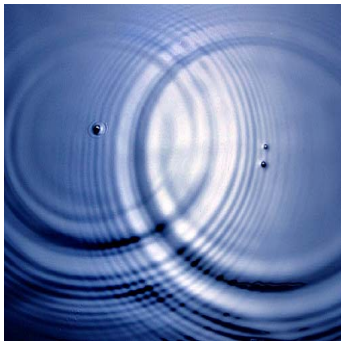
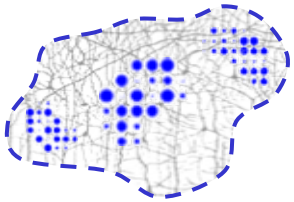
INSTITUT DES SYSTEMES COMPLEXES


“Tapestries, Ponds and RAIN”

Vers une élucidation du niveau neuronal *mésoscopique*, entre neurodynamique complexe et cognition



René Doursat

http://doursat.free.fr

Entre neurodynamique complexe et cognition

1. Vers une science cognitive unifiée
   Des neurones aux symboles : le niveau mésoscopique manquant

2. L'importance du codage temporel
   Le "binding problem" et les représentations structurées

3. Le cerveau comme machine morphogénétique
   Des objets endogènes façonnables, stimulables et composables

4. Le paradigme émergent des systèmes complexes
   Connectivité récurrente, activité spontanée, compositionalité

5. Trois études mésoscopiques
   "Tapestry, ponds and RAIN" : synfire chains, ondes et résonance

L'état des sciences cognitives et de l'I.A.

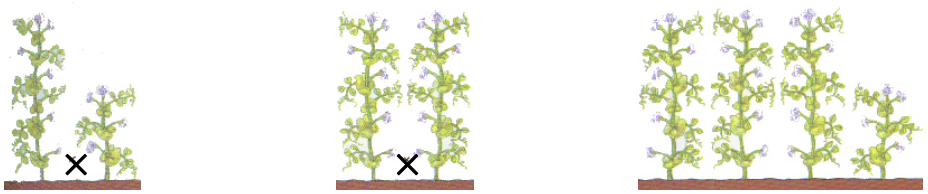
- I.A. : symboles, syntaxe → règles de production
  - ✓ *les systèmes logiques* définissent des *symboles* de haut niveau qui peuvent être *composés* de façon générative
  - → *il leur manque une "microstructure" fine, nécessaire pour expliquer la catégorisation floue en perception, contrôle moteur, apprentissage, etc.*

- Chaînon manquant : niveau de description "mésoscopique"
  - ✓ *les phénomènes cognitifs émergent de la neurodynamique complexe sous-jacente, par l'intermédiaire de motifs spatio-temporels structurés*

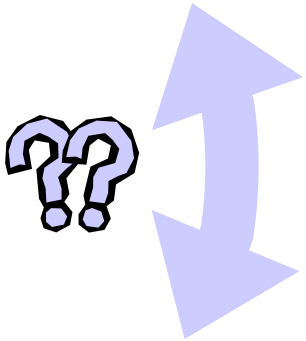
- Réseaux de neurones : nœuds, liens → règles d'activation
  - ✓ dans les *systèmes dynamiques* neuro-inspirés, les *nœuds* d'un réseau *s'activent* mutuellement par association
  - → *il leur manque une "macrostructure", nécessaire pour expliquer la compositionalité systématique du langage, du raisonnement, de la cognition*

L'état des sciences naturelles au XIX^{ème} siècle

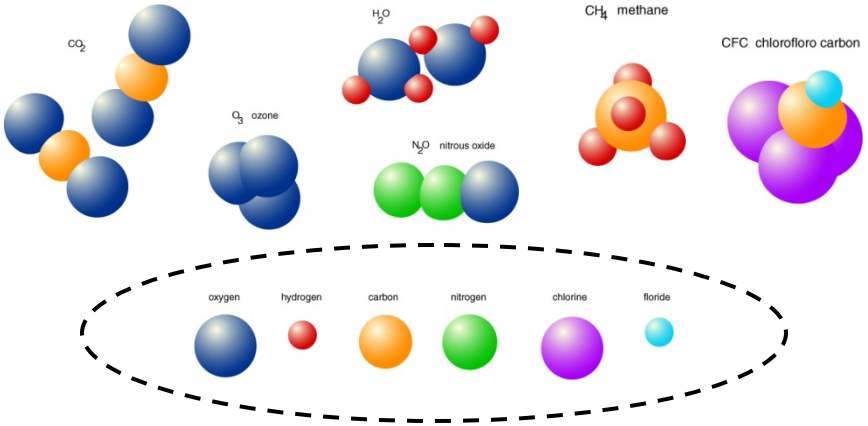
niveau macro :
lois génétiques



TT × Tt → Tt × Tt → TT, Tt, tT, tt



niveau micro :
atomes



L'état des sciences naturelles au XX^{ème} siècle

niveau macro :
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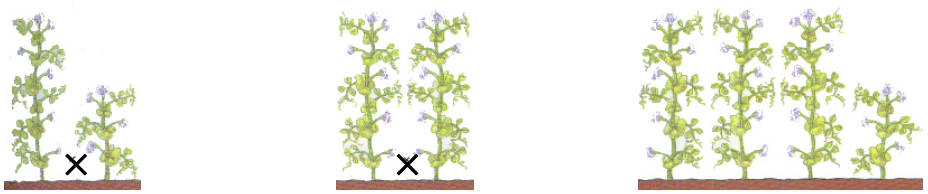
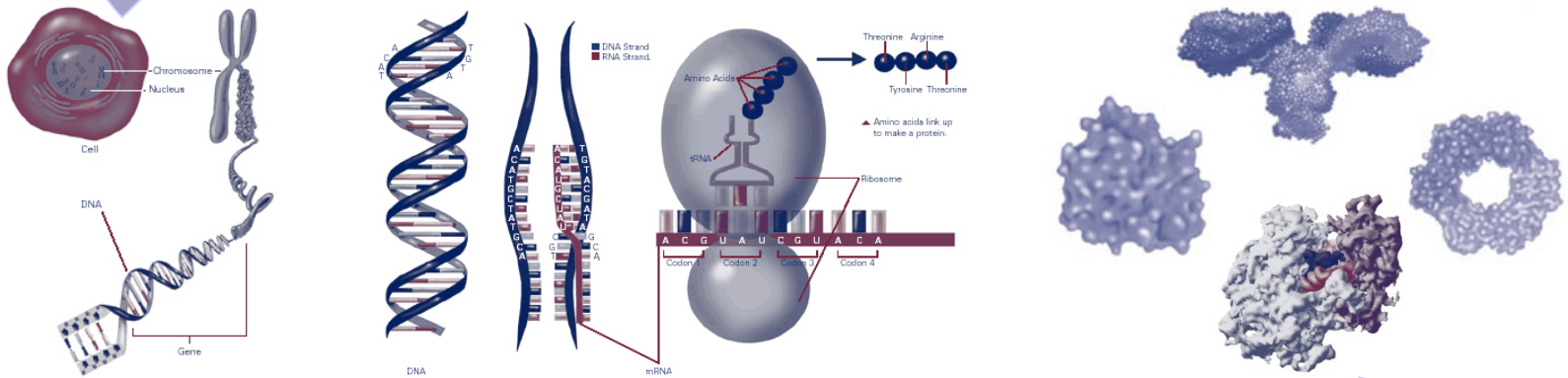
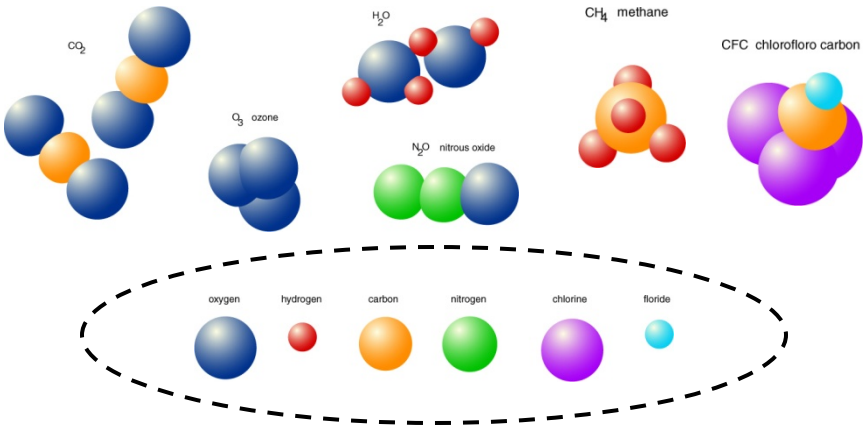


TT × Tt → Tt × Tt → TT, Tt, tT, tt

niveau méso :
biologie molléc.



niveau micro :
atomes

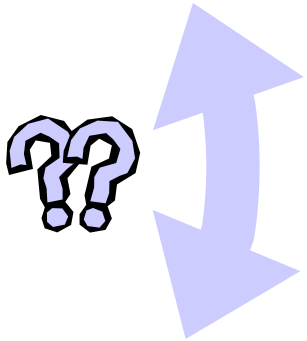


→ *système complexe multi-échelle*

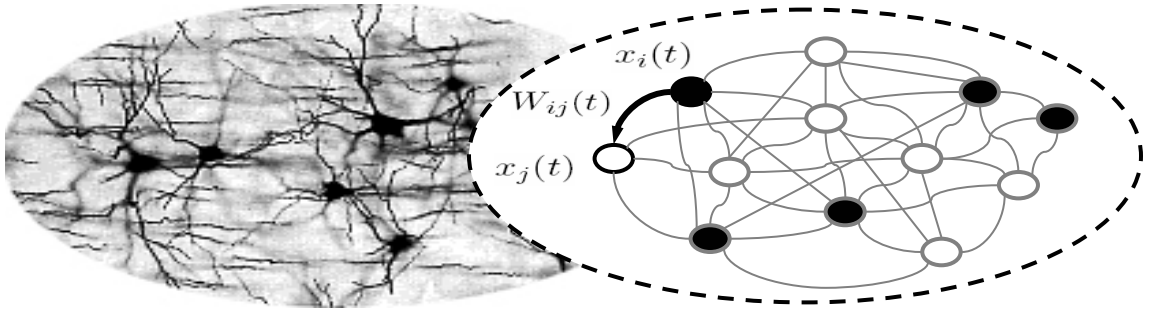
L'état des sciences cognitives au XX^{ème} siècle

niveau macro :
symboles

"John donne un livre à Mary" → **"Mary possède le livre"**



niveau micro :
neurones

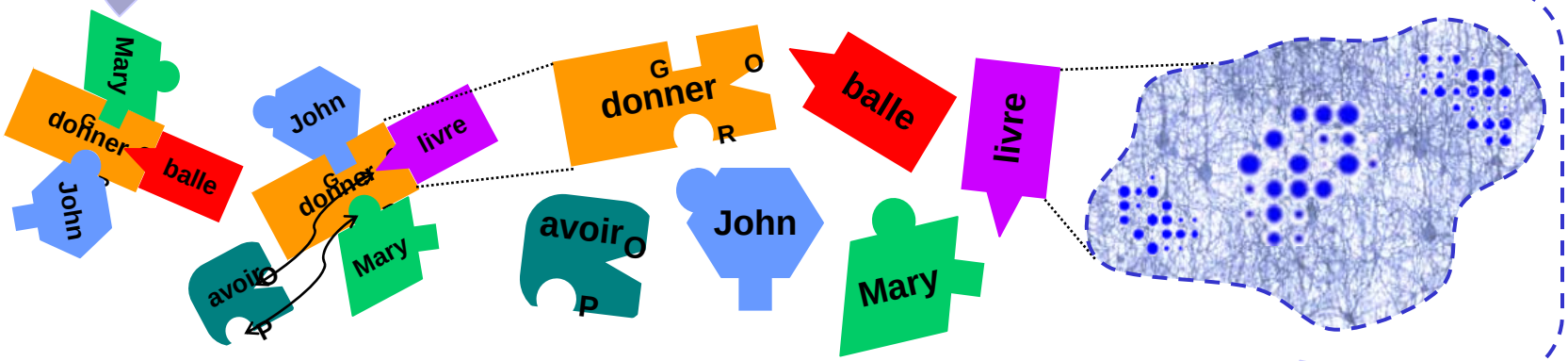


L'état des sciences cognitives au XXI^{ème} siècle?

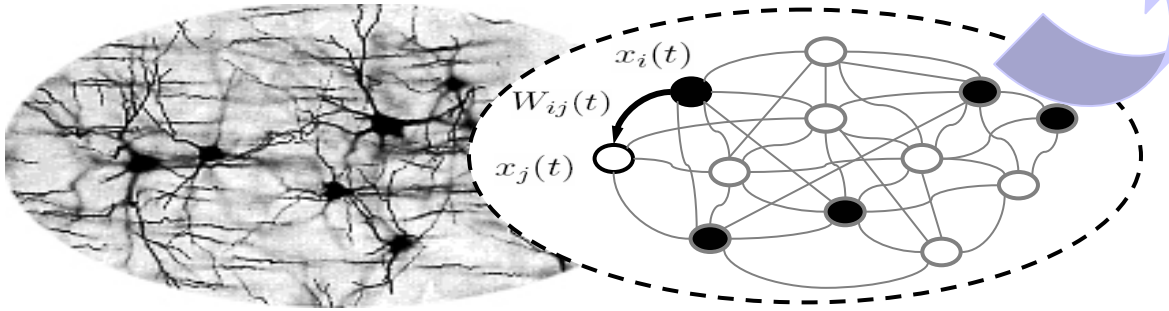
niveau macro :
symboles

"John donne un livre à Mary" → **"Mary possède le livre"**

niveau méso :
"cognition moléc."



niveau micro :
neurones



→ *système complexe multi-échelle*

Vers une science cognitive unifiée

- Pour expliquer des phénomènes macroscopiques à partir d'éléments microscopiques, des structures *mésoscopiques* sont nécessaires

  - ✓ pour expliquer et prédire les règles symboliques de la génétique à partir des atomes, la *biologie moléculaire* est nécessaire

  - ✓ de même, pour expliquer et prédire les règles symboliques du langage et de la perception (catégorisation, hiérarchie, inférence, composition) à partir des activités neuronales, une *"cognition mésoscopique"* est nécessaire

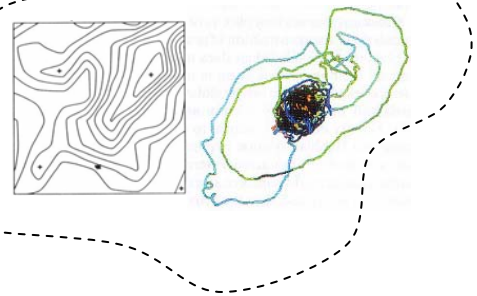
- Que pourraient donc être les "objets" d'une future science cognitive unifiée ?

Niveau mésoscopique de champs moyens

➢ Peupler le niveau mésoscopique (1) : modèles de champs

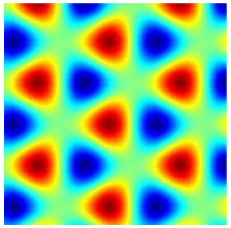
méso-niveau de champs moyens

EEGs spatiaux, attracteurs chaotiques



Freeman (1994)

"bumps", "blobs", bulles



Amari (1975, 1977)

- ✓ ensembles neuronaux caractérisés par des variables de *champ moyen*, continues dans le temps et/ou l'espace, par ex. :
  - local field potentials
  - fréquences de décharge (densités de spikes)
  - densités de neurotransmetteurs, etc.

Niveau mésoscopique de spikes

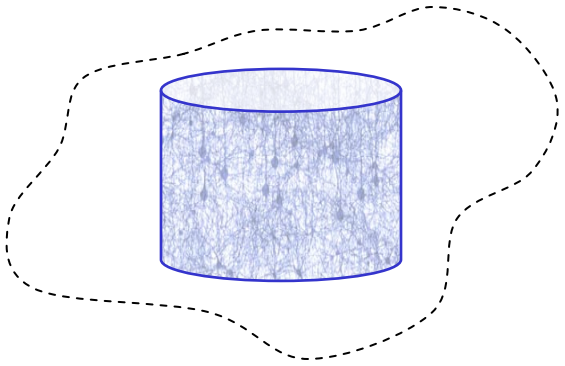
➢ Peupler le niveau mésoscopique (2) : modèles à spikes

- ✓ assemblées de cellules larges mais locales, présentant des régimes (digitaux-analogiques) complexes et *reproductibles* d'activité neuronale

→ *motifs spatio-temporels ("spatiotemporal patterns", STPs) structurés et modulaires, à une échelle fine*

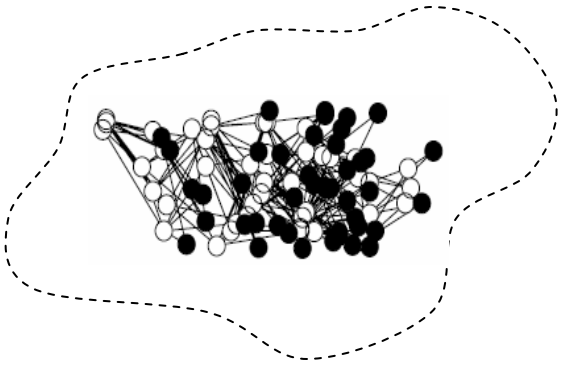
méso-niveau de spikes

BlueColumn (BlueBrain)



Markram (2006)

groupes polychrones



Izhikevich (2006)

. . .

