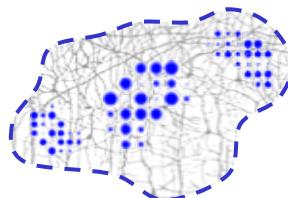


"Tapestries, Ponds and RAIN"

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



René Doursat

<http://doursat.free.fr>

Entre neurodynamique complexe et cognition

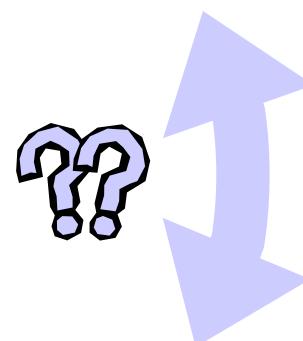
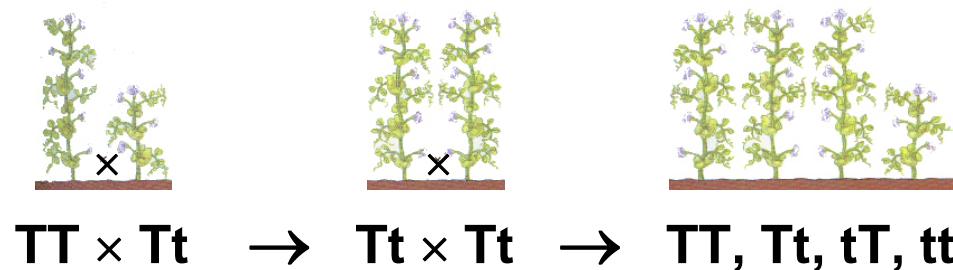
1. Vers une science cognitive unifiée
Des neurones aux symboles : le niveau mésoscopique manquant
2. L'importance du codage temporel
Le “binding problem” et les représentations structurées
3. Le cerveau comme machine morphogénétique
Des objets endogènes façonnables, stimulables et composables
4. Le paradigme émergent des systèmes complexes
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“Tapestry, ponds and RAIN” : synfire chains, ondes et résonance

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

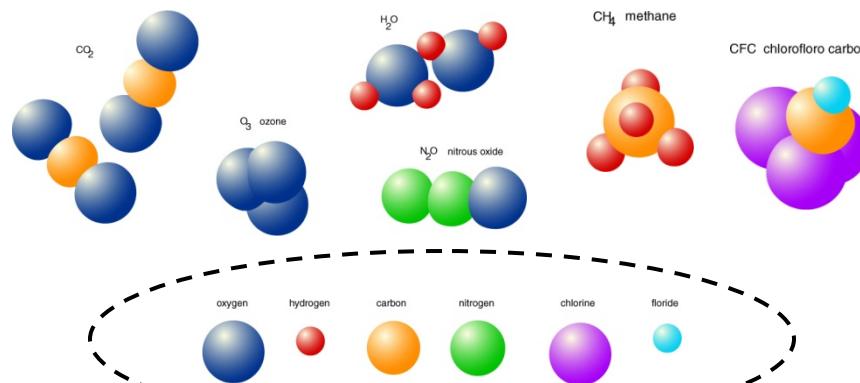
- I.A. : symboles, syntaxe → règles de production
 - ✓ *les systèmes logiques* définissent des *symboles* de haut niveau qui peuvent être *composés* de façon générative
 - *il leur manque une “microstructure” fine, nécessaire pour expliquer la catégorisation floue en perception, contrôle moteur, apprentissage, 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 : noeuds, liens → règles d'activation
 - ✓ dans les *systèmes dynamiques* neuro-inspirés, les *noeuds* d'un réseau *s'activent* mutuellement par association
 - *il leur manque une “macrostructure”, nécessaire pour expliquer la compositionnalité systématique du langage, du raisonnement, de la cognition*

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

*niveau macro :
lois génétiques*

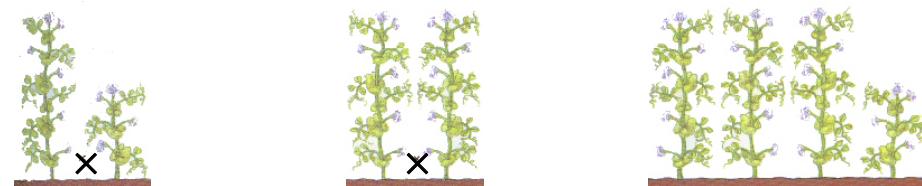


*niveau micro :
atomes*



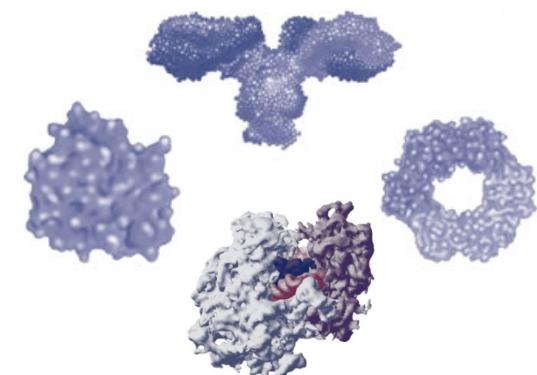
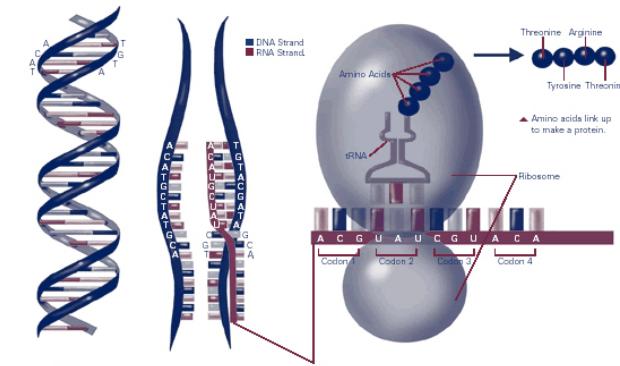
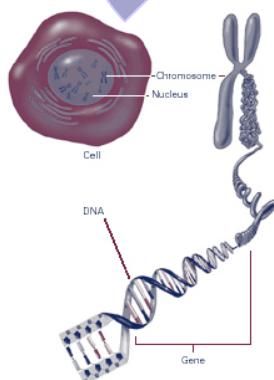
L'état des sciences naturelles au XX^{ème} siècle

