 2D: $$\Delta w_{ii'}(t) = \alpha\Big(-w_{ii'}(t) + w_0 f\Big(\sqrt{s_{ii'}^{Xx}(0)\, s_{ii'}^{Yy}(0)}\Big)\Big)$$
    $$s_{ii'}^{Xx}(0) = \langle u_i^X(t')\ u_{i'}^x(t')\rangle_{t-T_s}^{t} \qquad f(s) = (1+e^{-\lambda(s-s_0)})^{-1}$$



➢ Synfire braids – *2D wave-matching*

✓ to drive the system to the best match (global minimum), internal coupling k in graph-2 layer is regularly lowered and increased again

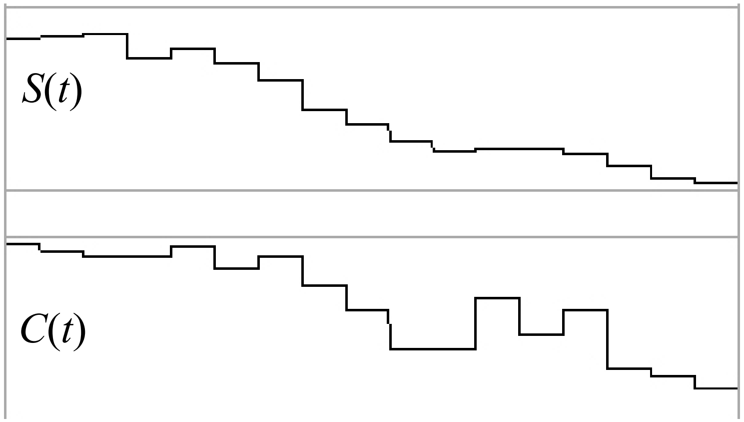
- if match is weak, this will perturb STP 2 and undo matching links
- if match is strong, this will not perturb STP 2 because it will be sustained by matching links $\rightarrow$ ***resonance*** between links and STPs

global "correlation" order parameter S:

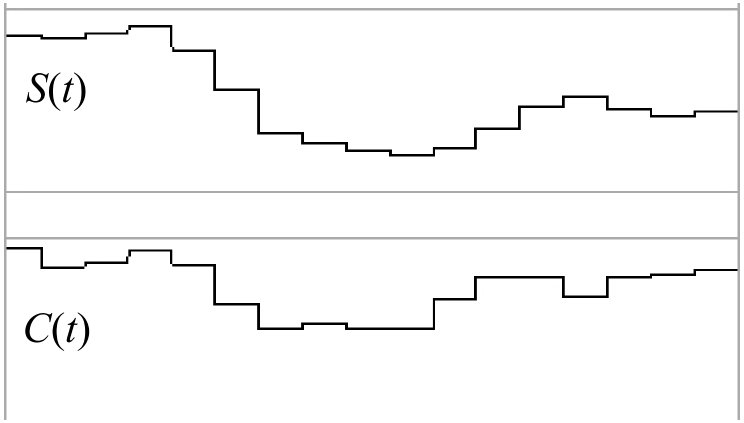
$$S(t) = \frac{1}{N(N-1)} \sum_{i \neq j} \langle u_i(t')\ u_j(t' - \tau_{ij}) \rangle_{t-T_s}^{t}$$

global "synchronicity" order parameter C:

$$C(t) = \frac{1}{N(N-1)} \sum_{i \neq j} \cos\left(\frac{2\pi}{T}(t_i(t) - t_j(t) - \tau_{ij})\right)$$