Niveau mésoscopique de spikes

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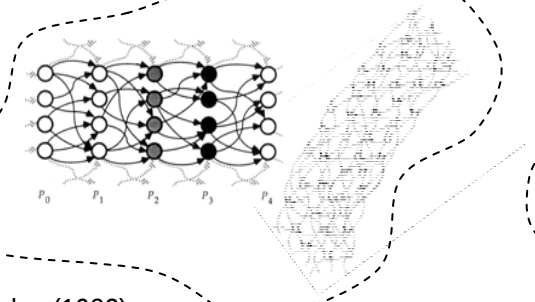
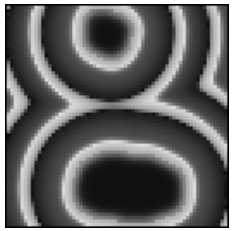
méso-niveau de spikes

"synfire chains" et tresses



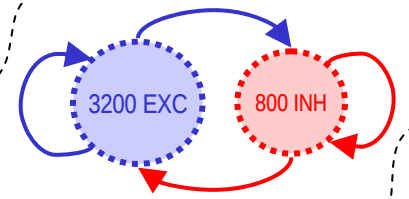
Abeles (1982),
Doursat (1991), Bienenstock (1995), D & B (2006)

ondes morphodynamiques



Doursat & Petitot (1997, 2005)

résonance "clé-serrure"



Vogels & Abbott (2006)
Doursat & Goodman (2006)

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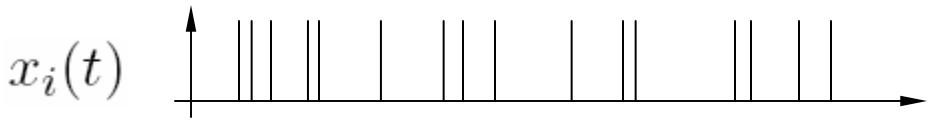
Temporal coding vs. rate coding

- There is more to neural signals than mean activity rates



- ✓ rate coding: average spike frequency

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

- ✓ temporal coding: spike correlations
  - not necessarily oscillatory
  - possibly delayed

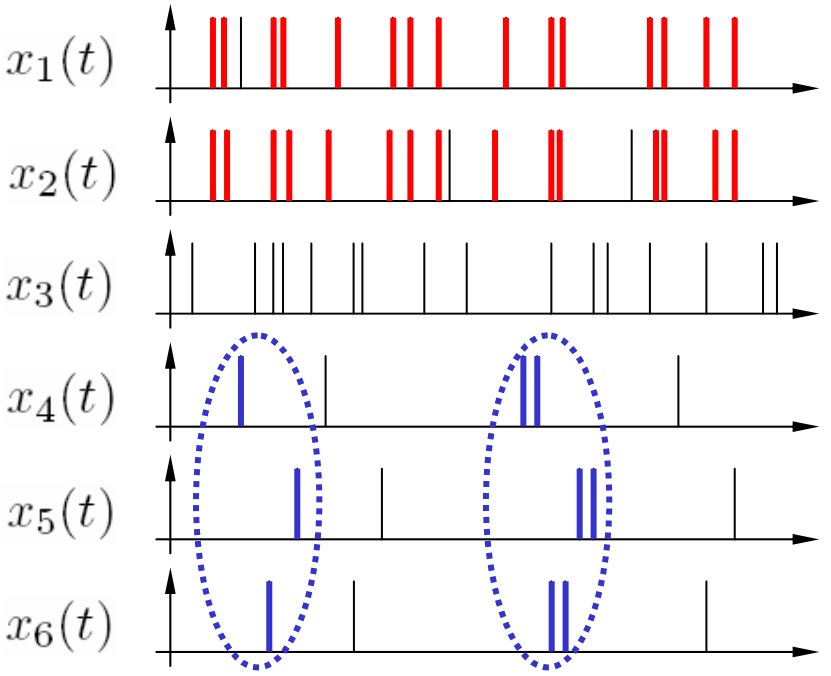
$$\langle\, x_i(t)\, x_j(t) \,\rangle$$

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

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

Temporal coding vs. rate coding

- **Below mean firing-rate coding: precise temporal coding**
  - ✓ more than mean rates → *temporal correlations* among spikes



temporal coding

rate coding

$\langle x_1(t) \rangle =$ ● 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

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

- 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)

Temporal coding vs. rate coding

➢ Historical motivation for rate coding

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

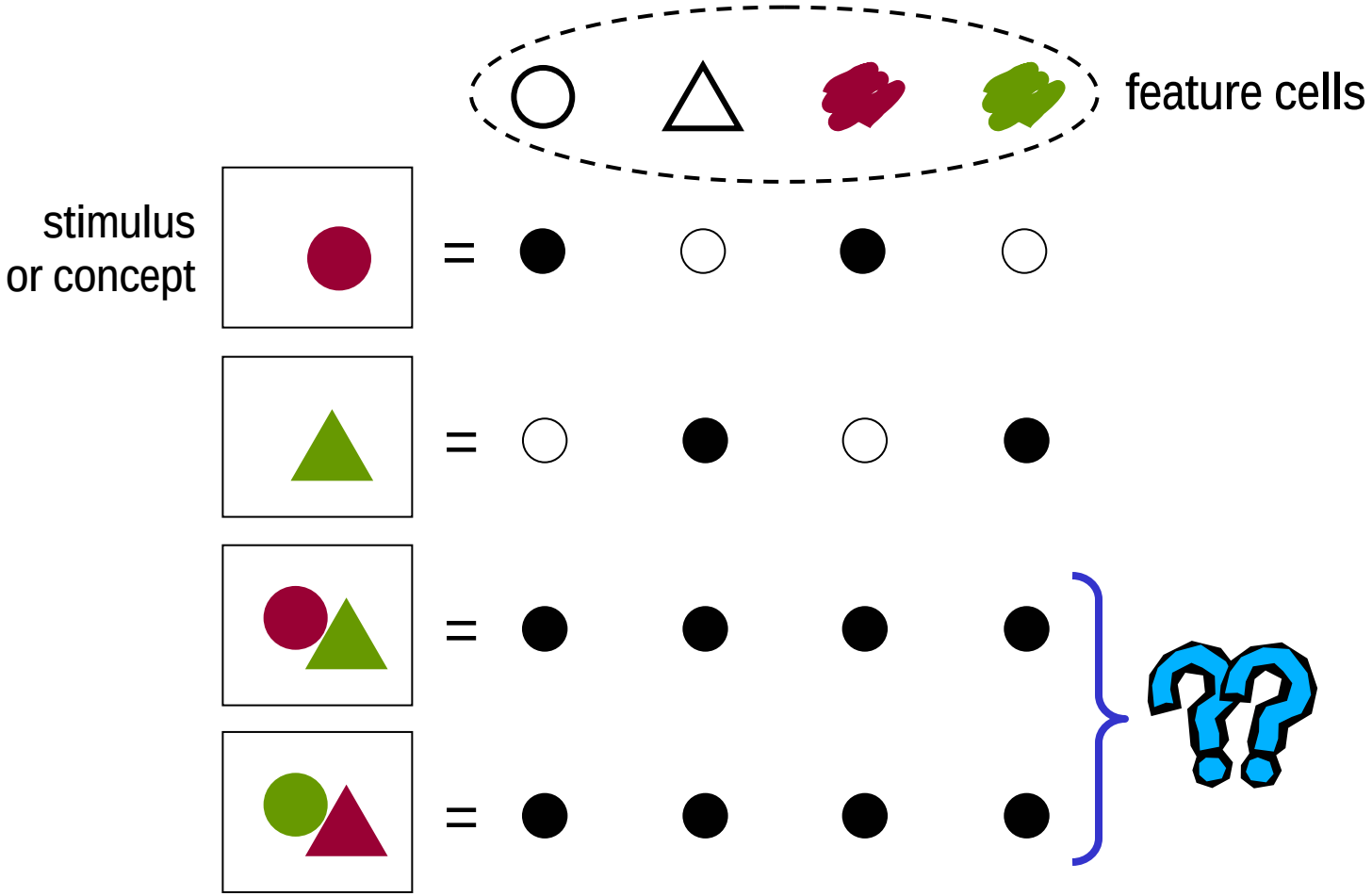
→ rate coding is confirmed in sensory system and primary cortical areas, however increasingly considered insufficient for integrating the information

➢ Modern temporal coding "boom": a few milestones

- 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*

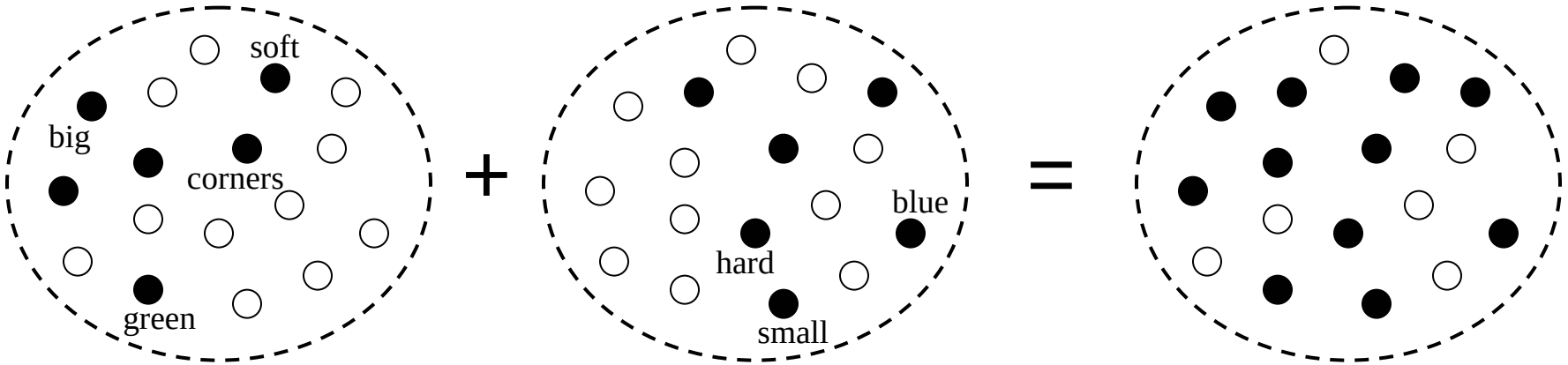
Binding with Temporal Code

- The “binding problem”
  - ✓ how to represent relationships?



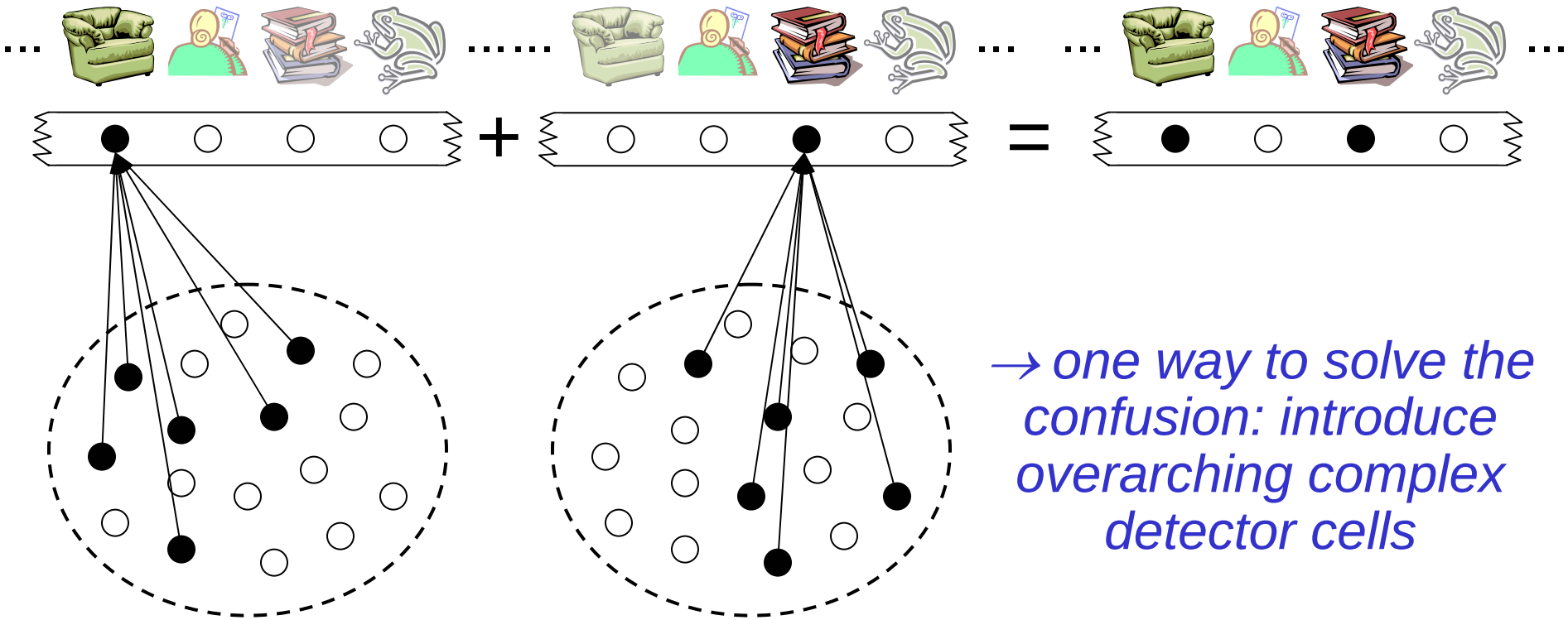
Binding with Temporal Code

- More generallly: feature binding in cell assemblies
  - ✓ unstructured lists or “sets” of features lead to the “superposition catastrophe”



Binding with Temporal Code

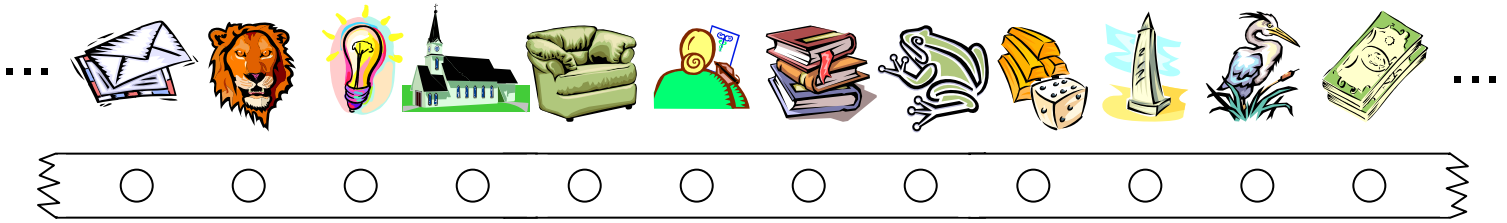
- "Grandmother" cells?



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

Binding with Temporal Code

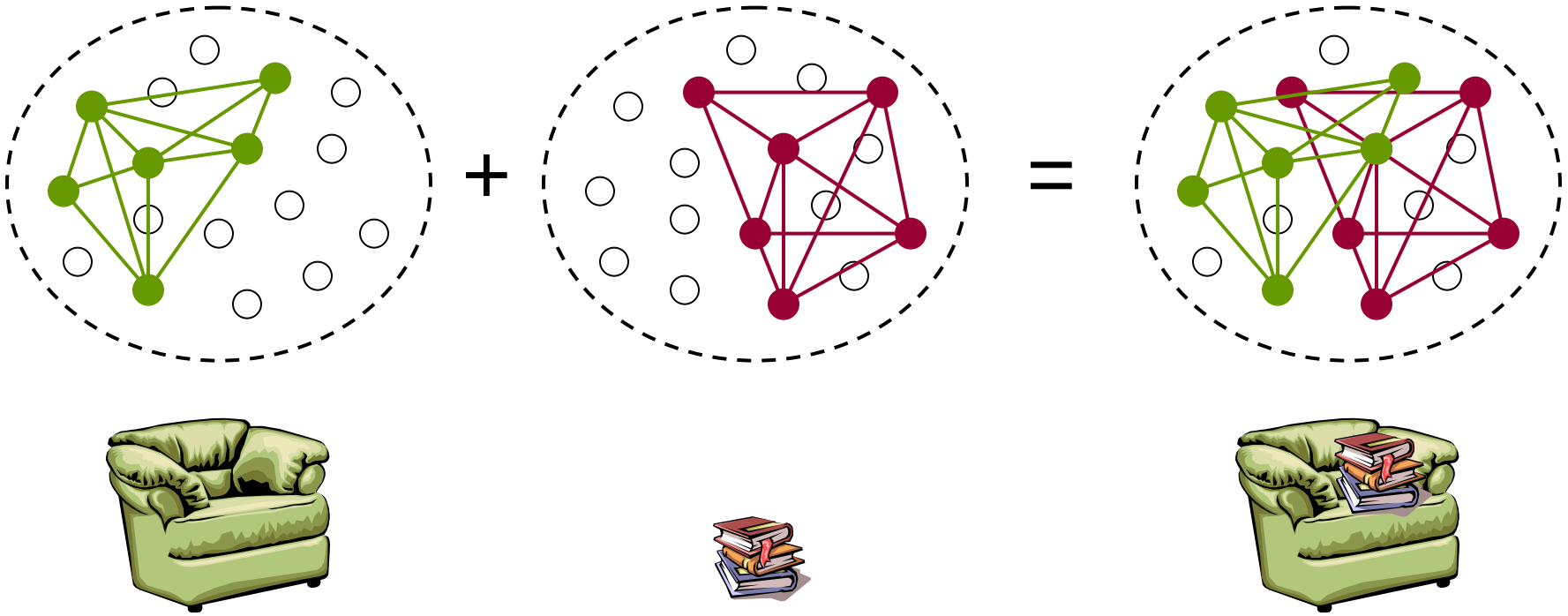
- “Grandmother” cells?