*niveau macro :
lois génétiques*

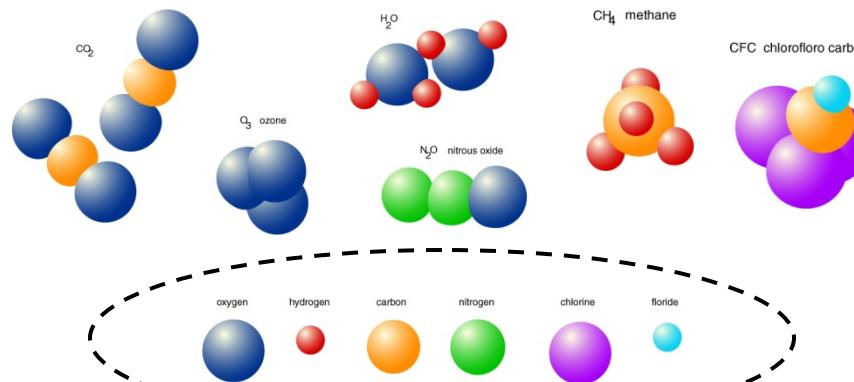


$$TT \times Tt \rightarrow Tt \times Tt \rightarrow TT, Tt, tT, tt$$

*niveau méso :
biologie moléc.*



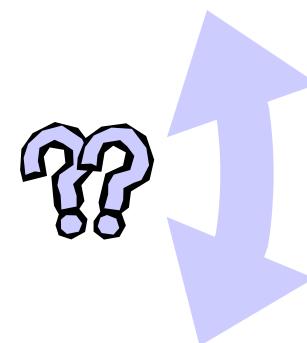
*niveau micro :
atomes*



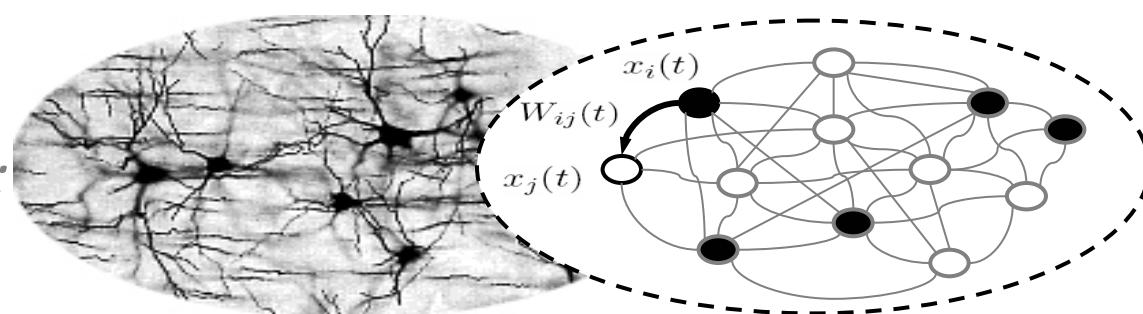
→ *système complexe multi-échelle*

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?

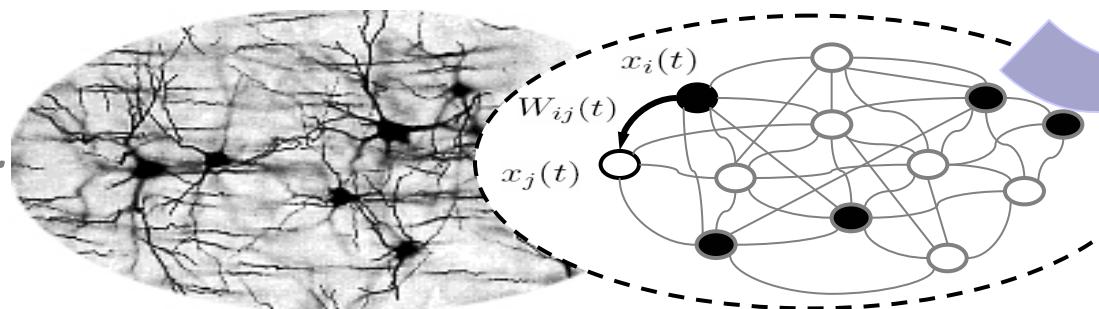
niveau macro :
symboles

“John donne un livre à Mary” → “Mary possède le livre”

niveau mésò :
“cognition moléc.”



niveau micro :
neurones



→ système complexe multi-échelle

Vers une science cognitive unifiée

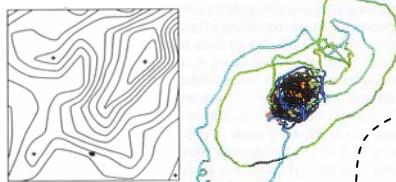
- Pour expliquer des phénomènes macroscopiques à partir d'éléments microscopiques, des structures mésoscopiques sont nécessaires
 - ✓ pour expliquer et prédire les règles symboliques de la génétique à partir des atomes, la *biologie moléculaire* est nécessaire
 - ✓ de même, pour expliquer et prédire les règles symboliques du langage et de la perception (catégorisation, hiérarchie, inférence, composition) à partir des activités neuronales, une nouvelle discipline de “*cognition moléculaire*” est nécessaire
- Que pourraient donc être les “macromolécules” d'une future science cognitive unifiée ?

Niveau mésoscopique de champs moyens

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

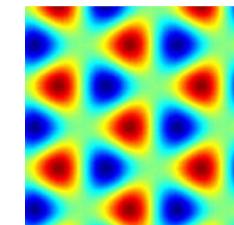
méso-niveau de champs moyens

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.

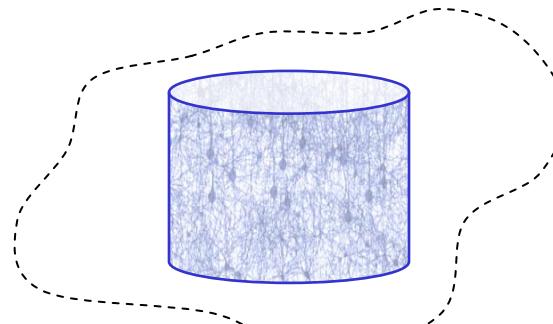
Niveau mésoscopique de spikes

➤ 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*

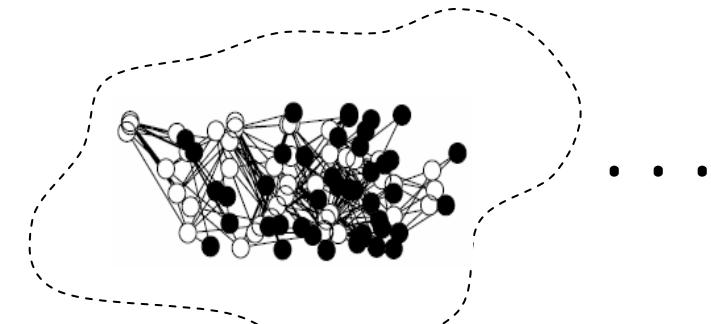
méso-niveau de spikes

BlueColumn (BlueBrain)



Markram (2006)

groupes polychrones



Izhikevich (2006)

Niveau mésoscopique de spikes

➤ 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*



tapestries



ponds



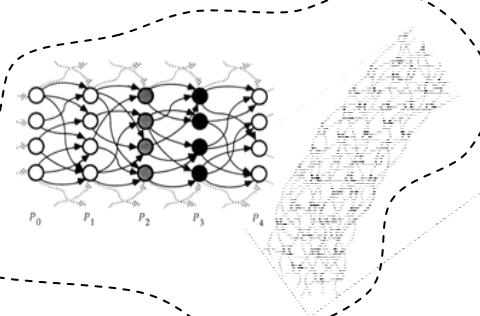
RAIN

méso-niveau de spikes

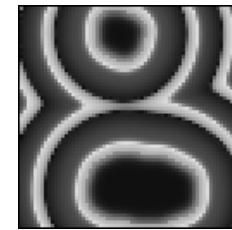
“synfire chains” et tresses

ondes morphodynamiques

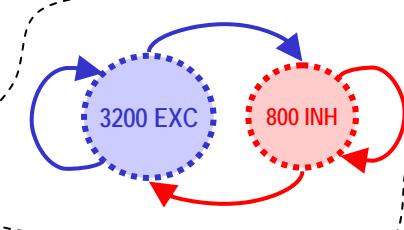
résonance “clé-serrure”



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



Doursat & Petitot (1997, 2005)



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

Entre neurodynamique complexe et cognition

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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