weak (mis)match $\rightarrow$ undone by uncoupling

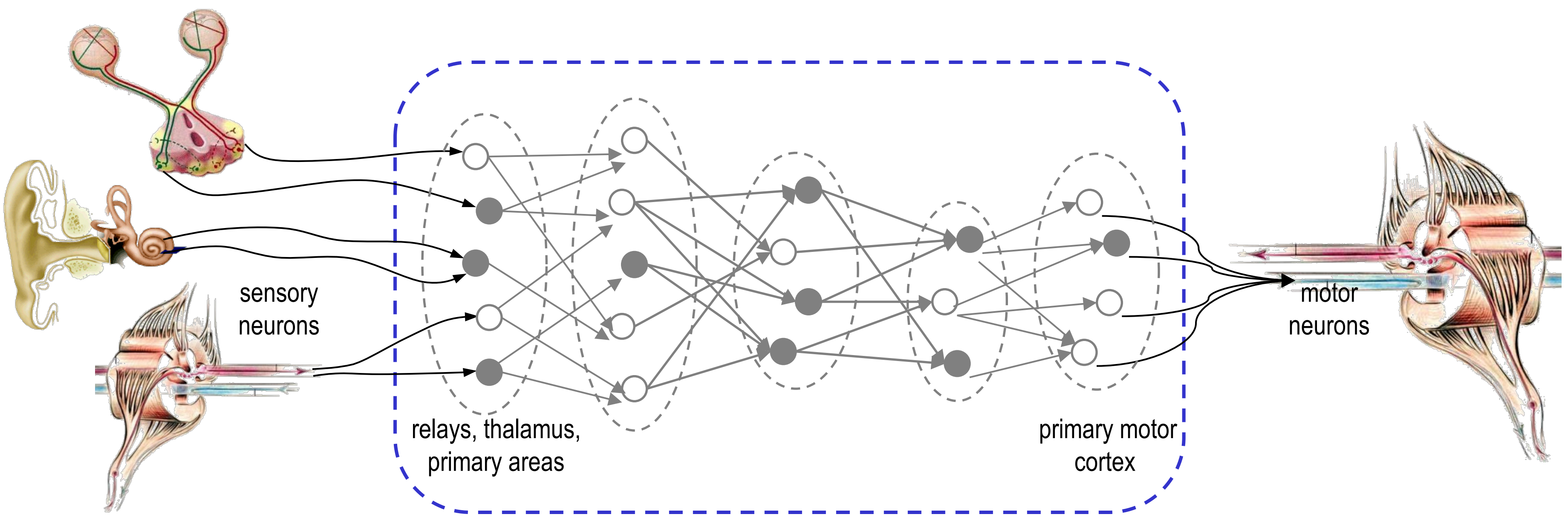


strong match $\rightarrow$ resistant to uncoupling

Toward Emergent Neurodynamics

➢ The naive engineering paradigm: “signal processing”

- ✓ ***feed-forward*** structure – activity literally “moves” from one corner to another, from the input (problem) to the output (solution)
- ✓ ***activation*** paradigm – neural layers are initially silent and are literally “activated” by potentials transmitted from external stimuli
- ✓ ***coarse-grain*** scale – a few units in a few layers are already capable of performing complex “functions”