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

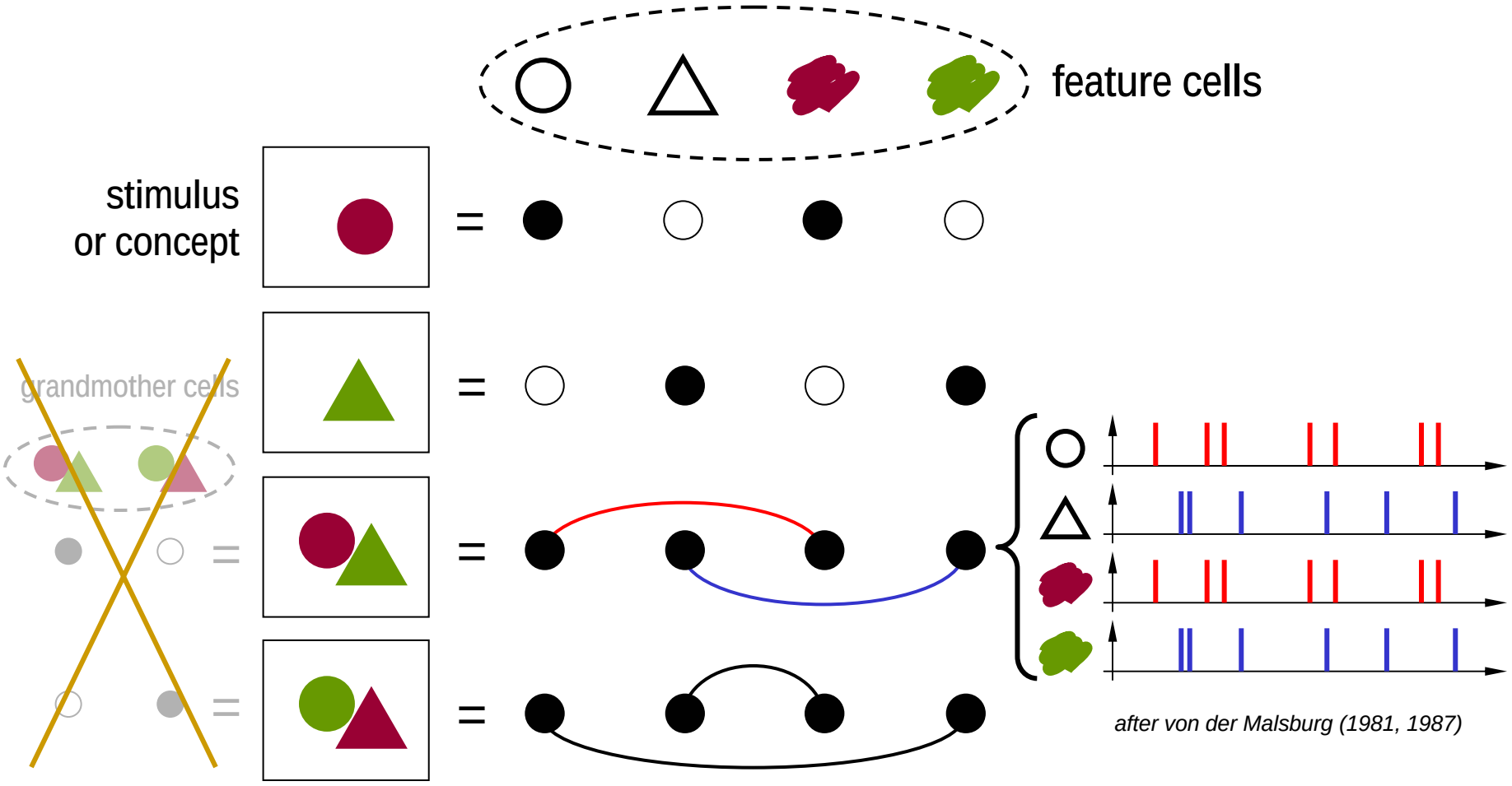
Binding with Temporal Code

- Relational representation: graph format
  - ✓ a better way to solve the confusion: represent relational information with *graphs*



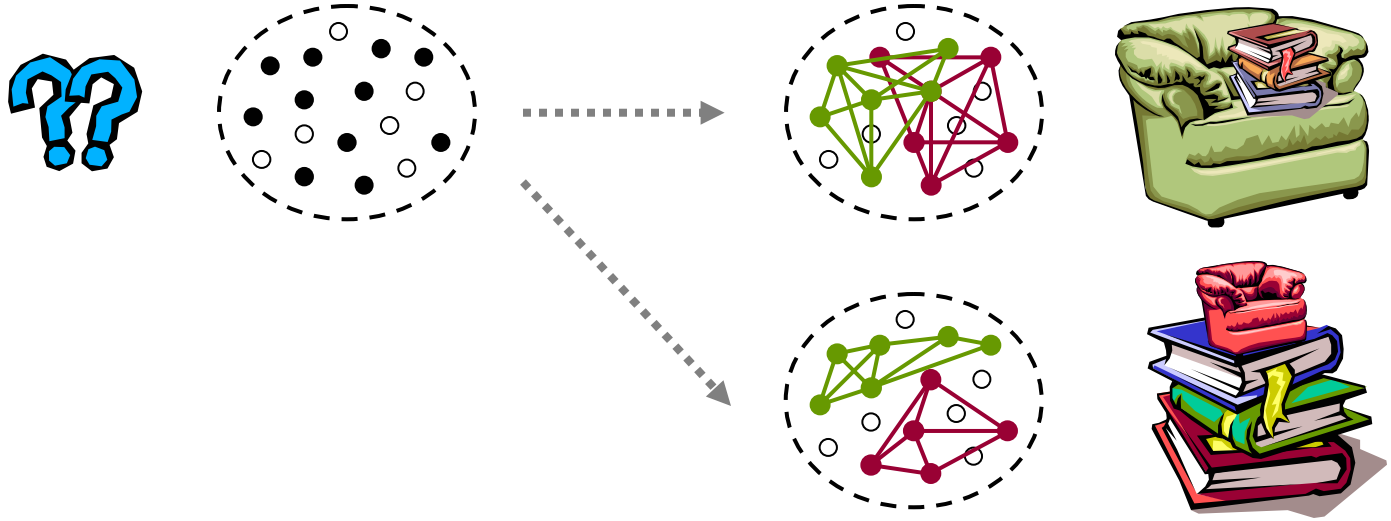
Binding with Temporal Code

- Idea: relational information can be encoded *temporally!*
  - ✓ back to the binding problem: a solution using temporal coding

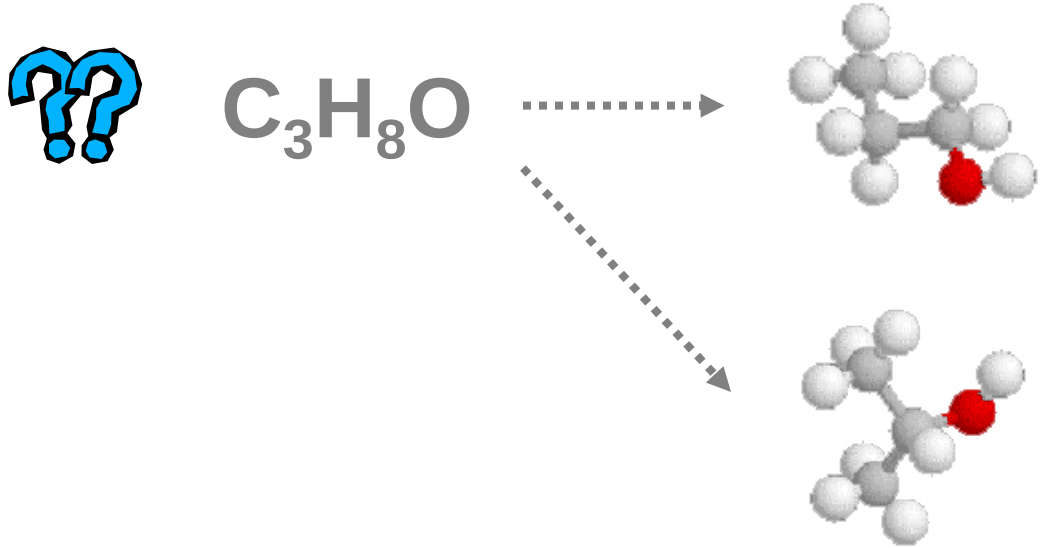


Binding with Temporal Code

- Molecular metaphor: spatiotemporal patterns

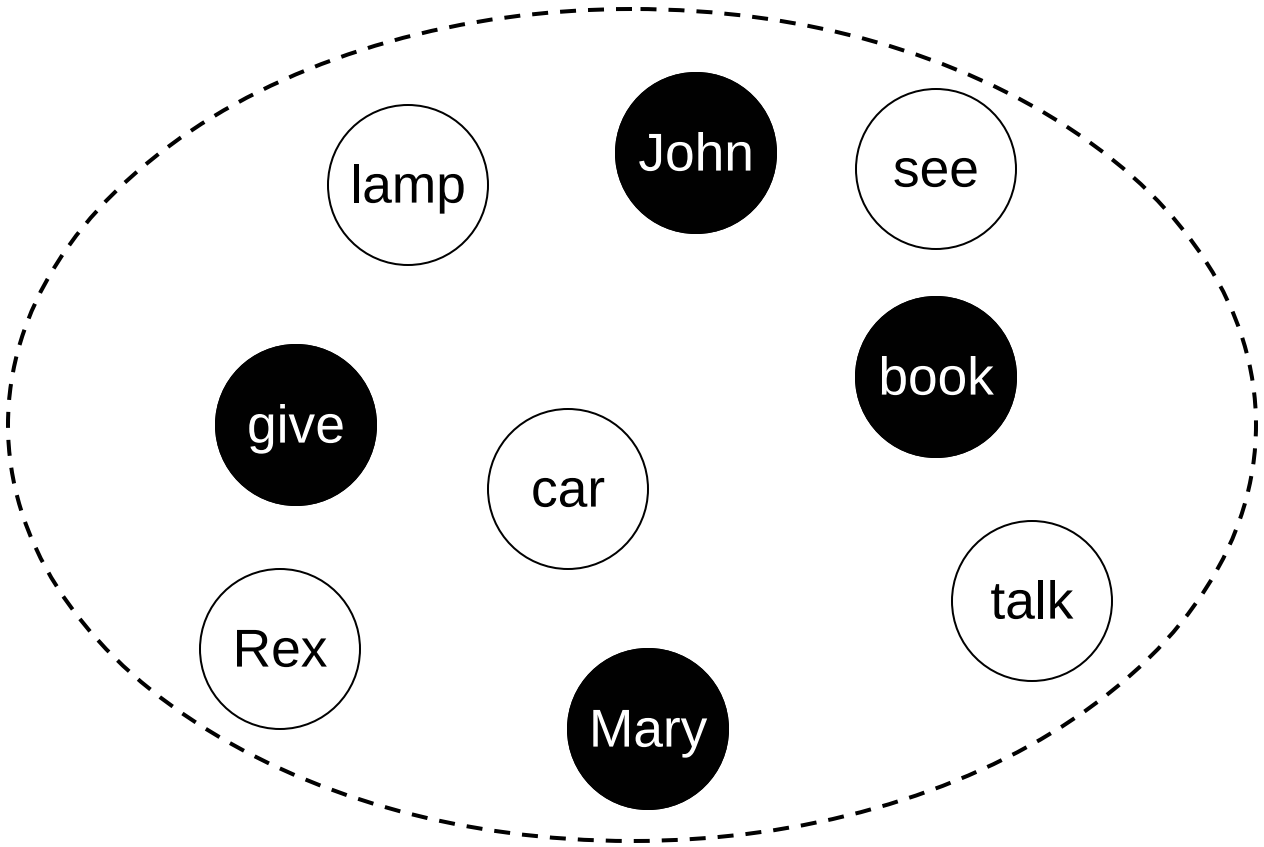


"cognitive isomers" made of the same atomic features



Binding with Temporal Code

- Problems of compositionality again—in language



(a) John gives a book to Mary.
(b) Mary gives a book to John.
(c)* Book John Mary give.

Binding with Temporal Code

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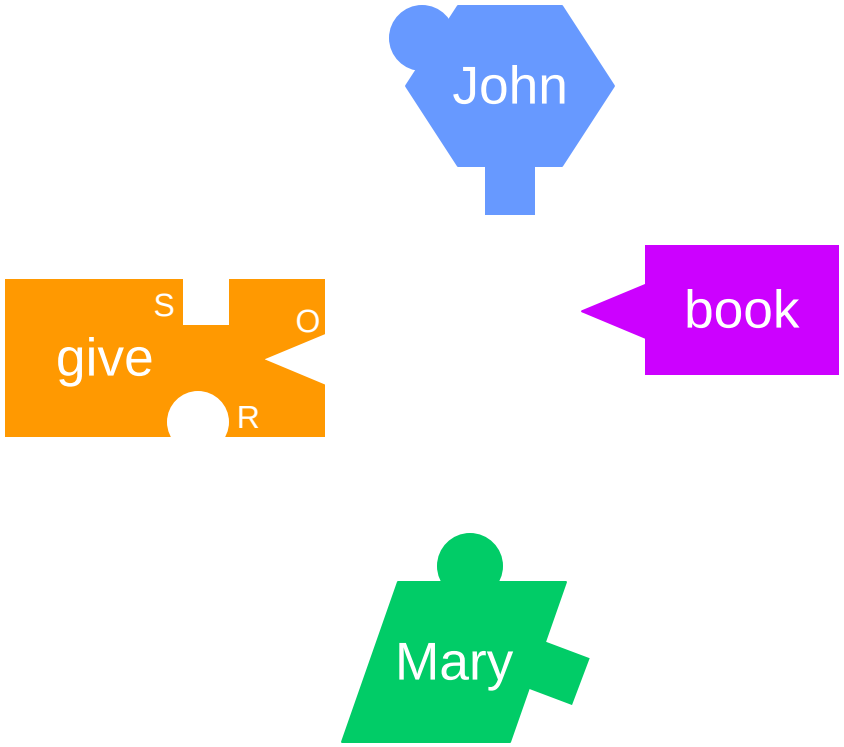
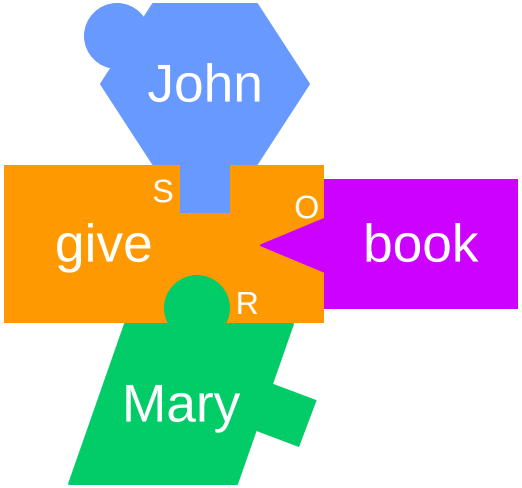


Binding with Temporal Code

- Problems of compositionality again—in language
  - ✓ language is a construction game of “building blocks”



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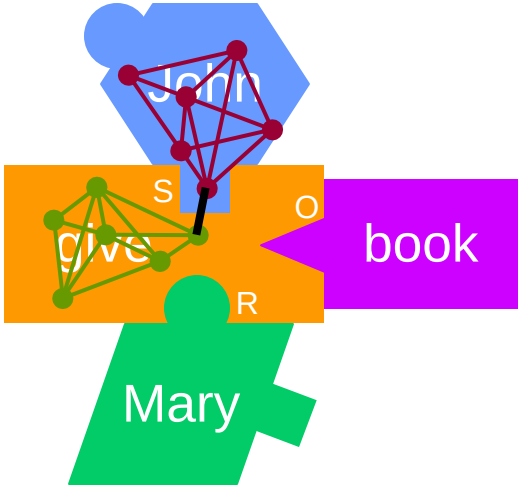
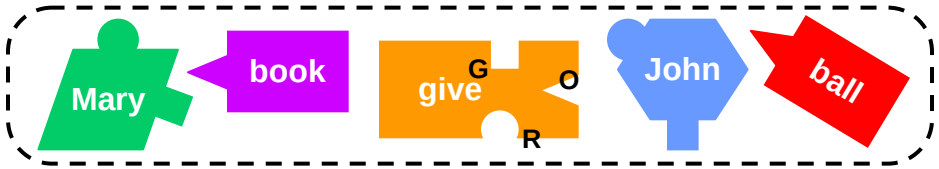
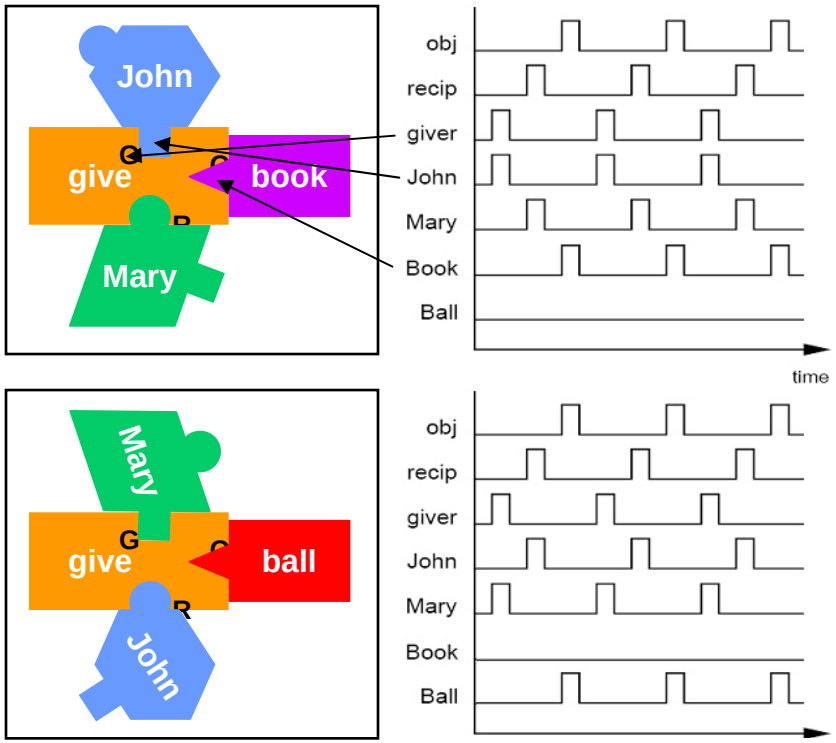