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

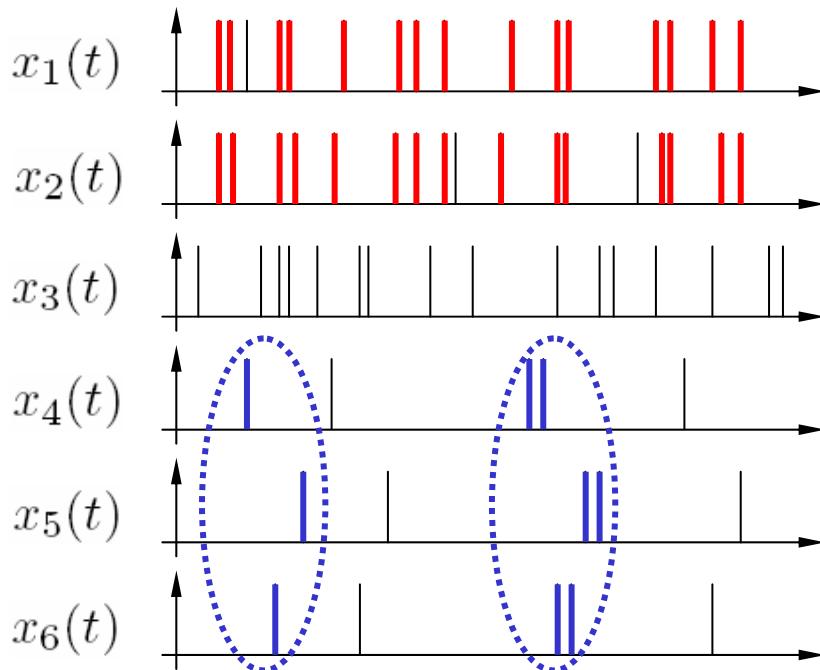
$$\langle x_i(t) x_j(t - \tau_{ij}) \rangle$$

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

Temporal coding vs. rate coding

➤ Below mean firing-rate coding: precise temporal coding

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



temporal coding

$\langle x_1(t) \rangle =$	●	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

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

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

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

➤ 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*

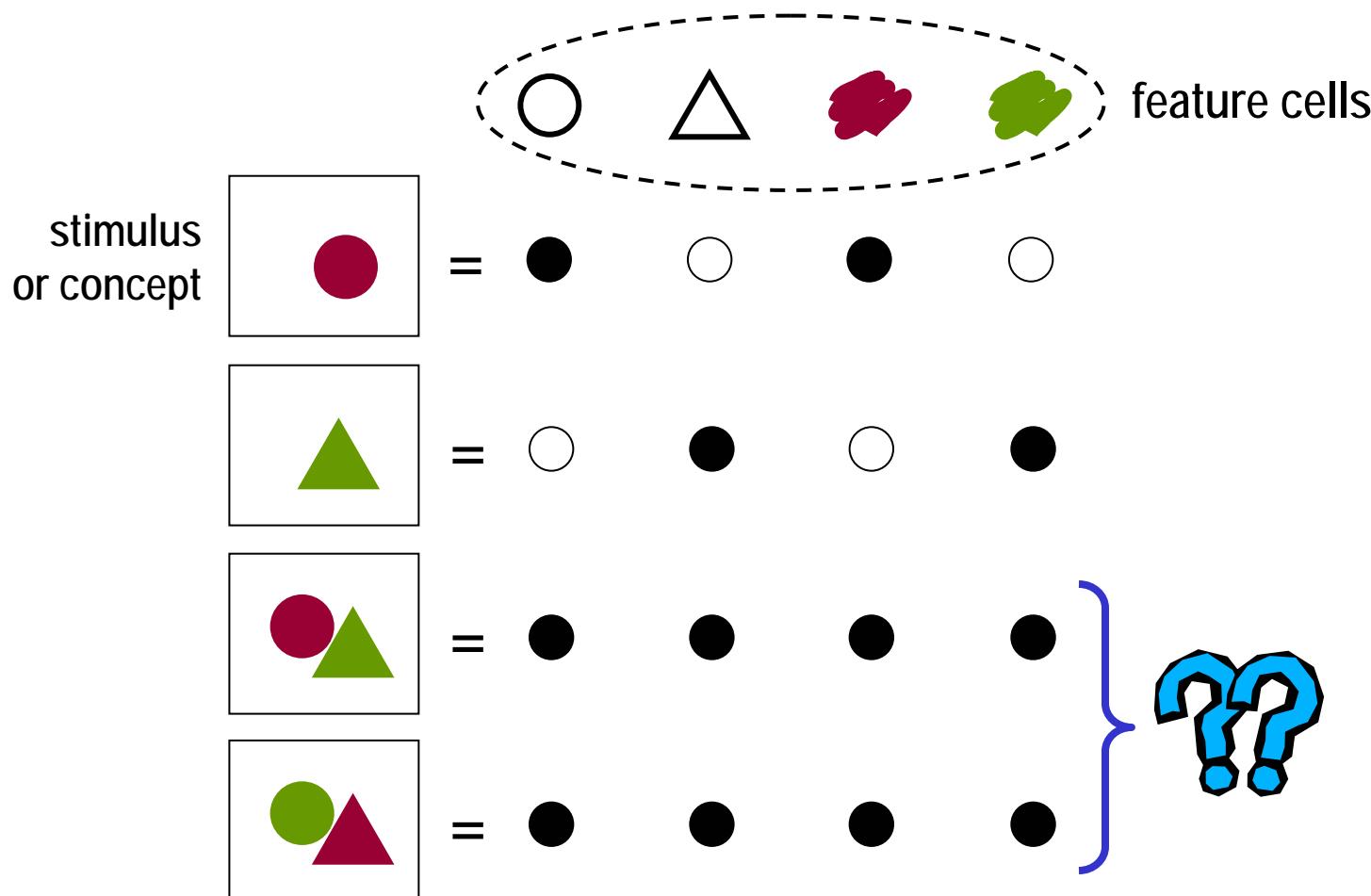
➤ Recent temporal coding “boom”: a few milestones

- 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

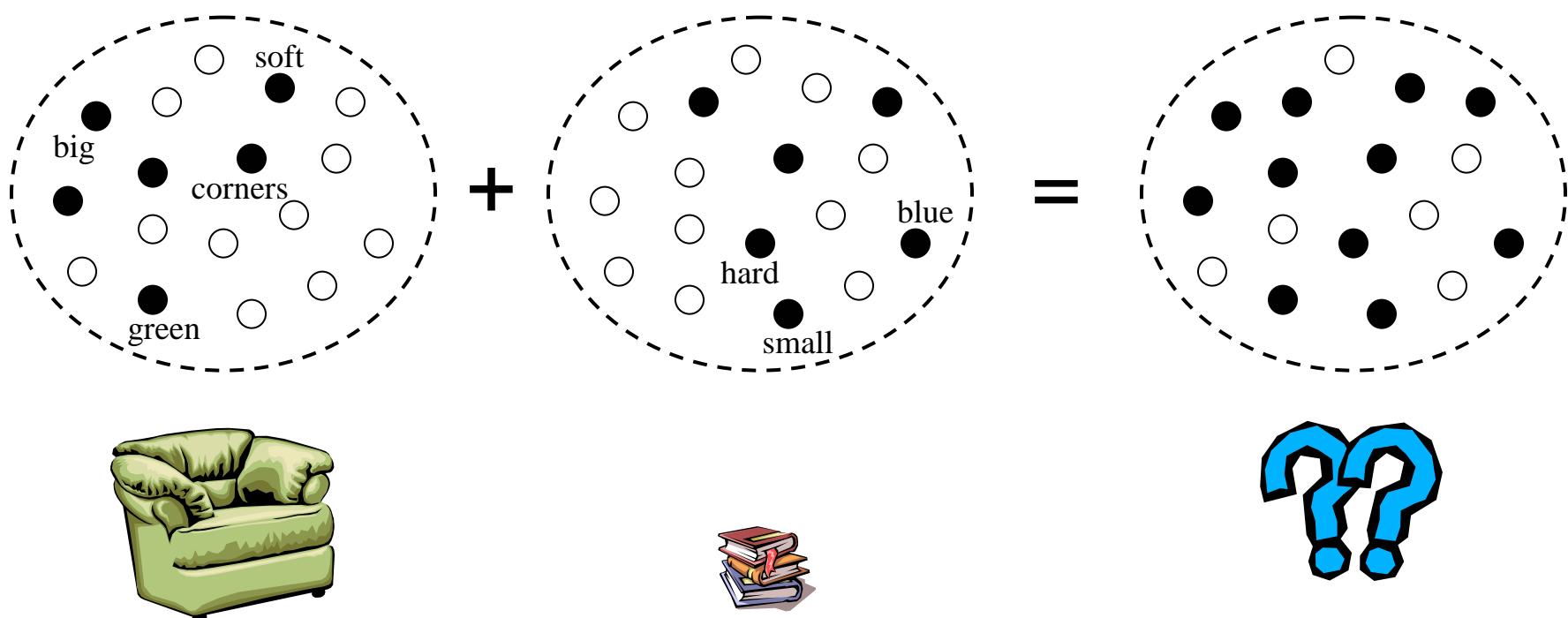
➤ The “binding problem”