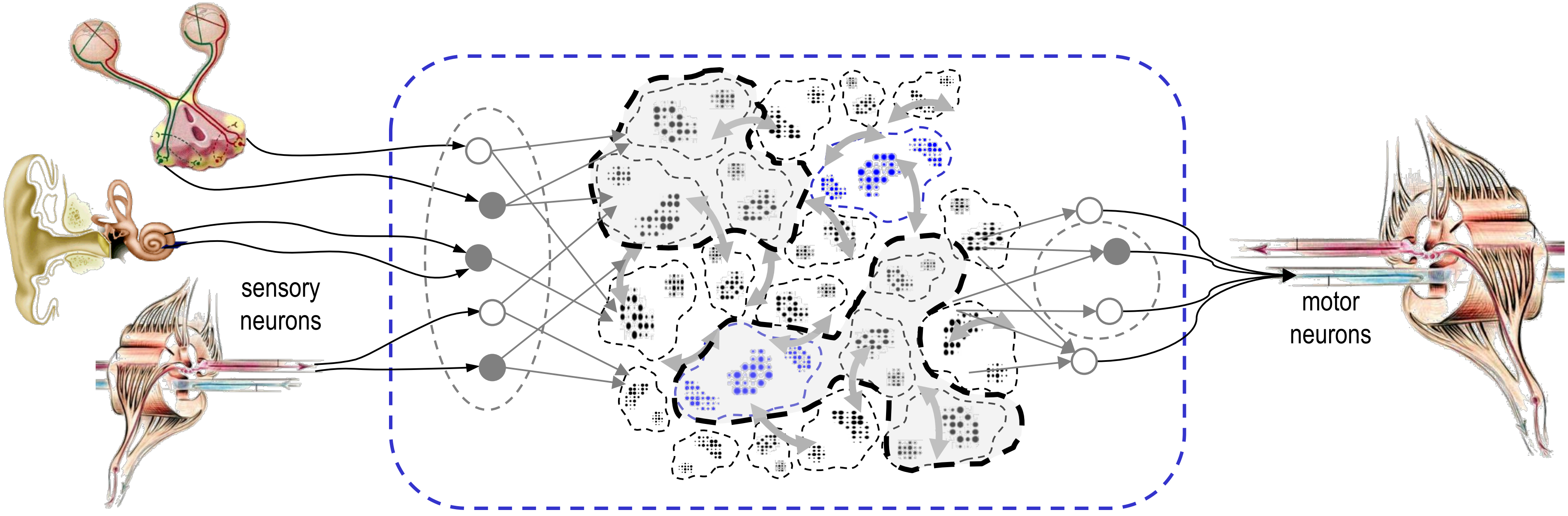
Toward Emergent Neurodynamics

It is not because the brain is an intricate network of microscopic causal transmissions (neurons activating or inhibiting other neurons) that the appropriate description at the mesoscopic functional level should be "signal / information processing".

This denotes a confusion of levels: mesoscopic dynamics is emergent, i.e., it creates mesoscopic objects that obey mesoscopic laws of interaction and assembly, qualitatively different from microscopic signal transmission

➢ The emergent dynamical paradigm: excitable media

- ✓ ***recurrent*** **structure** – activity can "flow" everywhere on a fast time scale, continuously forming new patterns; output is in the patterns
- ✓ ***perturbation*** **paradigm** – dynamical assemblies are already active and only "influenced" by external stimuli and by each other
- ✓ ***fine-grain*** **scale** – myriads of neurons form quasi-continuous media supporting structured pattern formation at multiple scales



5. Toward Emergent Neurodynamics

- **Tenet 1: mesoscopic neural pattern formation is of a fine spatiotemporal nature**
- **Tenet 2: mesoscopic STPs are individuated entities that are**

  a) endogenously produced by the neuronal substrate,

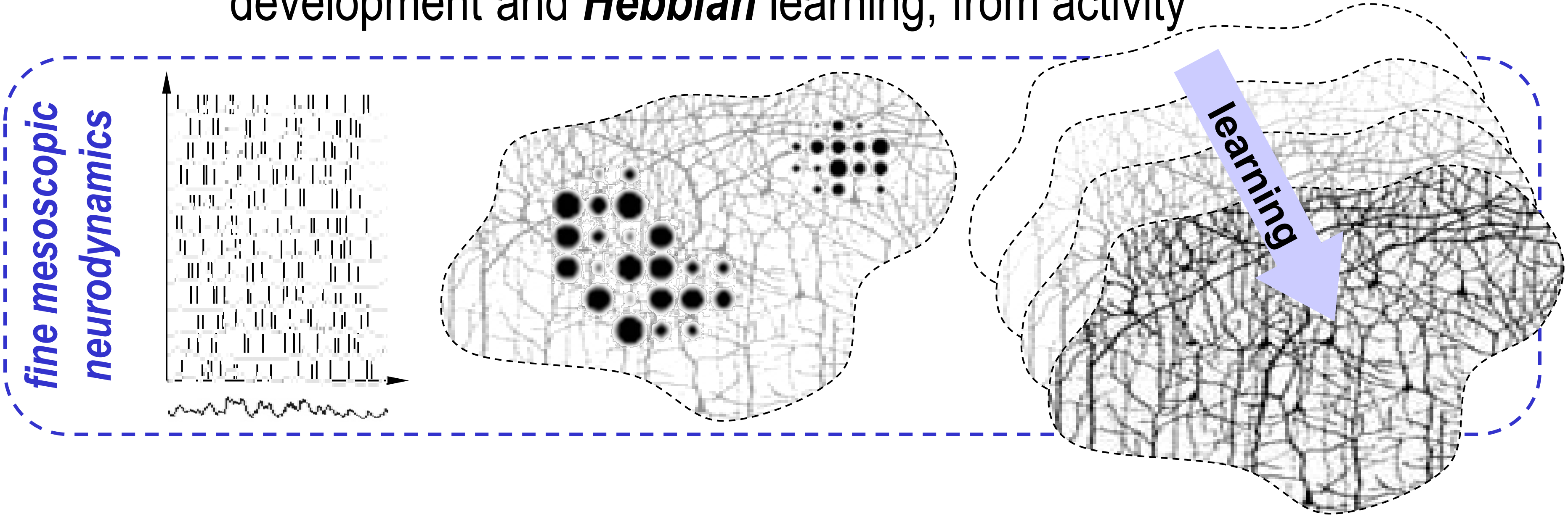
  b) exogenously evoked & perturbed under the influence of stimuli,