Binding with Temporal Code

A building-block game of language





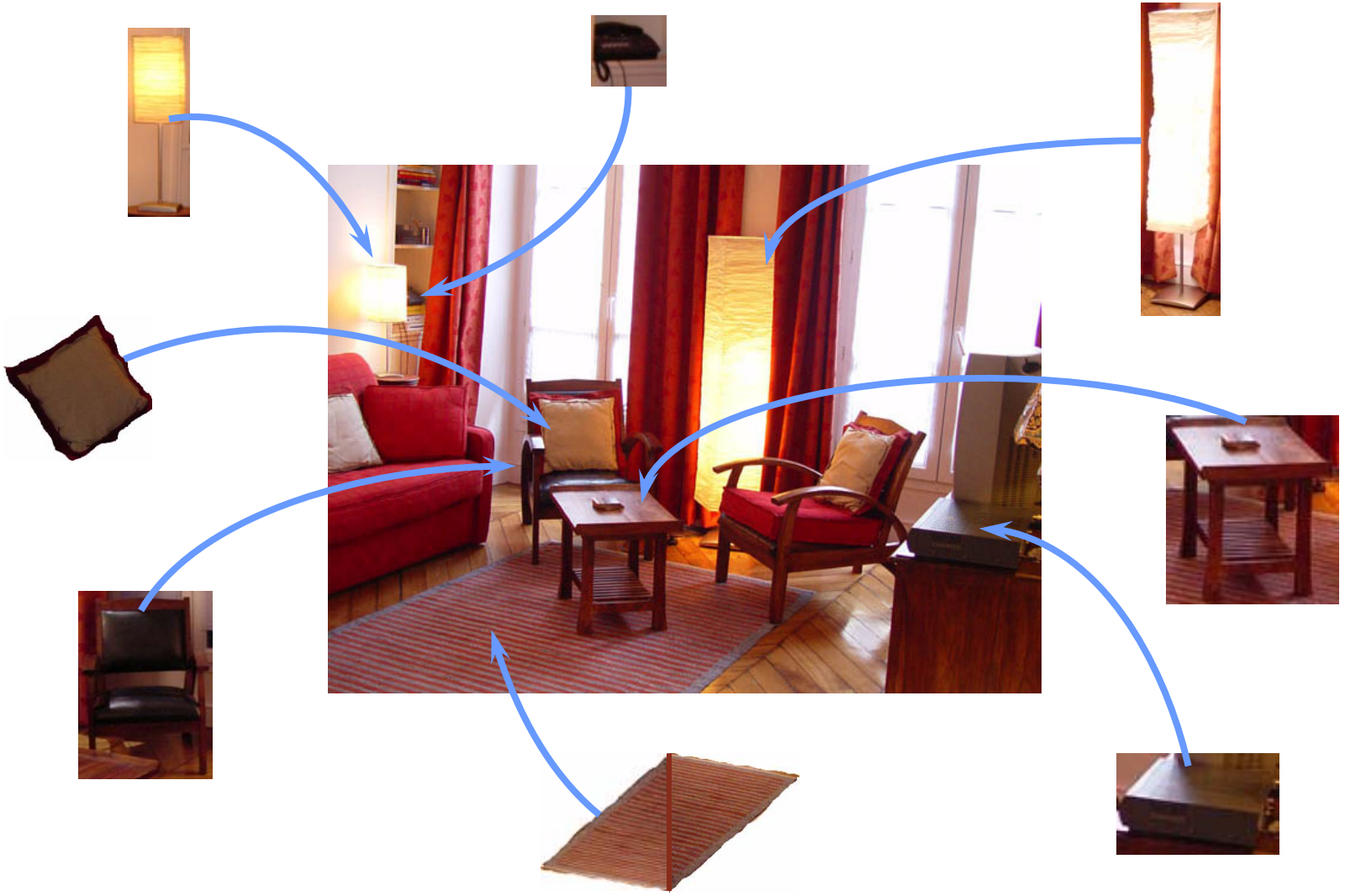
after Bienenstock (1995)

after Shastri & Ajjanagadde (1993)

- ✓ the "blocks" are elementary representations (linguistic, perceptive, motor) that *assemble dynamically* via temporal binding
- ✓ representations possess an internal spatiotemporal structure at all levels

Binding with Temporal Code

- Problems of compositionality again—in vision



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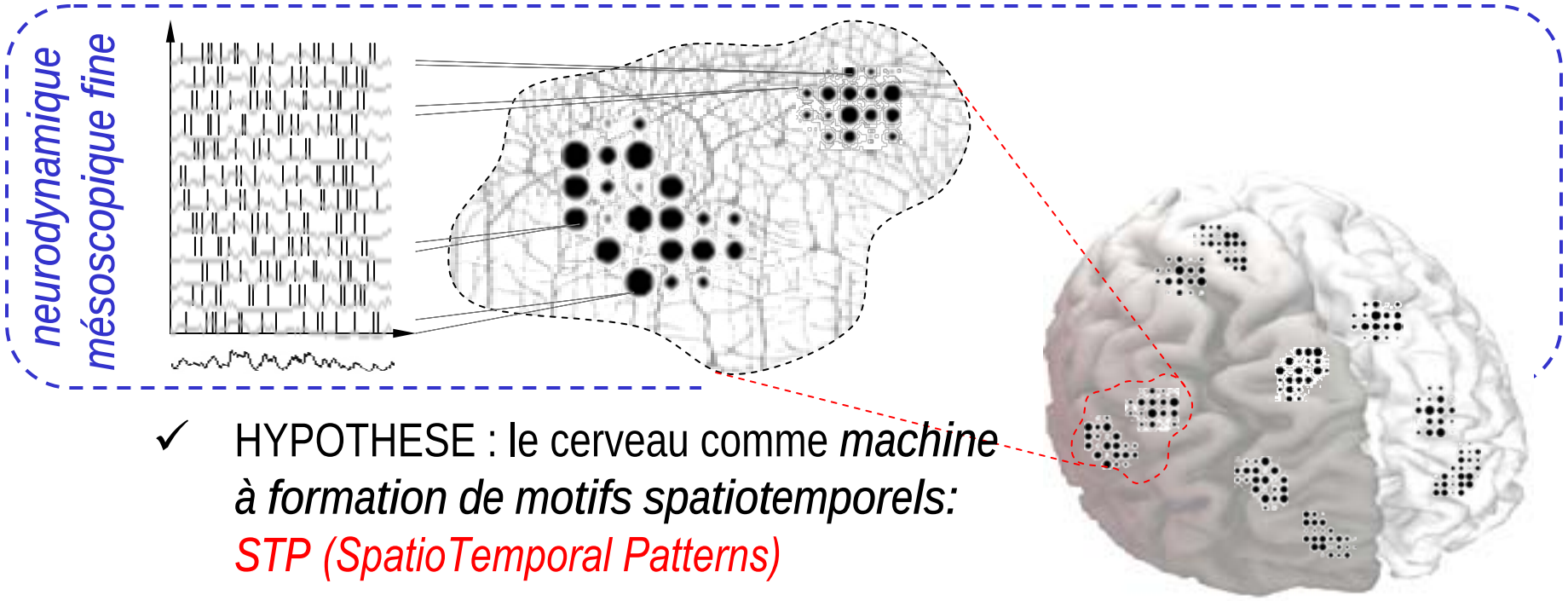
Vers une neurodynamique mésoscopique fine

➢ La richesse dynamique des motifs spatiotemporels

- ✓ des assemblées neuronales dynamiques produisant des régimes complexes d'activité *reproductibles*
- ✓ ces régimes d'activité sont soutenus par une *connectivité récurrente* (plus ou moins) spécifique et ordonnée



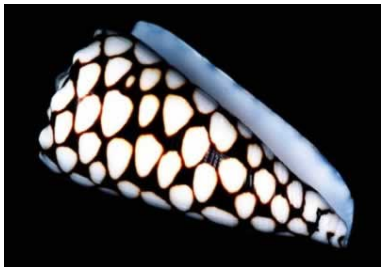
- ✓ HYPOTHESE : le cerveau comme *machine à formation de motifs spatiotemporels:*
  STP (SpatioTemporal Patterns)

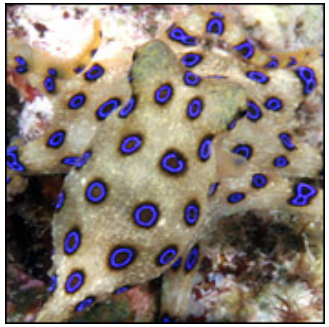
Formation de motifs

➢ Le développement biologique est affaire de motifs

✓ motifs du manteau épithélial, chromatophores, etc.





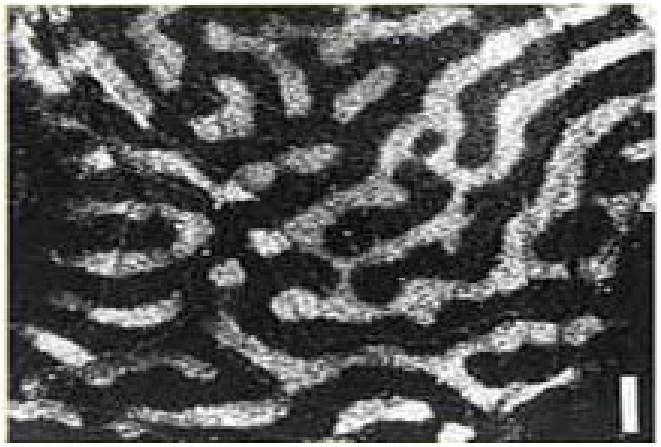



Scott Camazine, http://www.scottcamazine.com

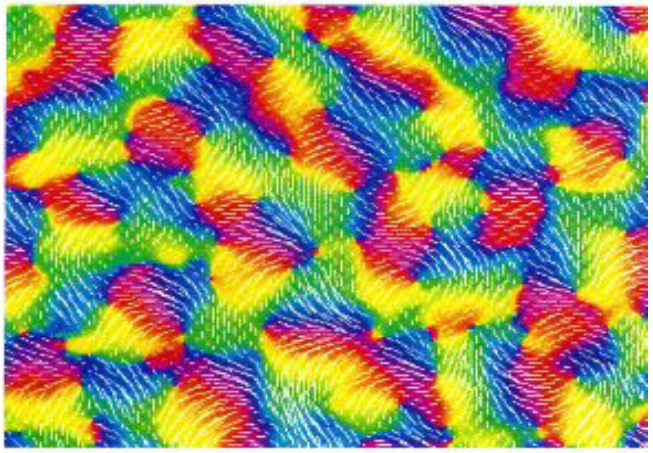
.... en quoi le cerveau serait-il différent?

cartes de connexions, rayures fonctionnelles, etc.

ocular dominance stripes Hubel & Wiesel, 1970



orientation column "pinwheels" Blasdel, 1992

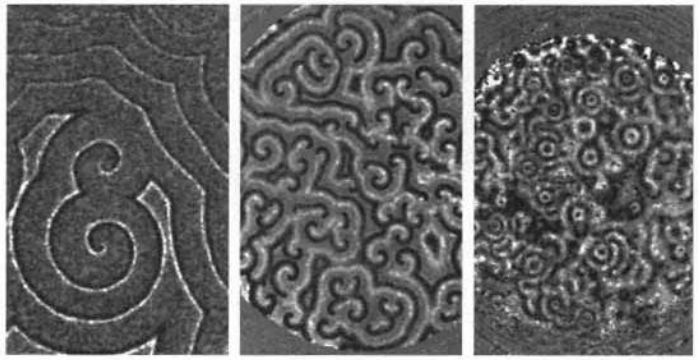


Formation de motifs

➢ La physiologie multicellulaire est aussi affaire de motifs

✓ motifs dynamiques fonctionnels

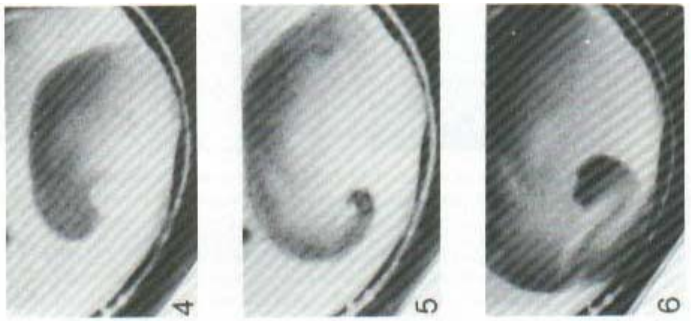
Aggregating slime mold
B. Goodwin, Schumacher College, UK



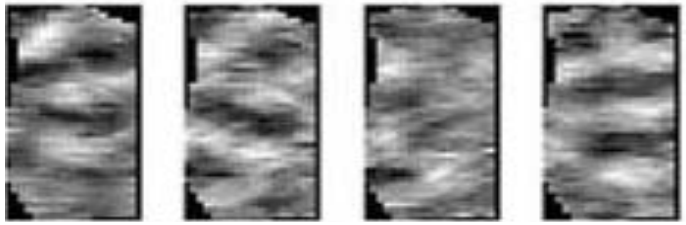
Model of dog heart
J. Keener, University of Utah

.... en quoi le cerveau serait-il différent?
blobs d'activité, ondes progressives, etc.

Chicken retina waves
Gorelova & Bures, 1983



Spontaneous VC activity Grinvald



Olfactory bulb phase pattern W. Freeman

Systems that are self-organized and architectured

free self-organization

the scientific challenge of complex systems: how can they exhibit a true ***architecture?***

Peugeot Picasso

designed architecture

the engineering challenge of complicated systems: how can they integrate ***self-organization?***

Peugeot Picasso

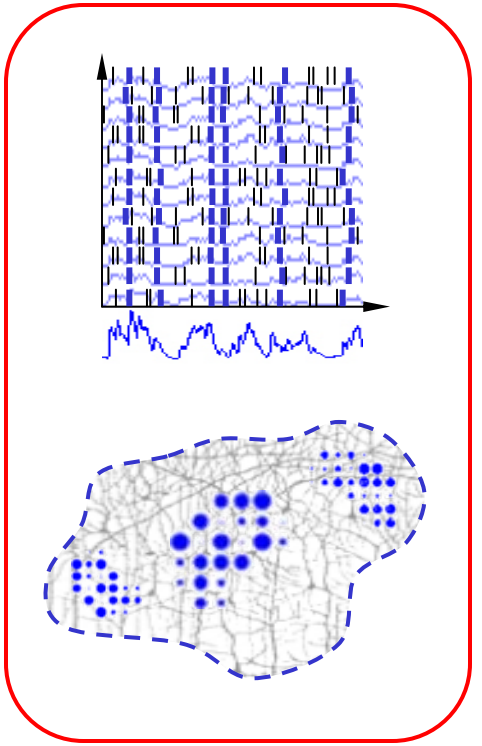
self-organized architecture / architectured self-organization

Le cerveau comme machine morphogénétique

- Vers des nuages de spikes “architecturés” ?

  - ✓ STP non triviales, douées d’une structure

⇔



Entre neurodynamique complexe et cognition

1. Vers une science cognitive unifiée
   Des neurones aux symboles : le niveau mésoscopique manquant

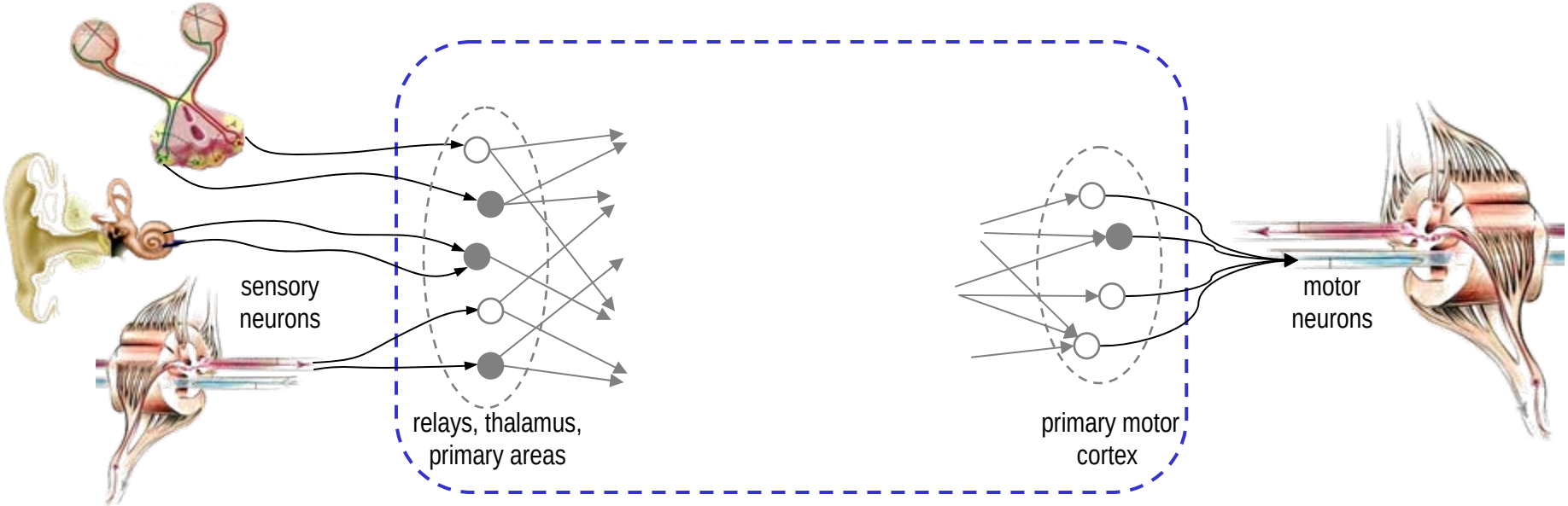
2. L'importance du codage temporel
   Le "binding problem" et les représentations structurées

3. Le cerveau comme machine morphogénétique
   Des objets endogènes façonnables, stimulables et composables

4. **Le paradigme émergent des systèmes complexes**
   Connectivité récurrente, activité spontanée, compositionalité