- ✓ how to represent relationships?



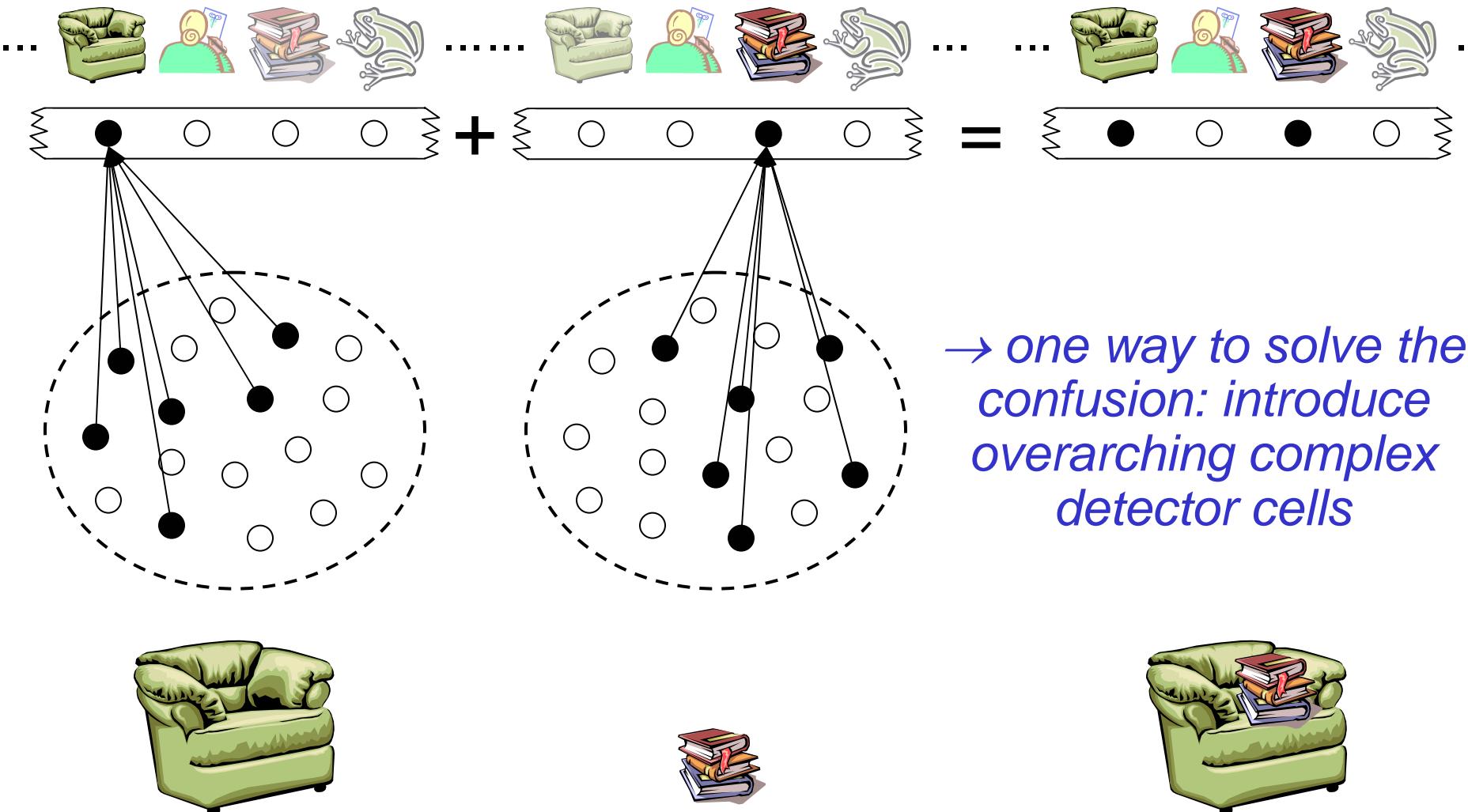
Binding with Temporal Code

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



Binding with Temporal Code

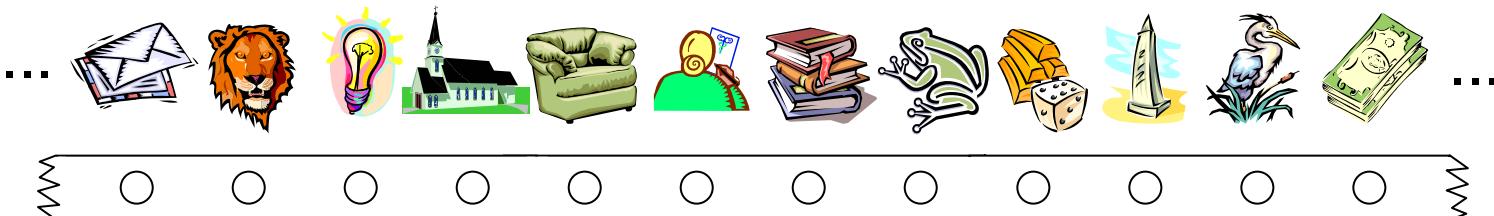
➤ “Grandmother” cells?



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

Binding with Temporal Code

- “Grandmother” cells?