  c) interactively binding to each other in competitive or cooperative ways.

5. Toward Emergent Neurodynamics

a) Mesoscopic patterns are endogenously produced

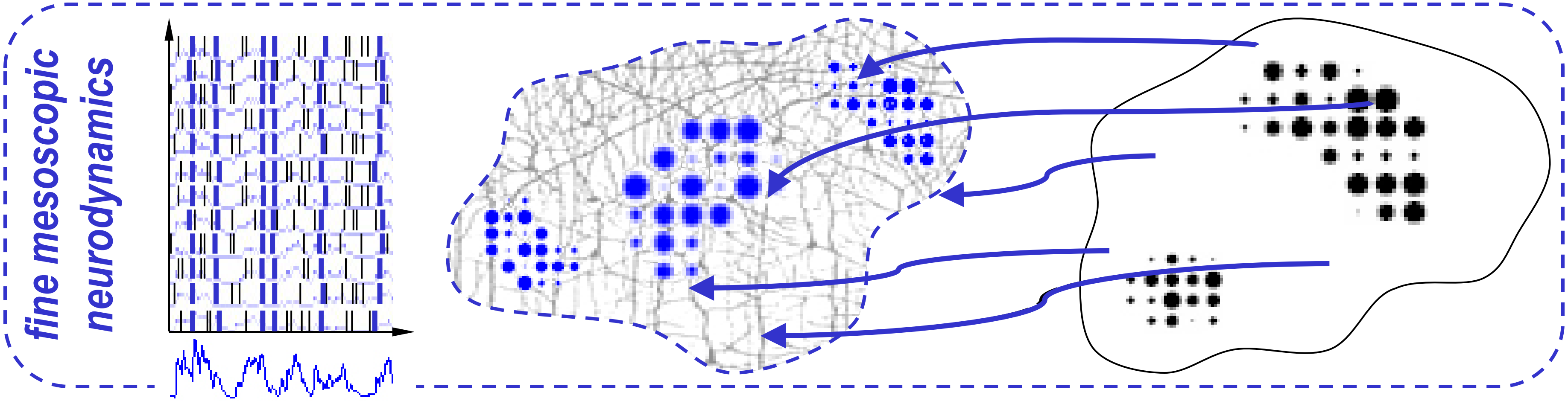
- ✓ given a certain connectivity pattern, cell assemblies exhibit various possible ***dynamical regimes***, modes, patterns of ongoing activity
- ✓ the underlying connectivity is itself the product of ***epigenetic*** development and ***Hebbian*** learning, from activity



→ *the identity, specificity or stimulus-selectiveness of a mesoscopic entity is largely determined by its internal pattern of connections*

b) Mesoscopic patterns are exogenously influenced

- ✓ external stimuli (via other patterns) may ***evoke & influence*** the pre-existing dynamical patterns of a mesoscopic assembly
- ✓ it is an indirect, ***perturbation*** mechanism; not a direct, activation mechanism