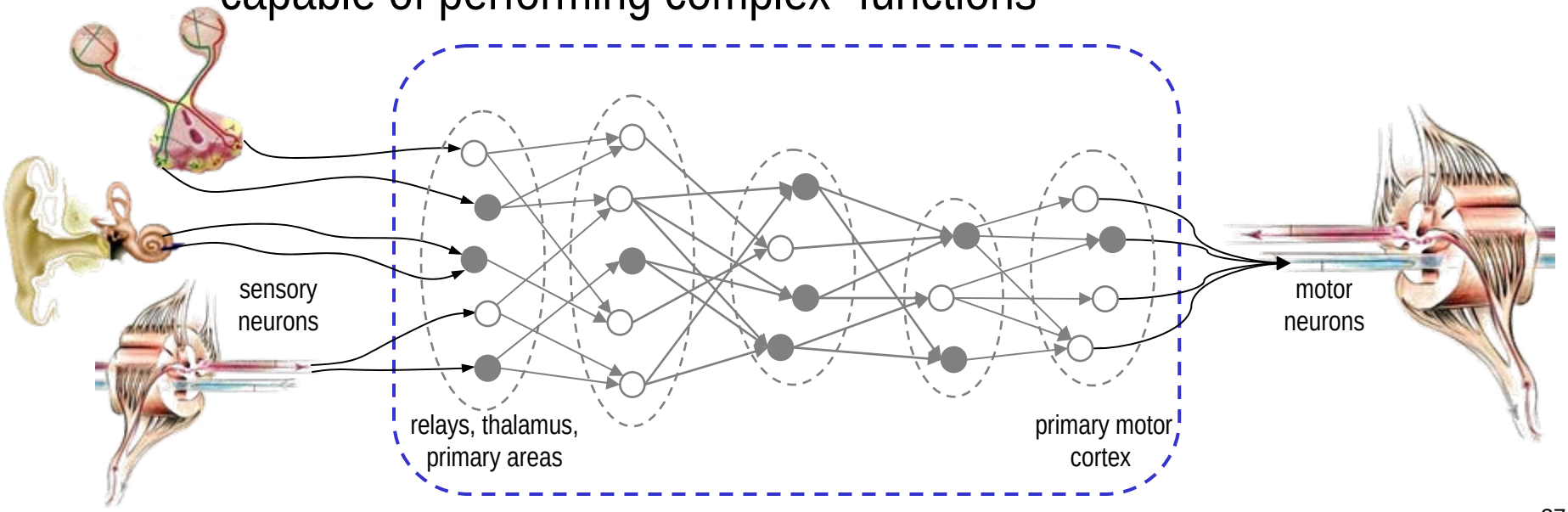
5. Trois études mésoscopiques
   "Tapestry, ponds and RAIN" : synfire chains, ondes et résonance

The litteral informational paradigm



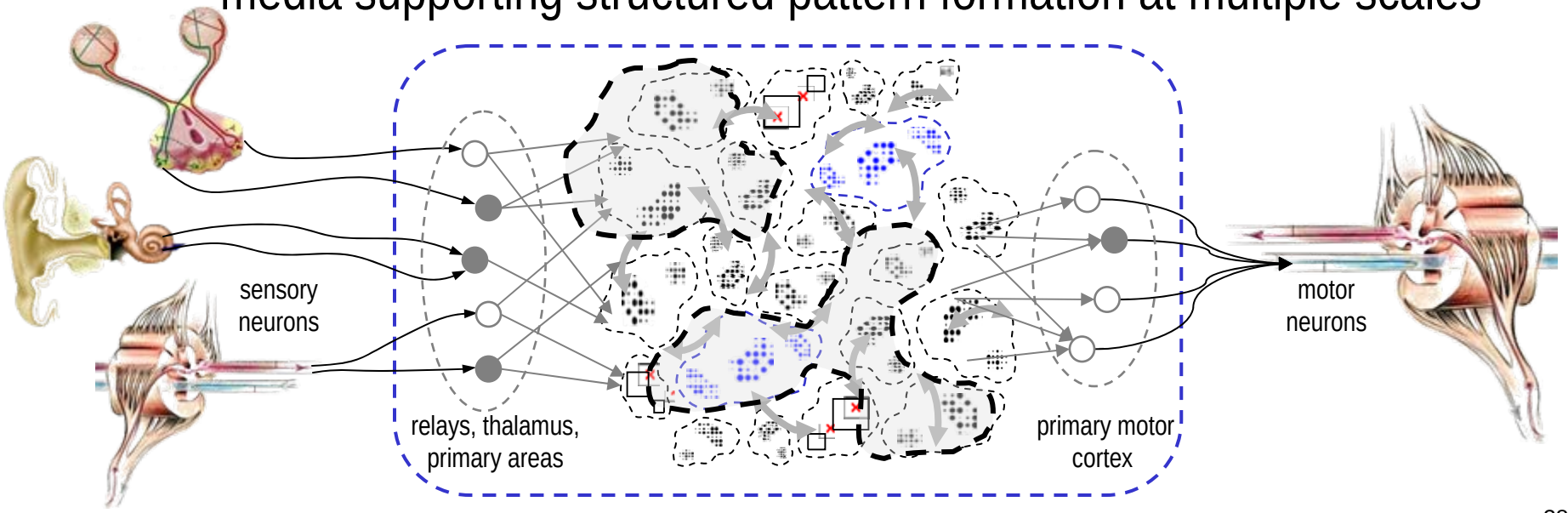
The litteral informational paradigm

- Questionable engineering metaphor: “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”



The emergent dynamical paradigm

- New dynamical metaphor: mesoscopic 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



Entre neurodynamique complexe et cognition

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Vers une neurodynamique complexe

1. Le niveau mésoscopique manquant

2. Trois objets neurodynamiques complexes

a. Une tapisserie auto-tressée de synfire chains

b. Ondes dans une mare morphodynamique

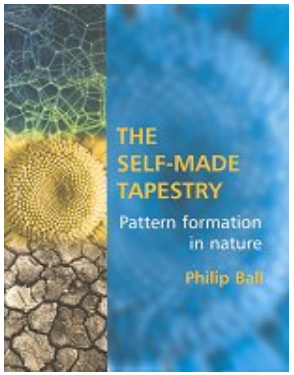
c. Résonance clé-serrure dans des "Recurrent Asynchronous Irregular Networks" (RAIN)

3. Une vue multi-échelle de la causalité neuronale

Tapestries

a) Une tapisserie auto-tressée de synfire chains

→ *constructing the architecture of STPs*

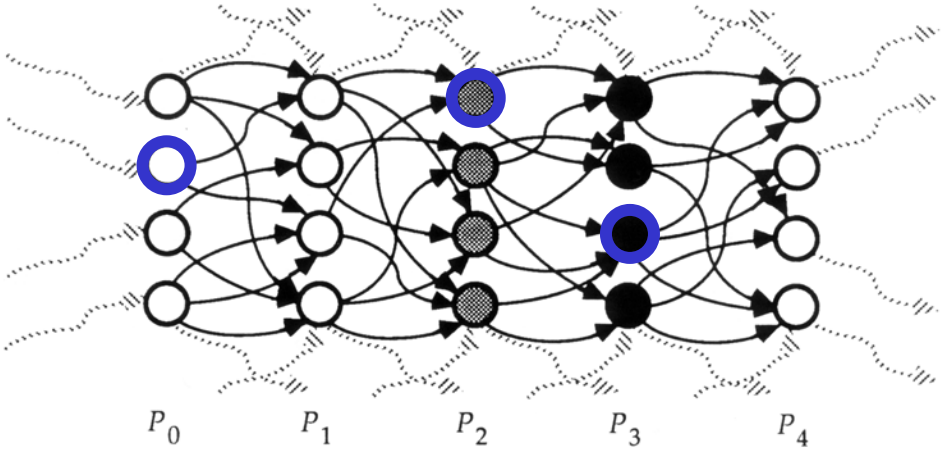


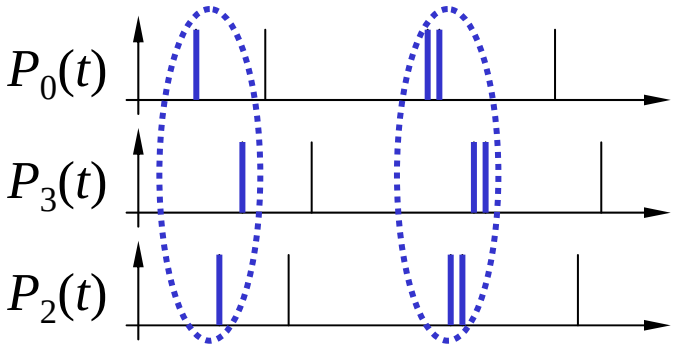
Doursat (1991), Bienenstock (1995), Doursat & Bienenstock (2005)

Tapestries

➢ What is a synfire chain?

- ✓ 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)

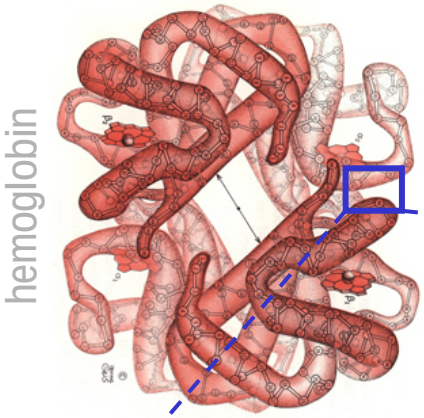




- ✓ synfire chains have been hypothesized to explain neurophysiological recordings containing statistically significant delayed correlations
- ✓ the redundant divergent/convergent connectivity of synfire chains can preserve accurately synchronized action potentials, even under noise

Tapestries

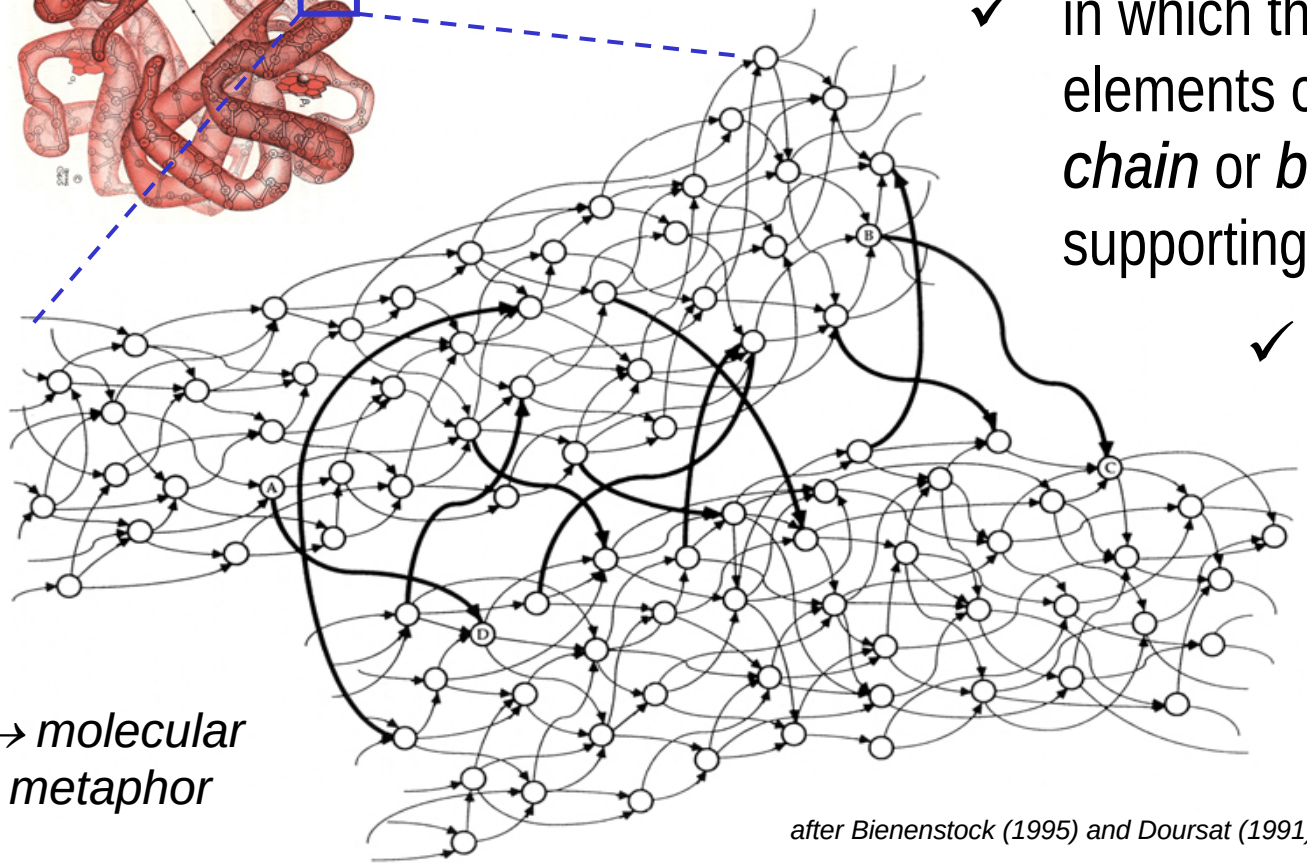
➢ Synfire patterns can *bind*, thus support compositionality



✓ cognitive compositions could be analogous to conformational interactions among proteins...

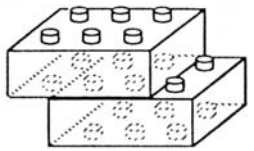
✓ in which the basic "peptidic" elements could be ***synfire chain*** or ***braid*** structures supporting traveling waves

✓ two synfires can bind by synchro-nization through *coupling links*



→ *molecular metaphor*

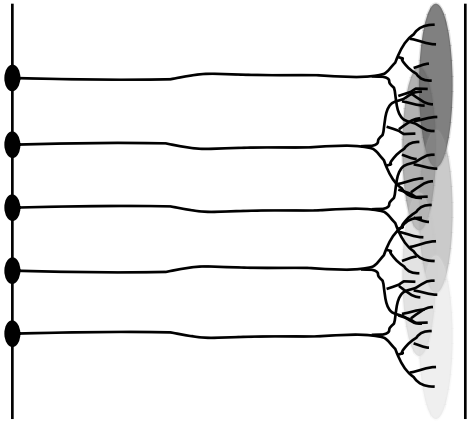
after Bienenstock (1995) and Doursat (1991)



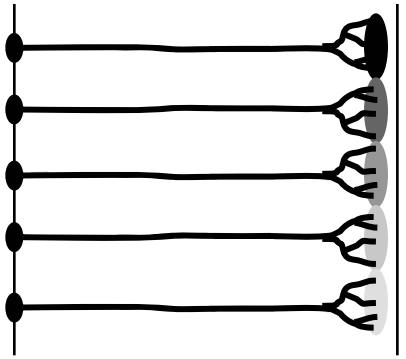
Tapestries

➢ A model of synfire growth: tuning connectivity by activity

- ✓ development akin to the *epigenetic structuration* of cortical maps



focusing of innervation in the retinotopic projection



after Willshaw & von der Malsburg (1976)

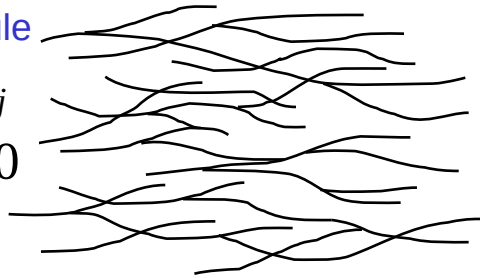
- ✓ in an initially broad and diffuse (immature) connectivity, some synaptic contacts are reinforced (selected) to the detriment of others

1. Hebbian rule

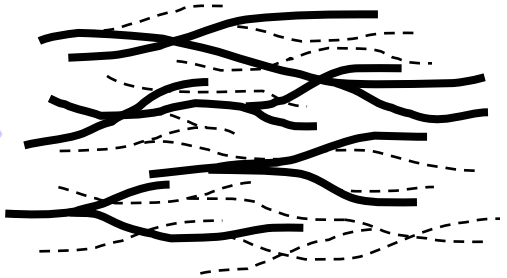
$$\Delta W_{ij} \sim x_i x_j$$

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

2. sum rule



"selective stabilization" by activity/connectivity feedback

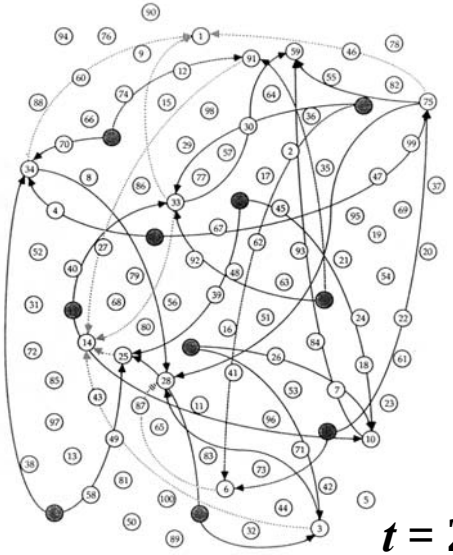


after Changeux & Danchin (1976)

Tapestries

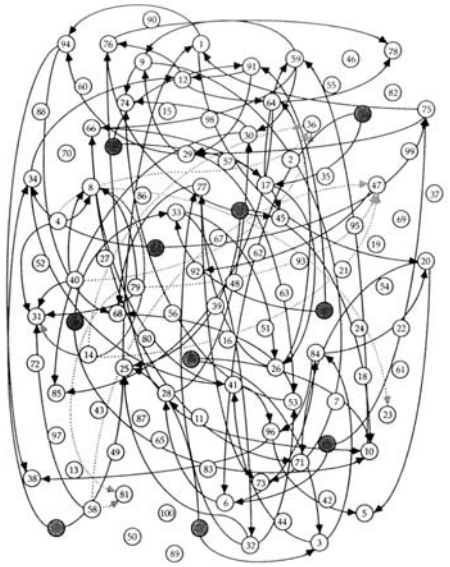
- Synfire chains develop recursively, adding groups 1 by 1

$$\begin{cases} \Delta W_{ij} \sim x_i x_j \\ \sum \Delta W_{ij} \sim 0 \end{cases}$$