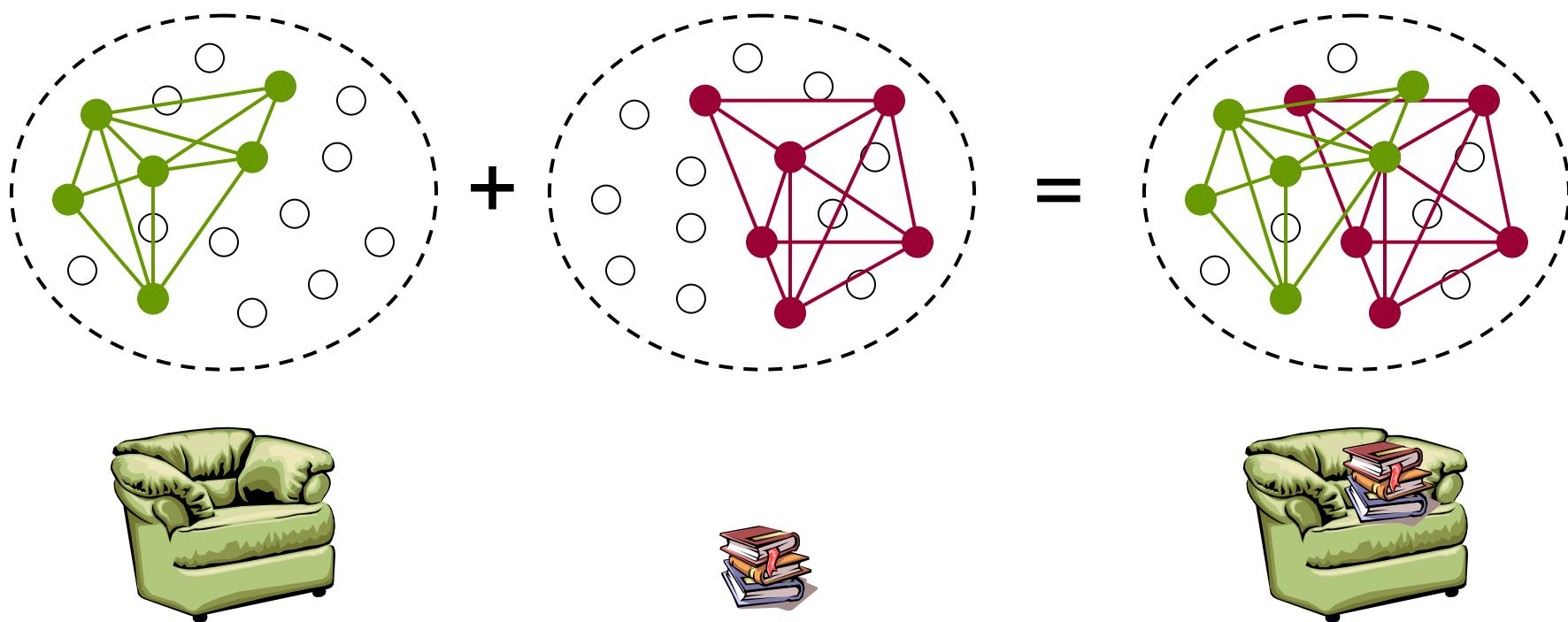


*. . . however, this soon
leads to an unacceptable
combinatorial explosion!*

Binding with Temporal Code

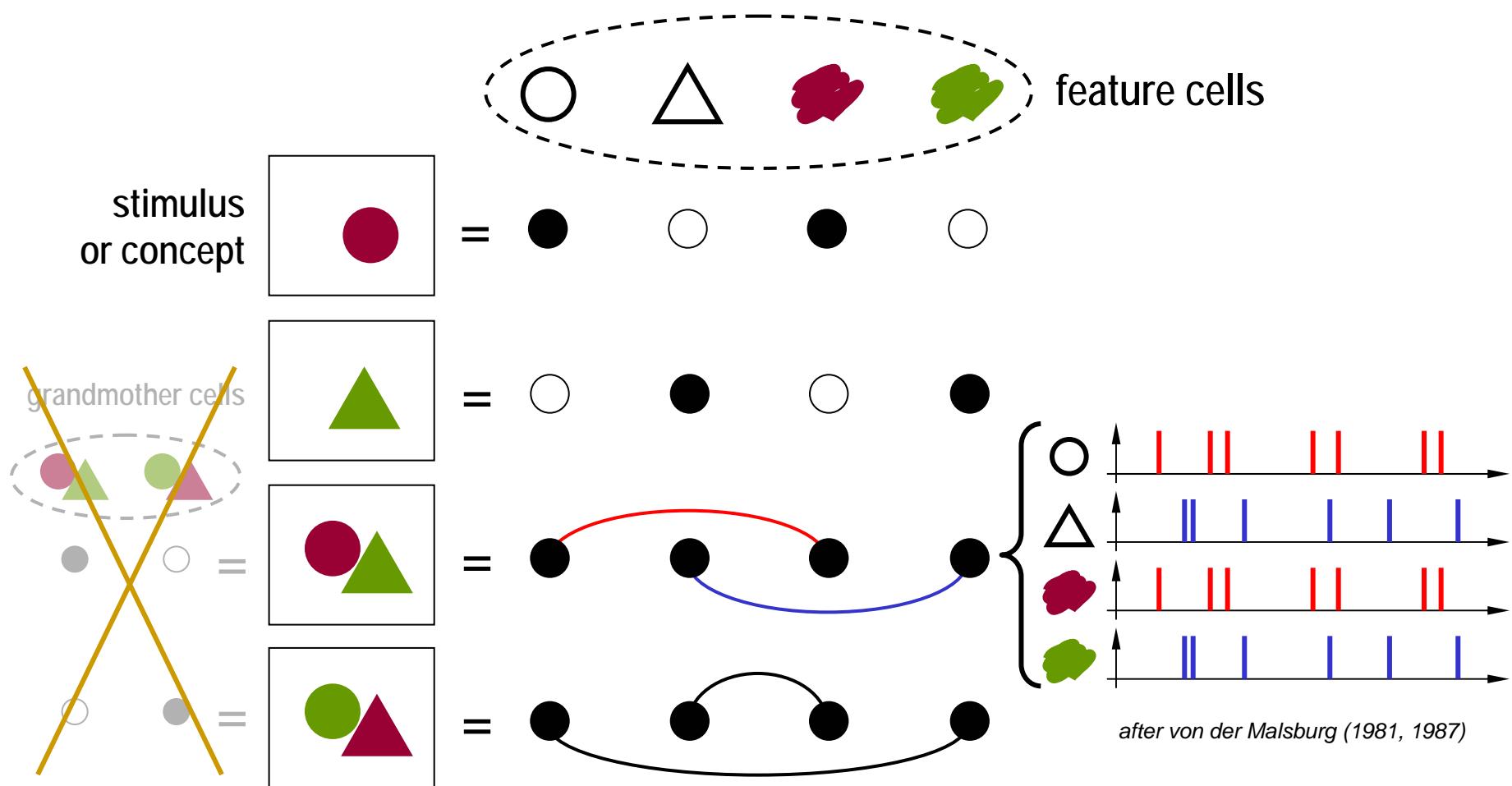
➤ Relational representation: graph format