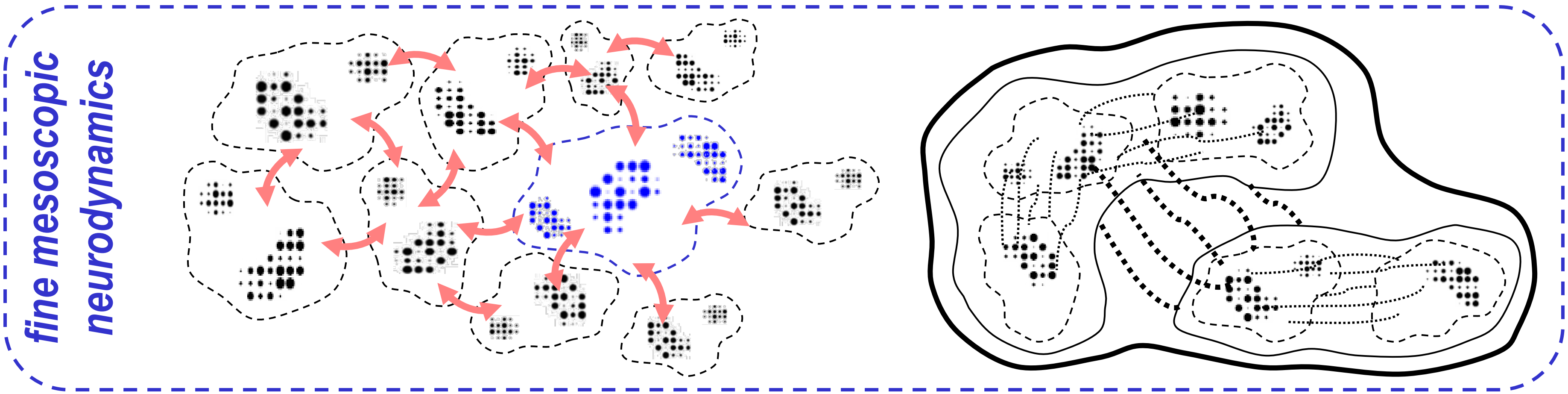


- ✓ mesoscopic entities may have stimulus-specific ***recognition or "representation"*** abilities, without being "templates" or "attractors" (no resemblance to stimulus)

5. Toward Emergent Neurodynamics

c) Mesoscopic patterns interact with each other

- ✓ populations of mesoscopic entities can ***compete & differentiate*** from each other to create specialized recognition units
- ✓ and/or they can ***bind*** to each other to create composed objects, via some form of temporal coherency (sync, fast plasticity, etc.)



evolutionary population paradigm

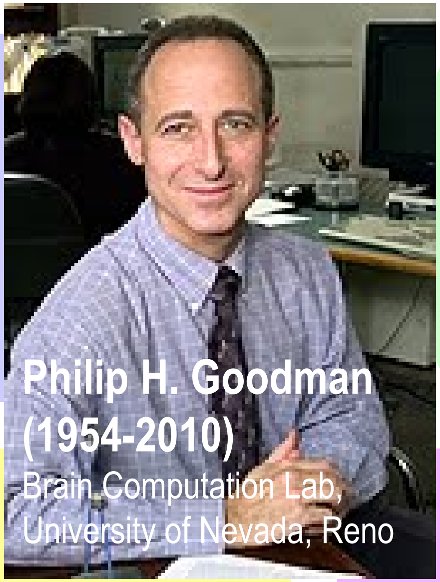
molecular compositionality paradigm

ACKNOWLEDGMENTS

Paul Bourgine
CREA / ISC-PIF
Ecole Polytechnique, Paris

Yves Frégnac
UNIC, CNRS Gif-sur-Yvette

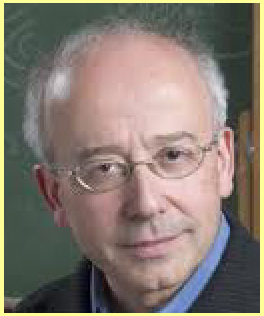
Christoph von der Malsburg
FIAS, Goethe-Universität, Frankfurt



Philip H. Goodman (1954-2010)
Brain Computation Lab,
University of Nevada, Reno

Carlos Sánchez
lattice simulations

Francisco Vico, GEB,
U. de Málaga



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