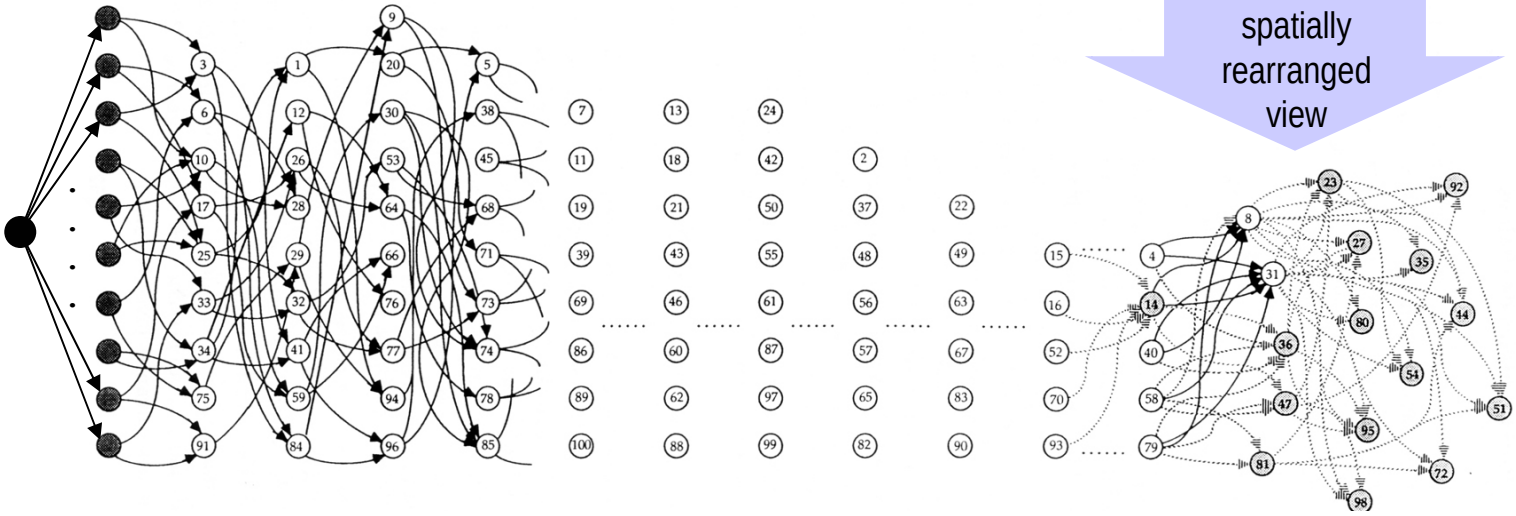
$t = 200$

network **structuration** by accretive synfire growth



$t = 4000$

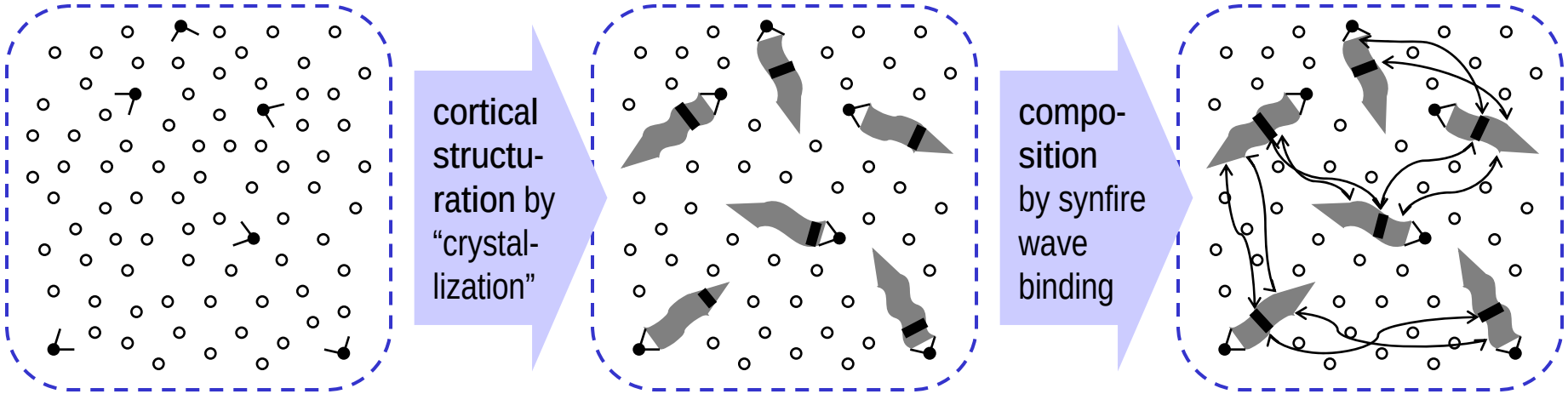
spatially rearranged view



Tapestries

➢ 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



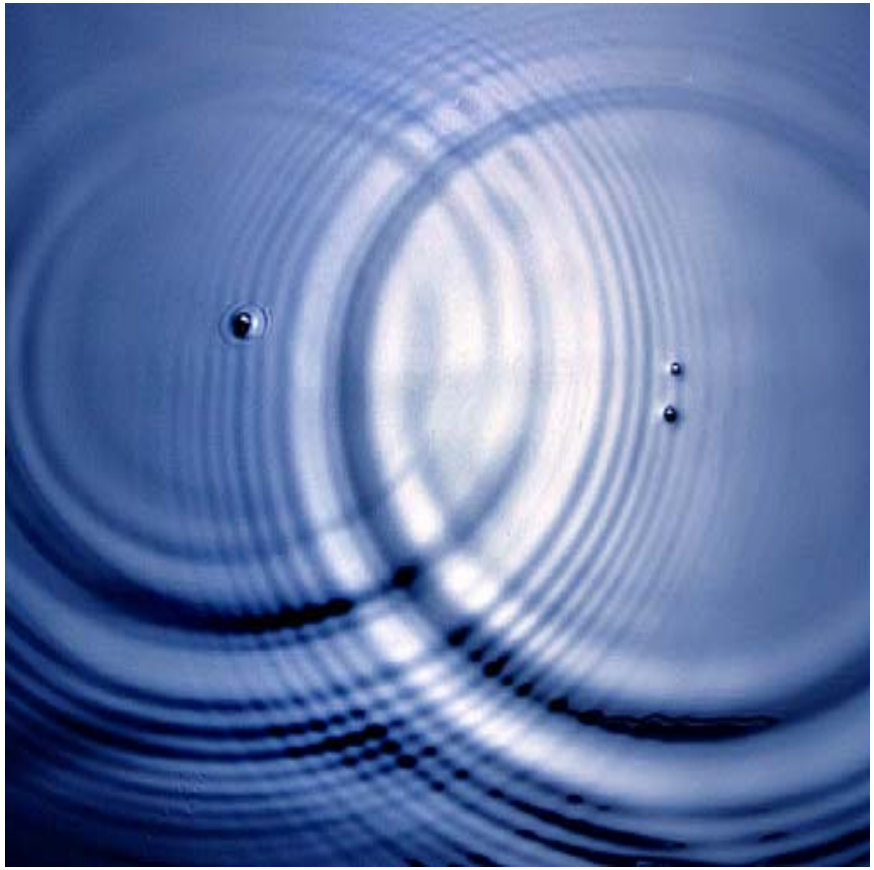
see Bienenstock (1995), Abeles, Hayon & Lehmann (2004), Trengrove (2005)

- ✓ 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
- ✓ dynamical binding & coalescence of multiple synfire waves on this medium provides the basis for compositionality and learning

Ponds

b) Ondes dans une mare morphodynamique

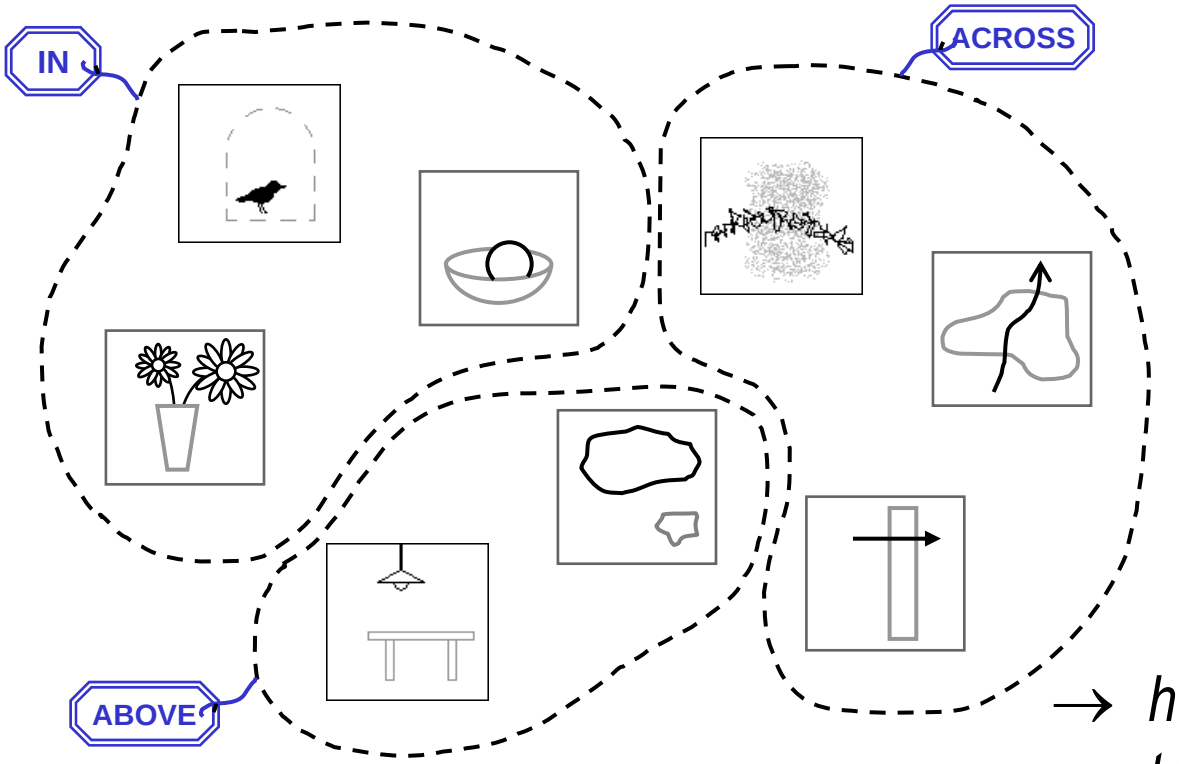
→ *STPs envisionned as excitable media, at criticality*



Doursat & Petitot (1997, 2005)

Ponds

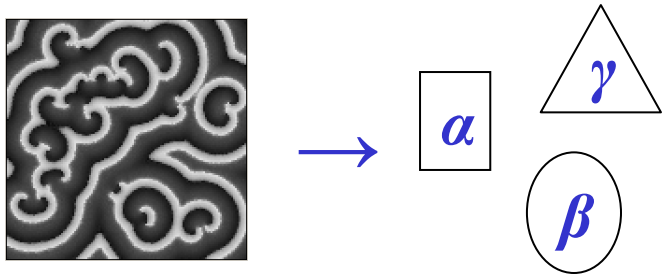
- Linguistic categories: the emergence of a symbolic level
  - ✓ we can map an infinite continuum of scenes to a few spatial labels



perception → language
continuous → discrete
physical, dynamical → symbolic, logic

→ *how are these transforms accomplished by the brain?*

Embodied . . . computation?



schematization

+

categorization

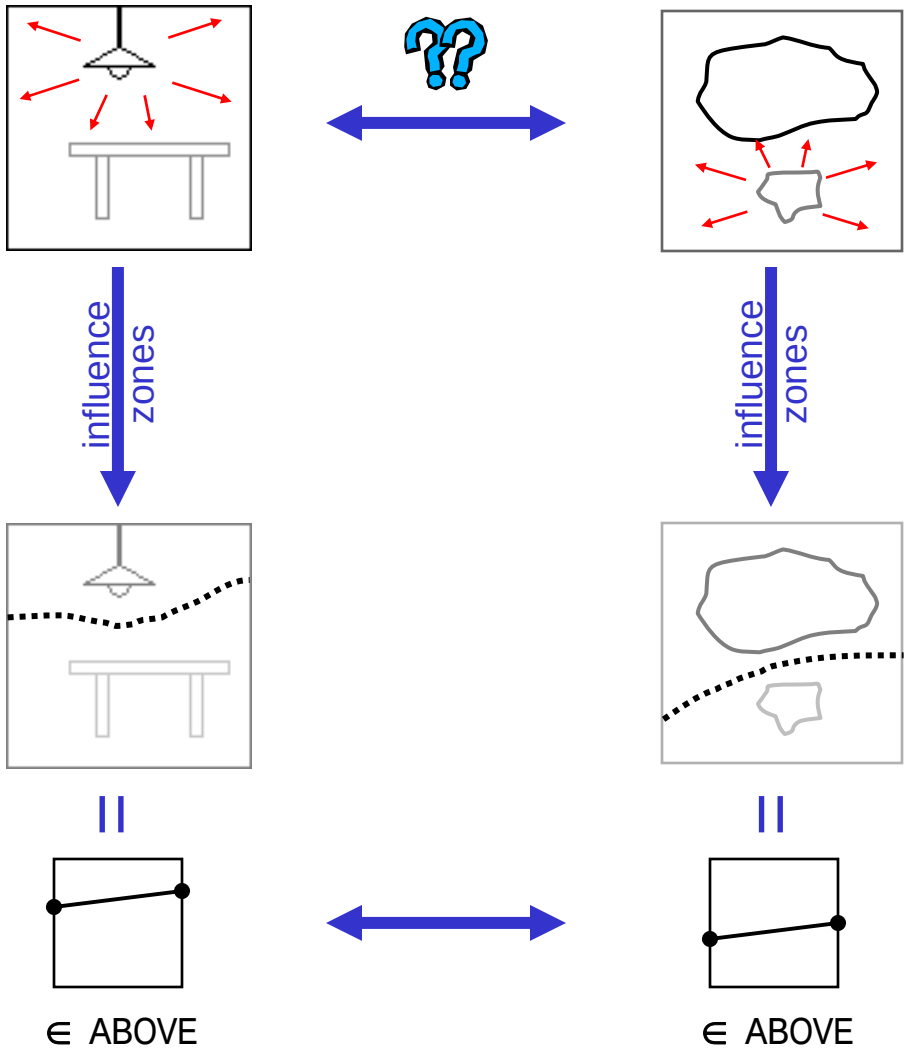
=

drastic reduction of information

- *The loss of a huge amount of physical / dynamical / morphological details in order to produce a few discrete / symbolic units of knowledge corresponds to* schematization *and* categorization.

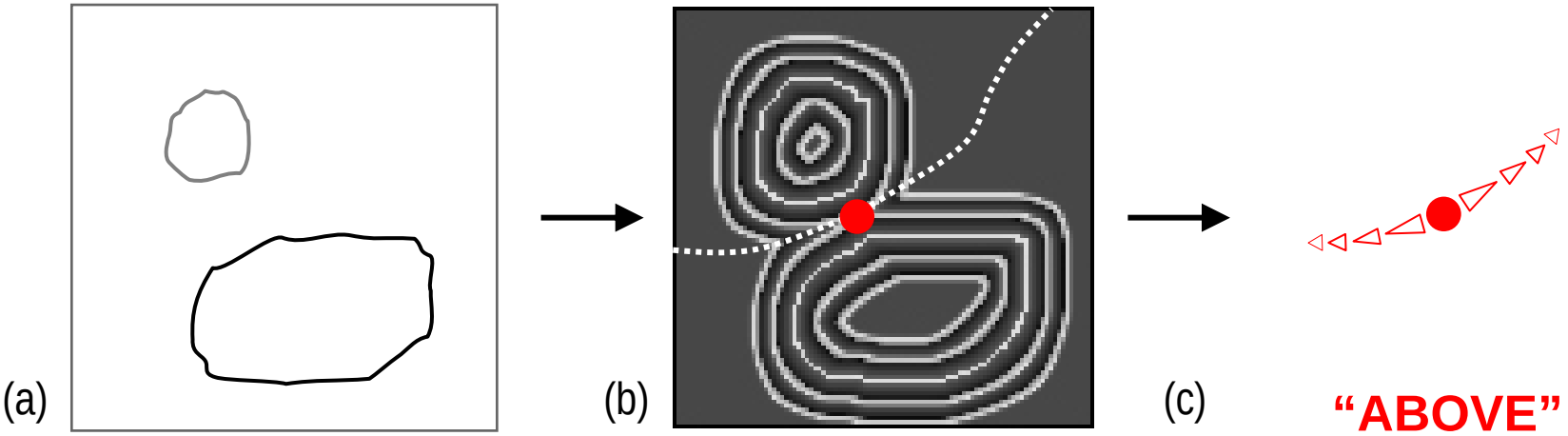
Ponds

- The path to invariance: drastic morphological transforms
  - ✓ scenes representing the same **spatial category** are not directly similar
  - ✓ what can be compared, however, are virtual structures generated by morphological transforms



Ponds

- Proposal: categorizing by morphological neurodynamics
  - ✓ discrete *symbolic* information could *emerge* in the form of *singularities* created by pattern formation in a large-scale complex dynamical system (namely, the cortical substrate)

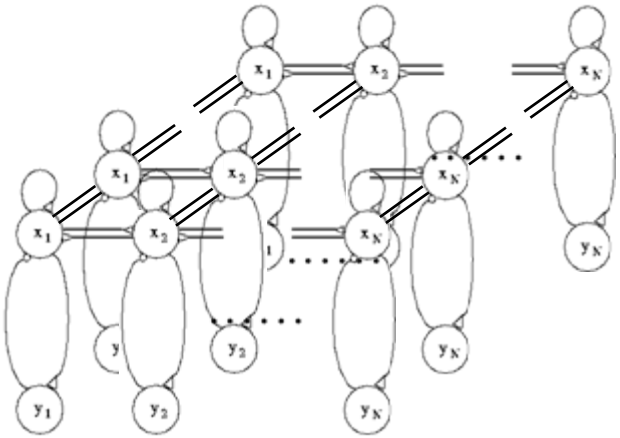


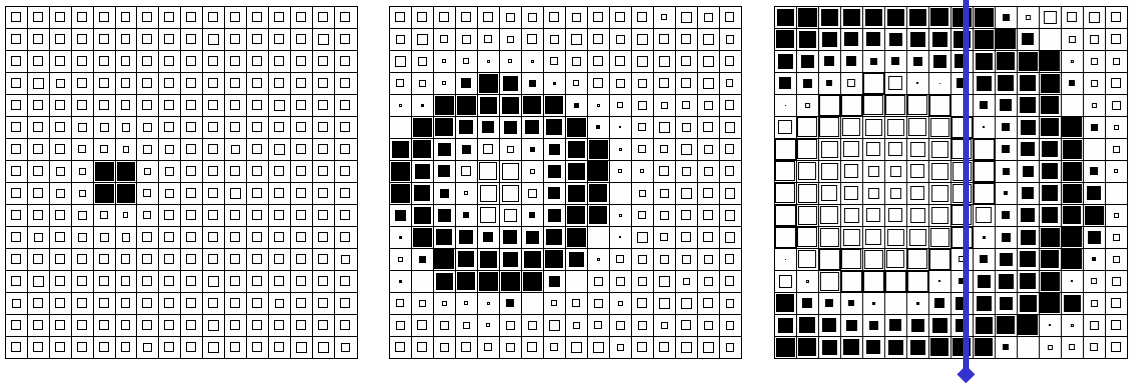
  - ✓ for ex: in *traveling waves*, singularities are collision points
  - ✓ (a) under the influence of an external input, (b) the internal dynamics of the system (c) spontaneously creates singularities that are characteristic of a symbolic category