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



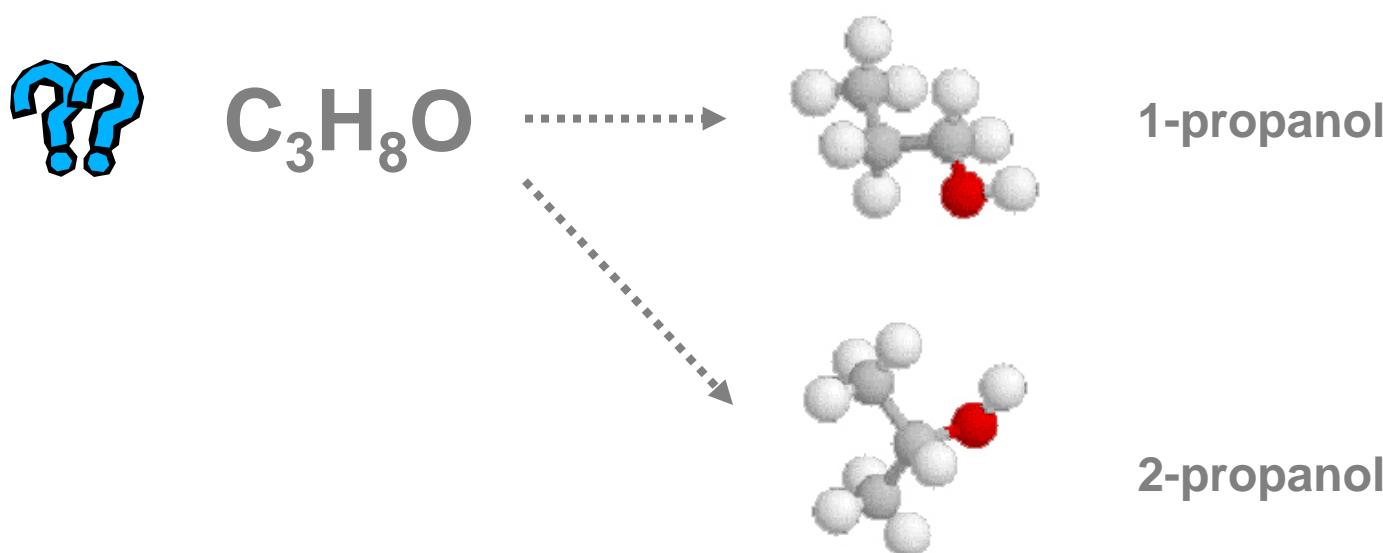
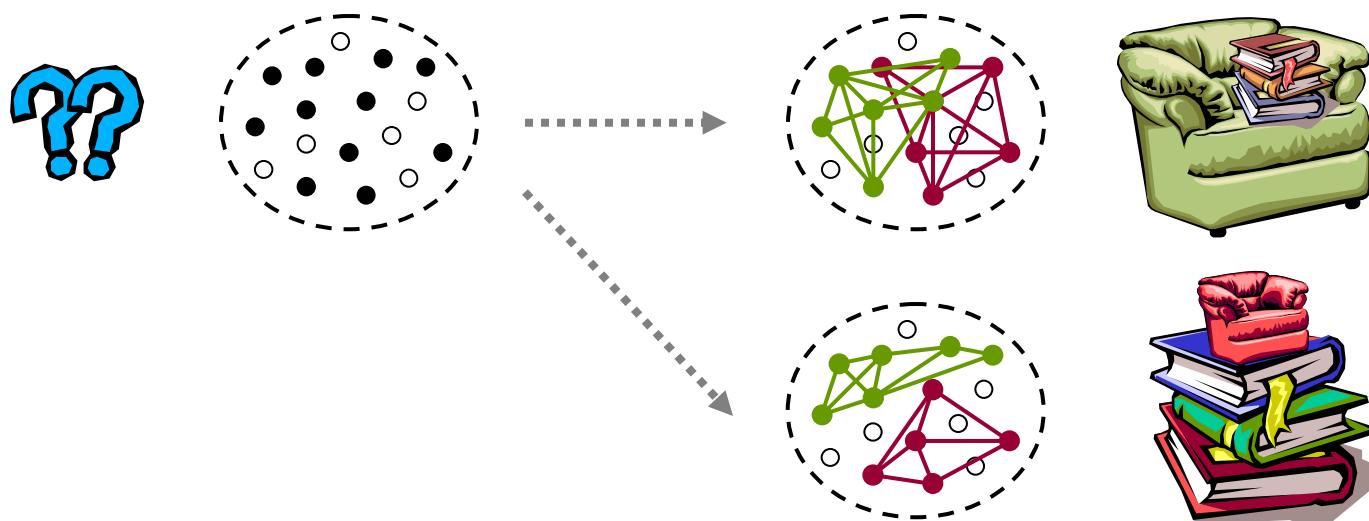
Binding with Temporal Code