Ponds

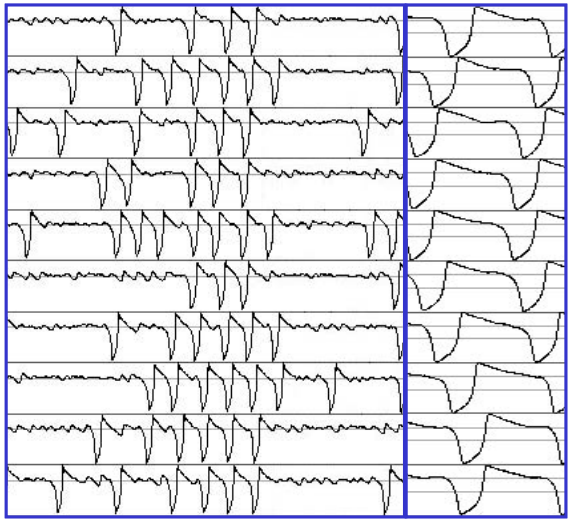
➢ Spiking neural networks as excitable media

- ✓ ex: “grass-fire” wave on a lattice of Bonhoeffer-van der Pol units



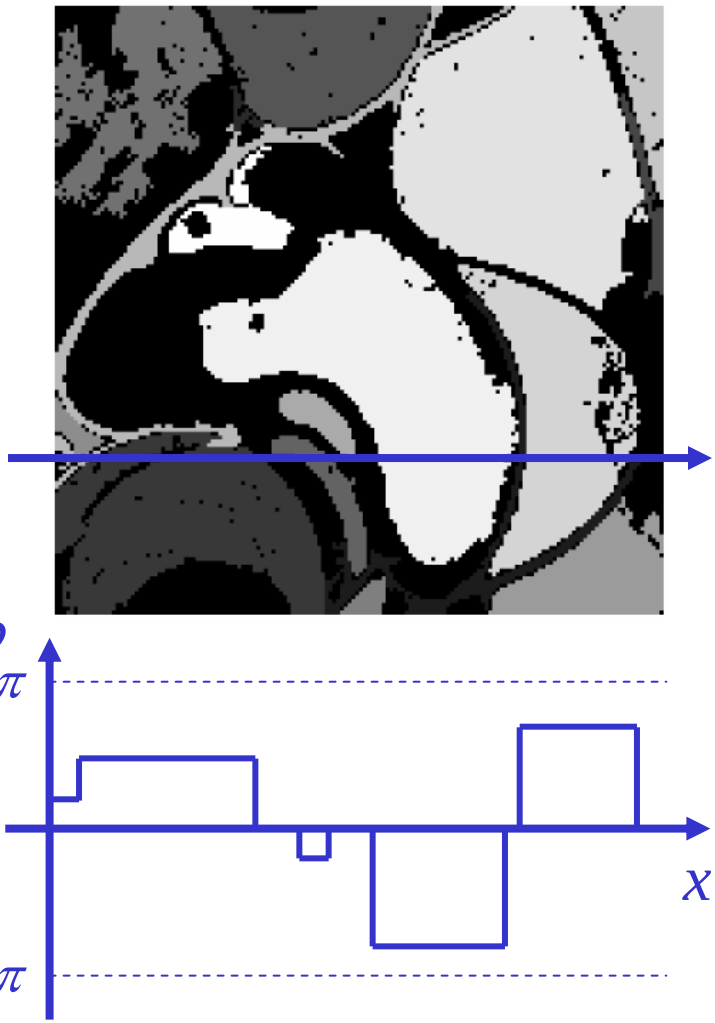


- ✓ *criticality* in neural dynamics: when slightly perturbed by an input, the network quickly transitions into a new regime of spatiotemporal order
- ✓ the structure and singularities of this regime are *influenced* by the input

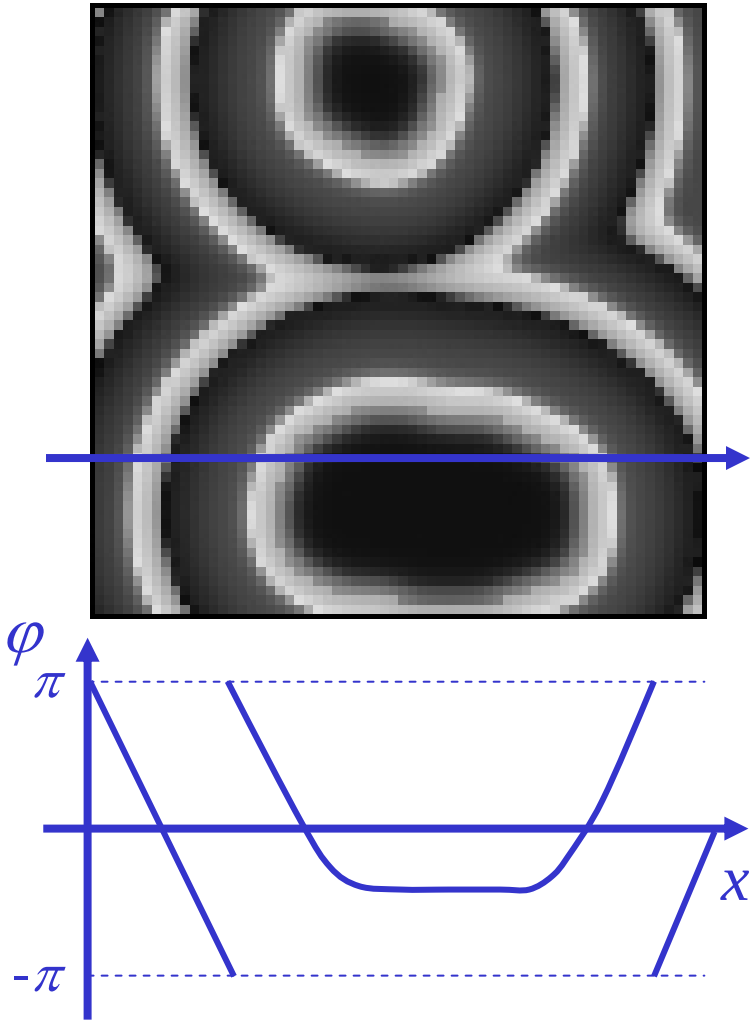


Instead of group synchronization: traveling waves

Instead of phase plateaus: phase gradients



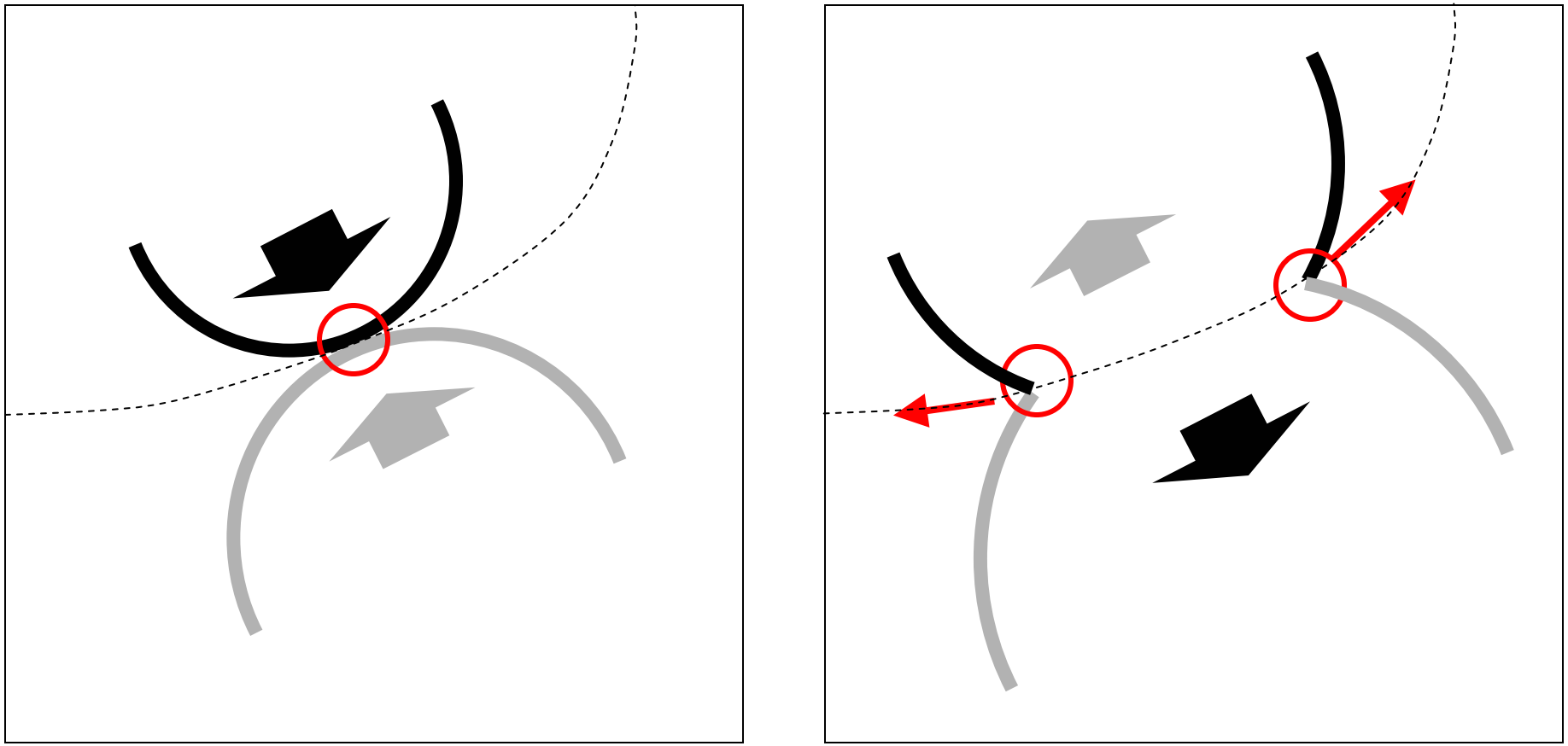
Wang, D. L. & Terman, D. (1997) Image segmentation based on oscillatory correlation. *Neural Computation*, 9: 805-836,1997



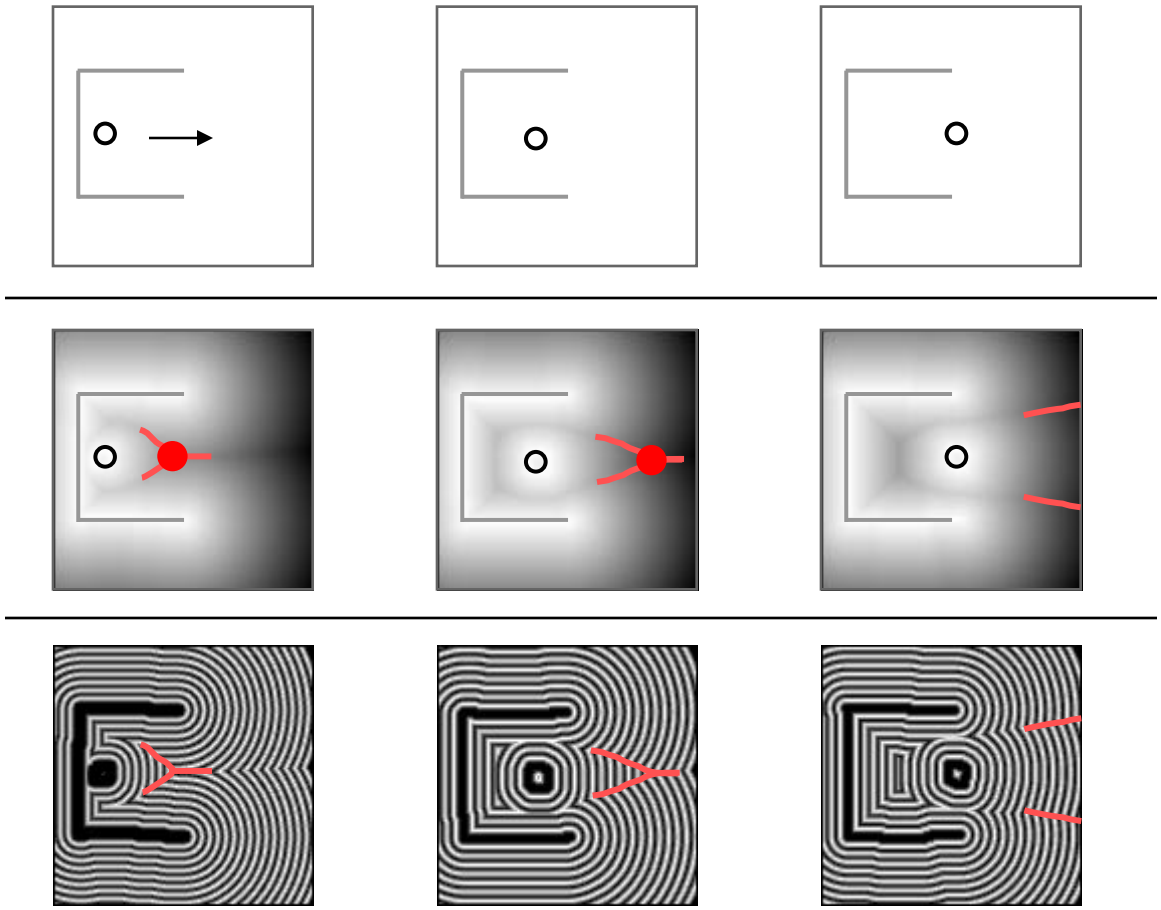
Doursat, R., & Petitot, J. (2005b) Dynamical models and cognitive linguistics: Toward an active morphodynamical semantics. To appear in *Neural Networks* (special issue on *IJCNN 2005*)

Spiking neural model supporting traveling waves

Detection of singular points



Dynamic evolution of singularities



“OUT OF”

- *The movie-scenario “out of” is revealed by a bifurcation: the singularity (red) disappears as the ball (black) exits the interior of the box; this is a robust phenomenon largely independent from the shape of the actors.*

Ponds

➢ Summary: key points of the morphodynamic hypothesis

- ✓ input stimuli literally “boil down” to a handful of critical features through the intrinsic pattern formation dynamics of the system

- ✓ these singularities reveal the characteristic “signature” of the stimulus’ category (e.g., the spatial relationship represented by the image)

→ *key idea: spatiotemporal singularities are able to encode a lot of the input’s information in an extremely compact and localized manner*

RAIN

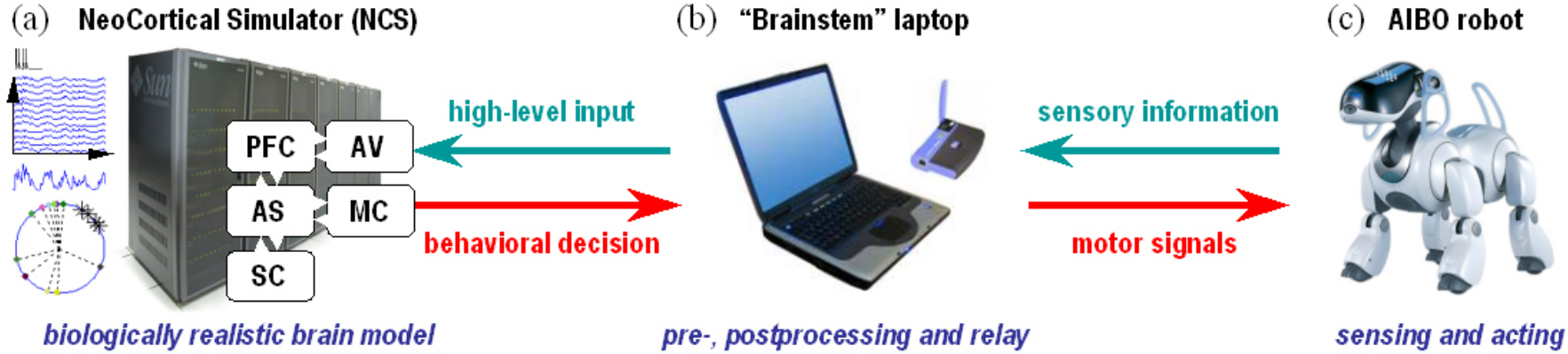
c) Résonance clé-serrure dans des RAIN Networks

→ *pattern recognition by specialized STPs*

Doursat & Goodman (2006), Goodman, Doursat, Zou et al. (2007)

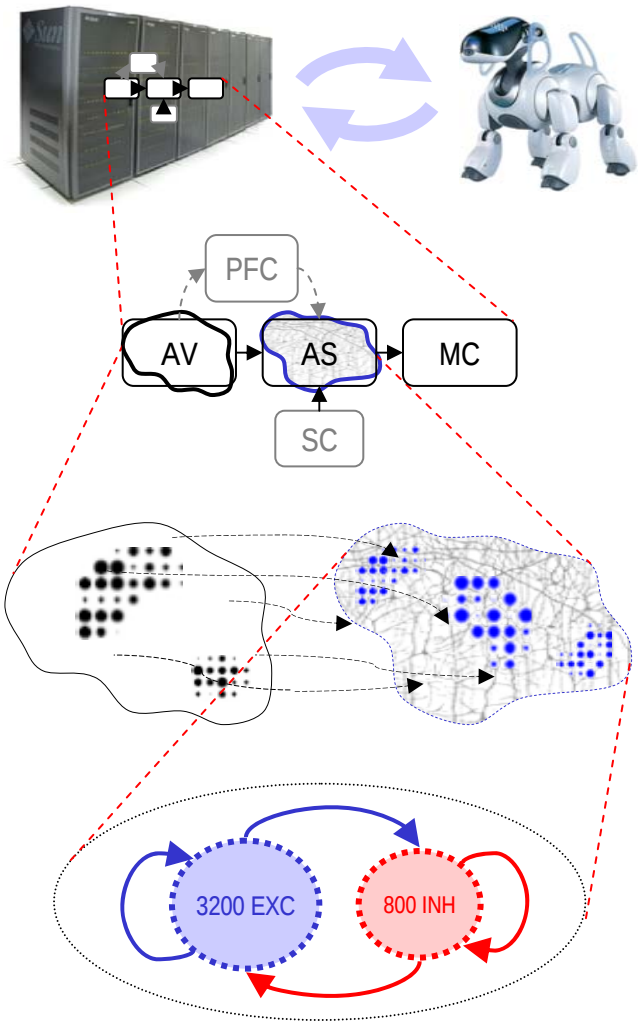
RAIN

- Complete sensorimotor loop between cluster and robot
  - ✓ original attempt to implement a real-time, embedded neural robot
  - c) a robot (military sentry, industrial assistant, etc.) interacts with environment and humans via sensors & actuators
  - a) NeoCortical Simulator (NCS) software runs on computer cluster; contains the brain architecture for decision-making and learning
  - b) "brainstem" laptop brokers WiFi connection: transmits multimodal sensory signals to NCS; sends actuator commands to robot