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



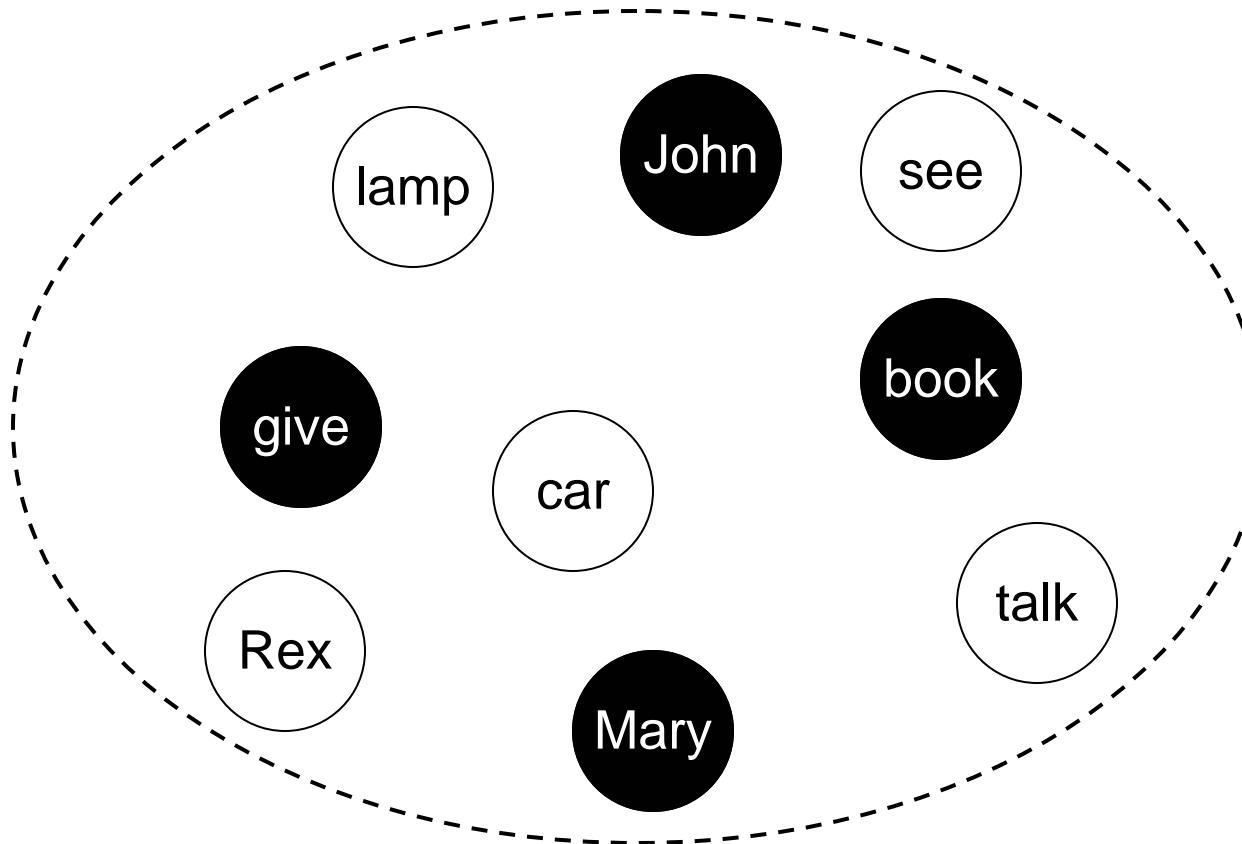
Binding with Temporal Code

➤ Molecular metaphor: spatiotemporal patterns

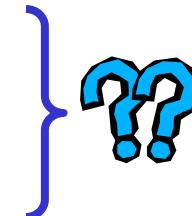


Binding with Temporal Code

➤ Problems of compositionality again—in language

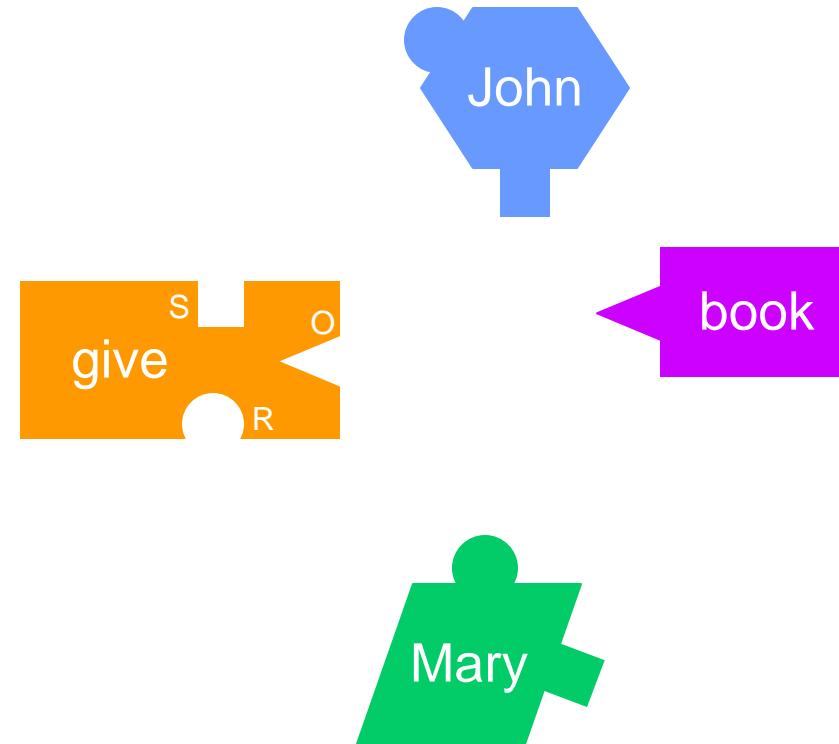


- (a) John gives a book to Mary.
- (b) Mary gives a book to John.
- (c)* Book John Mary give.



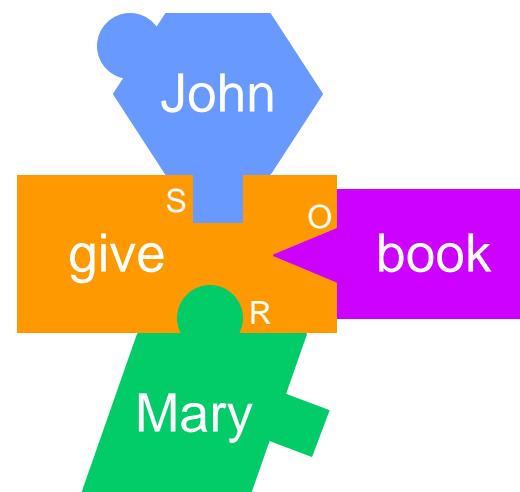
Binding with Temporal Code

- Problems of compositionality again—in language



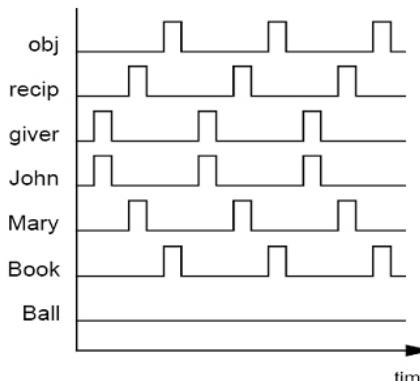
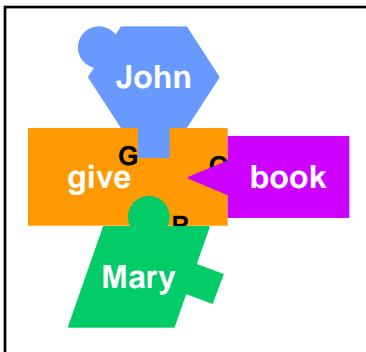
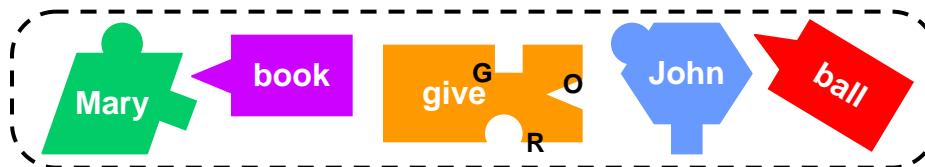
Binding with Temporal Code

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

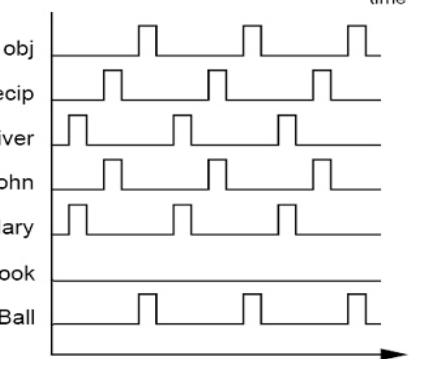
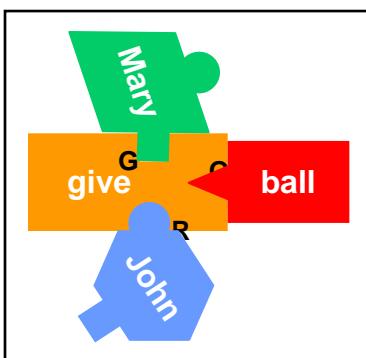


Binding with Temporal Code

➤ A building-block game of language



✓ the “blocks” are elementary representations (linguistic, perceptive, motor) that ***assemble dynamically*** via temporal binding



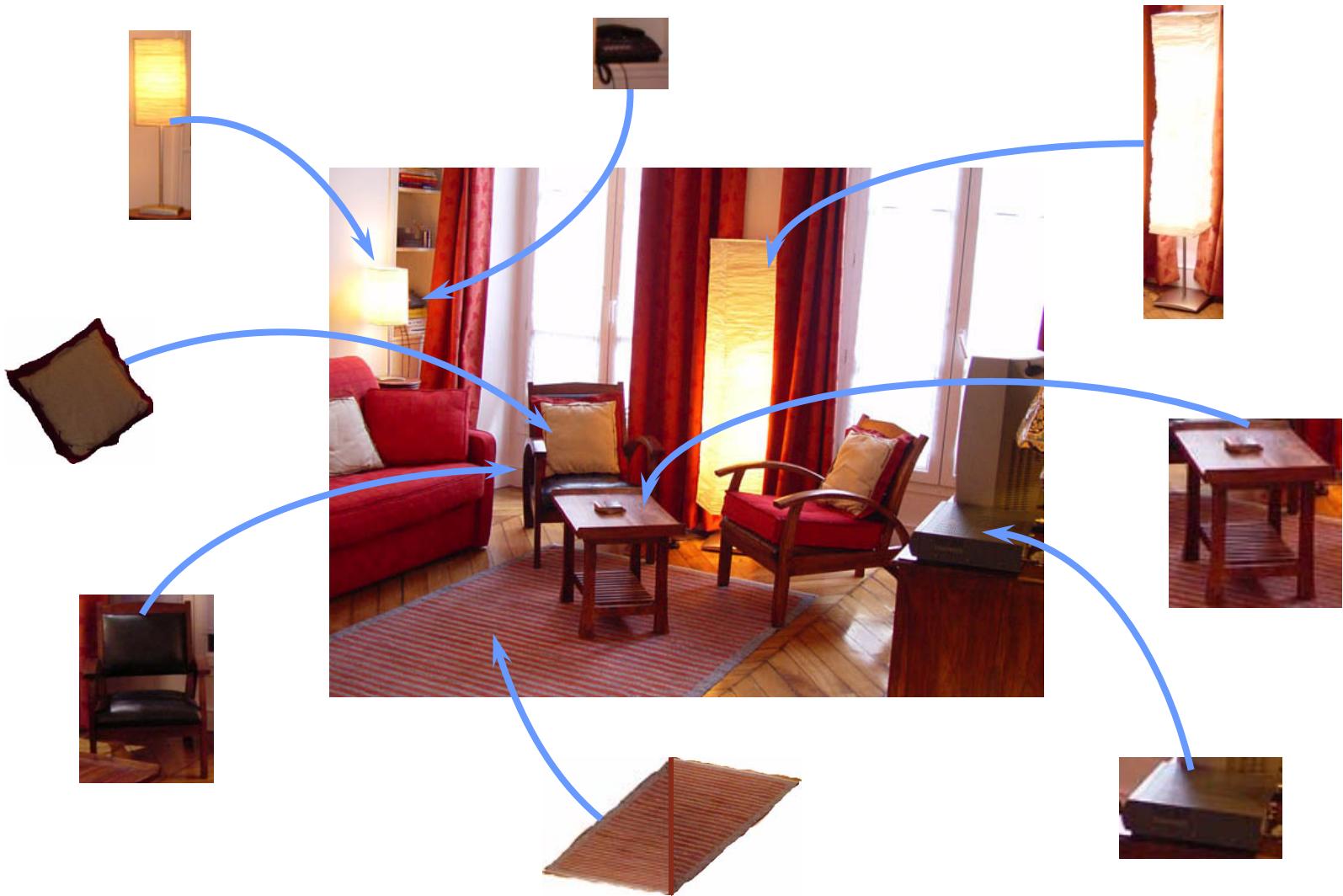
✓ representations possess an internal spatiotemporal structure at all levels