RAIN

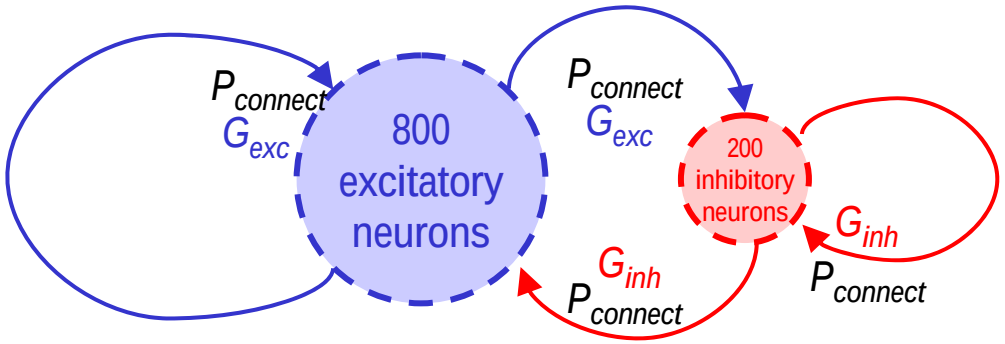
- Core of brain model: mesoscopic assemblies as RAINs

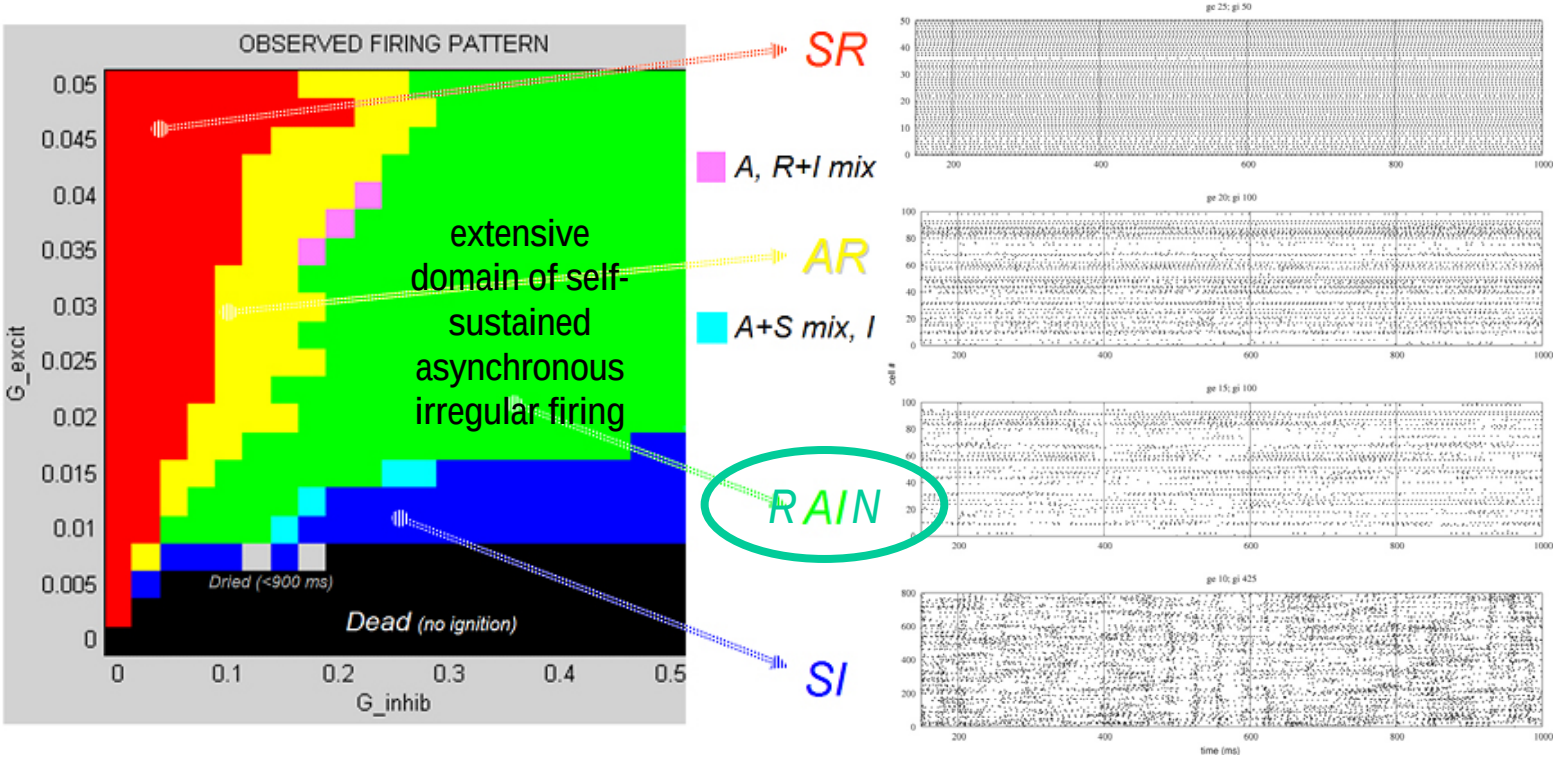


RAIN: Recurrent Asynchronous Irregular Network

RAIN

➢ Recurrent Asynchronous Irregular Network (RAIN)

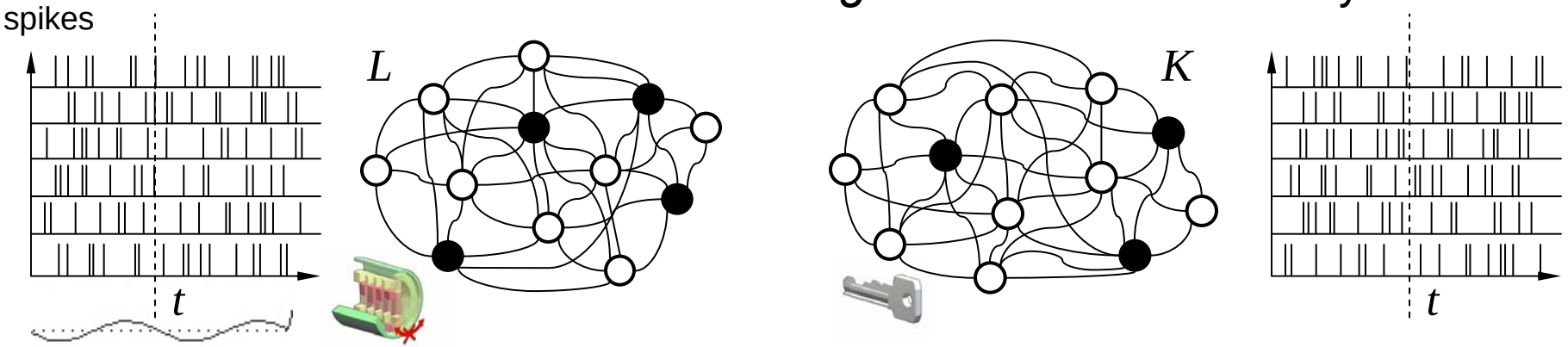




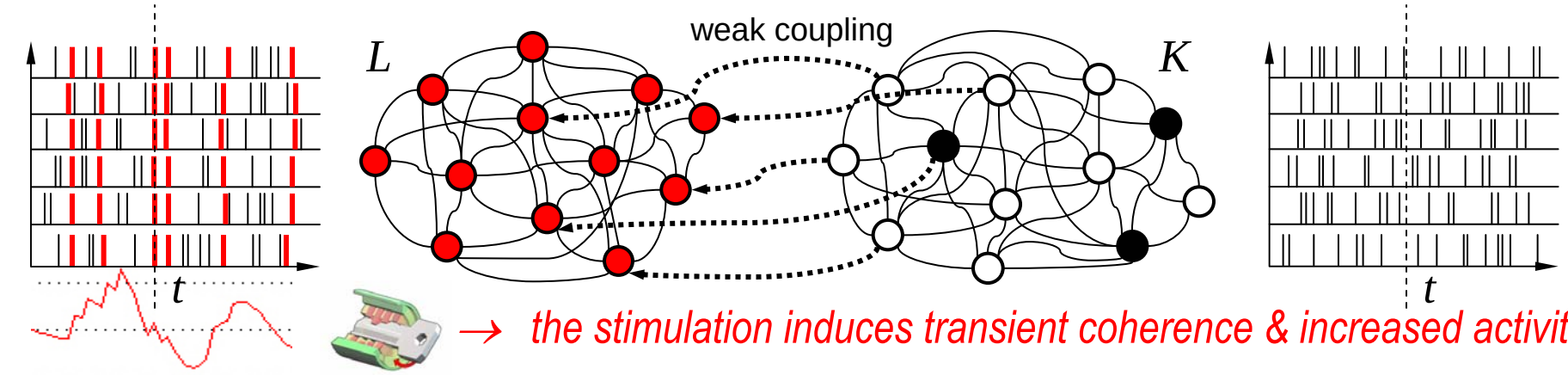
RAIN

➢ Coherence induction between RAIN networks

- ✓ spatiotemporal pattern "resonance" among ongoing active STPs
- ✓ subnetwork L alone has *endogenous modes* of activity



- ✓ by stimulating L, K "*engages*" (but does not create) L's modes

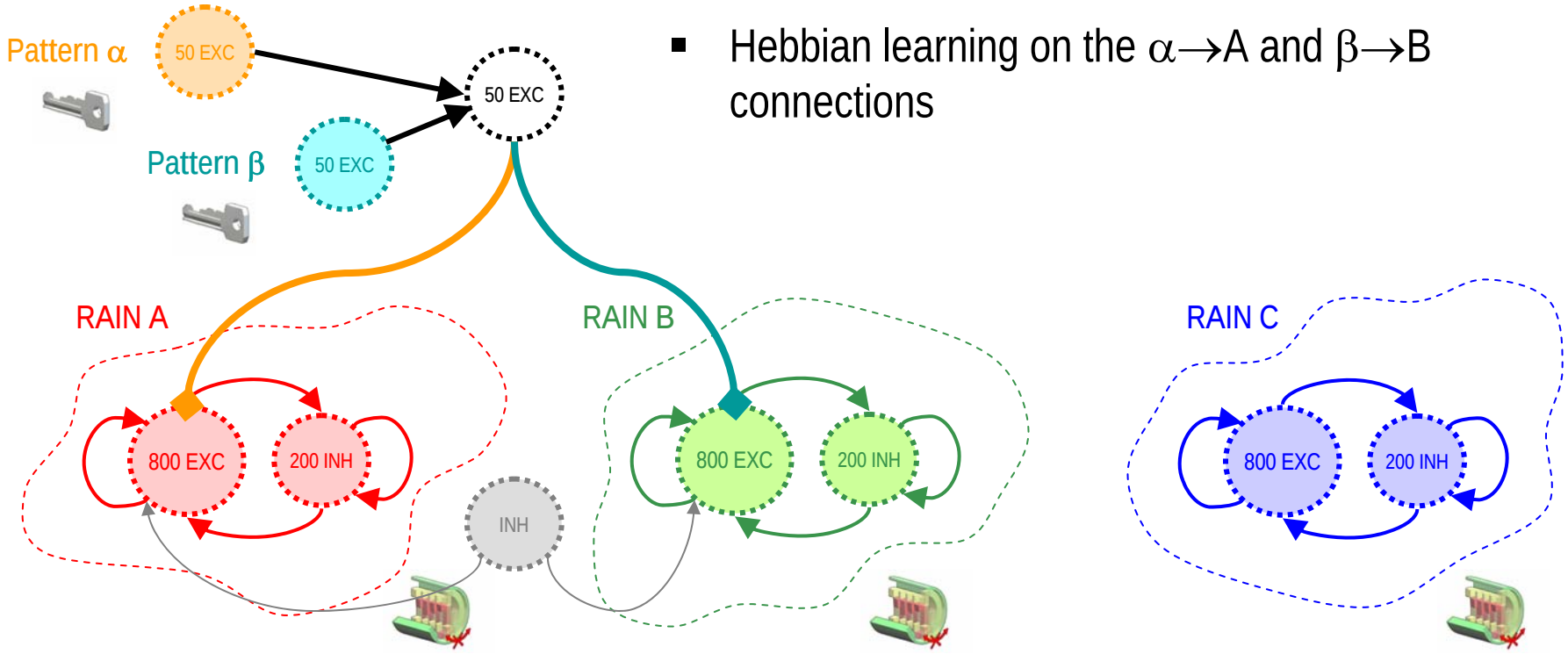


→ *the stimulation induces transient coherence & increased activity*

RAIN

➢ Multi-RAIN discriminate Hebbian/STDP learning (setup)

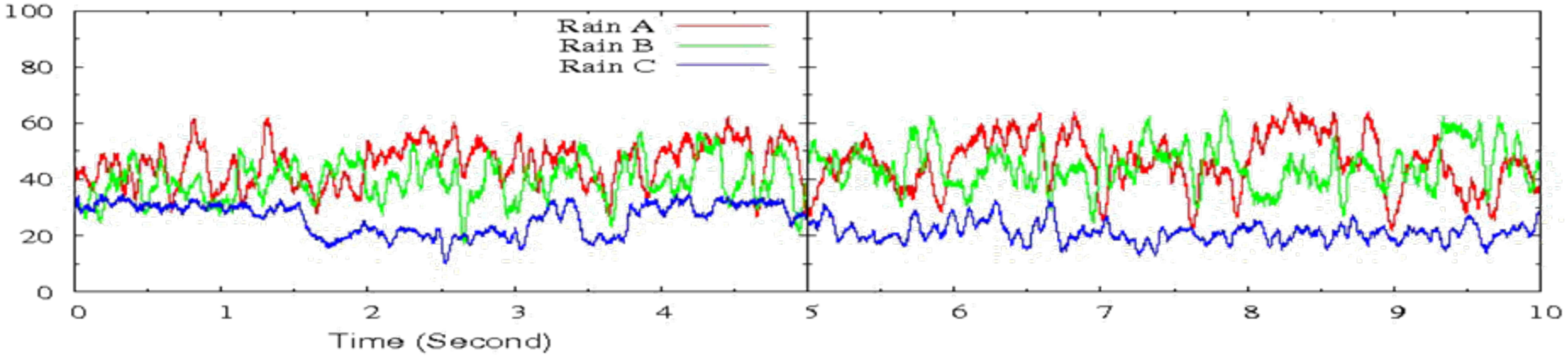
- ✓ numerical experiment involving
  - 2 RAINs, A and B stimulated by 2 patterns, α and β (RAIN extracts)
  - 1 control RAIN, C (not stimulated) and 1 control pattern γ (not learned)
  - 1 inhibitory pool common to A and B
  - Hebbian learning on the $\alpha \rightarrow$A and $\beta \rightarrow$B connections



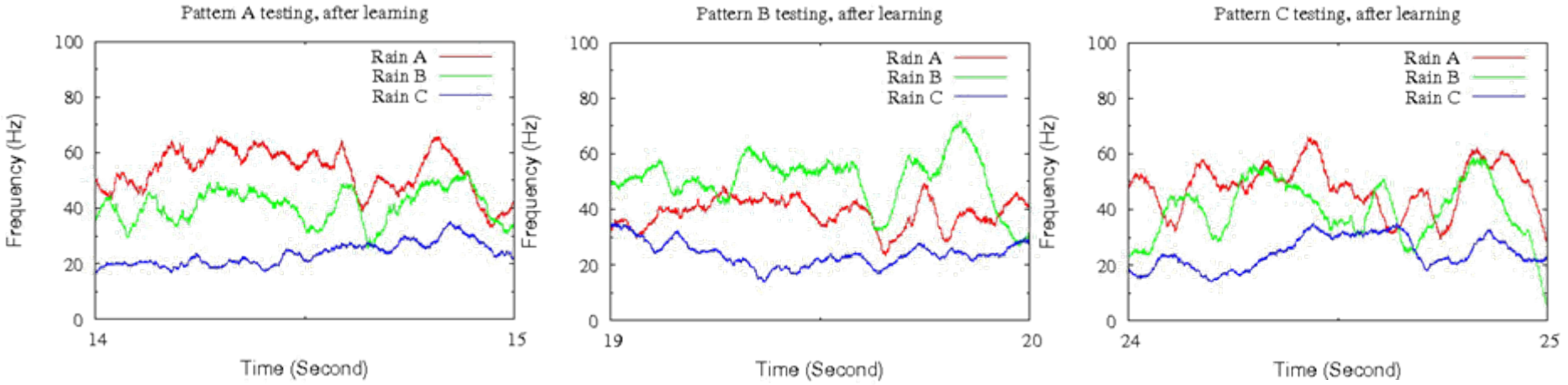
RAIN

➢ Multi-RAIN discriminate Hebbian/STDP learning (results)

✓ training phase: alternating α-learning on A and β-learning on B



✓ testing phase: A's (rsp B's) response to α (rsp β) significantly higher



Entre neurodynamique complexe et cognition

1. Vers une science cognitive unifiée
   Des neurones aux symboles : le niveau mésoscopique manquant

2. L'importance du codage temporel
   Le "binding problem" et les représentations structurées

3. Le cerveau comme machine morphogénétique
   Des objets endogènes façonnables, stimulables et composables

4. Le paradigme émergent des systèmes complexes
   Connectivité récurrente, activité spontanée, compositionalité

5. Trois études mésoscopiques
   "Tapestry, ponds and RAIN" : synfire chains, ondes et résonance