after Bienenstock (1995)

after Shastri & Ajjanagadde (1993)

Binding with Temporal Code

- Problems of compositionality again—in vision



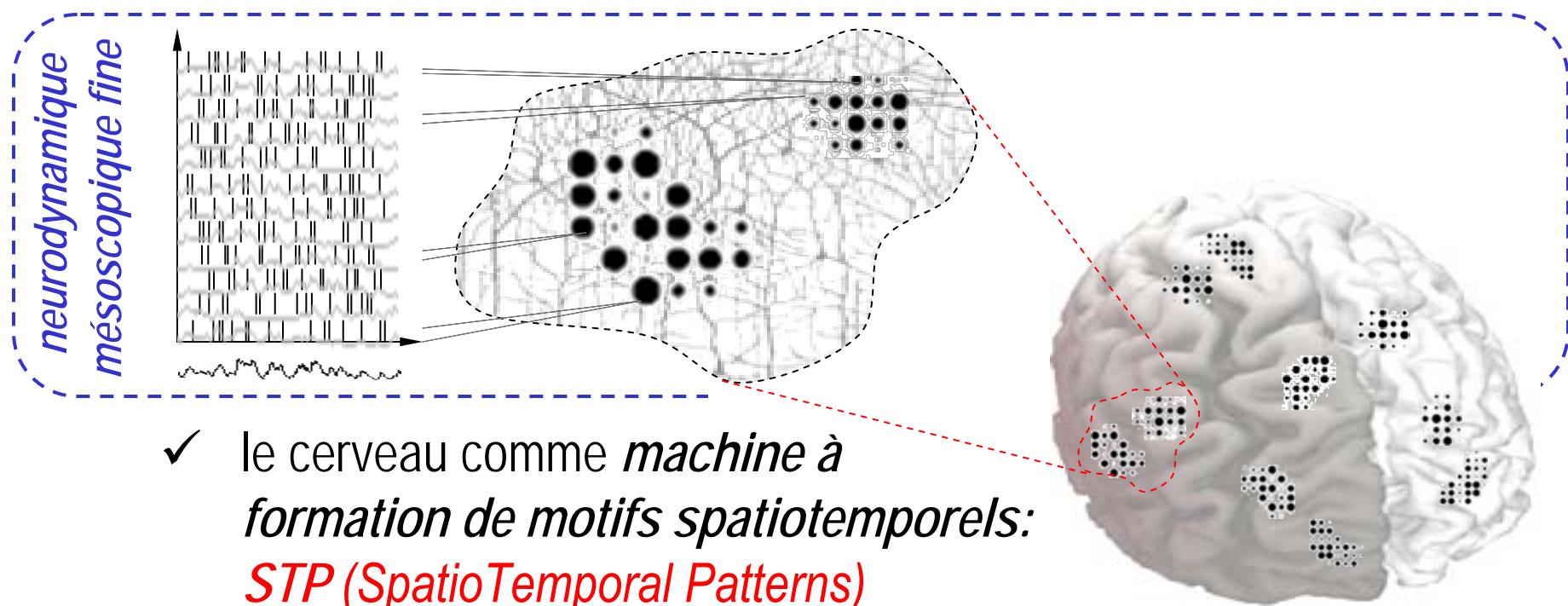
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Vers une neurodynamique mésoscopique fine

➤ 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



Formation de motifs

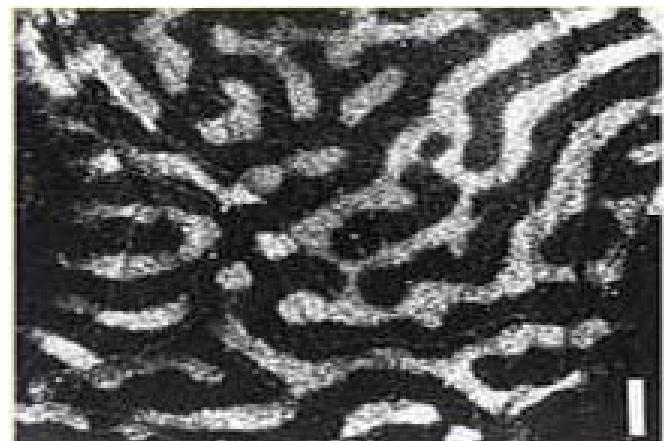
➤ Le développement biologique est affaire de motifs

- ✓ motifs du manteau épithéial, **chromatophores**, etc.

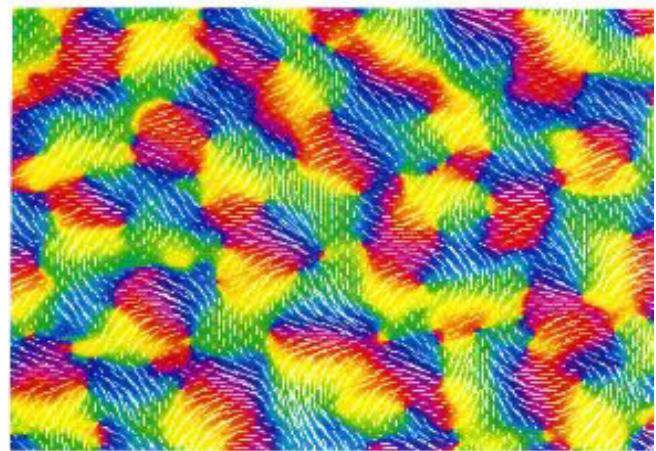


.... en quoi le cerveau serait-il différent?
cartes de connexions, rayures fonctionnelles, etc.

ocular dominance
stripes Hubel & Wiesel, 1970



orientation column
“pinwheels” Blasdel, 1992

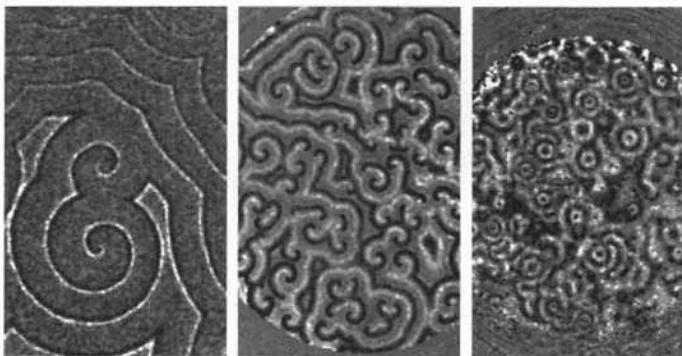


Formation de motifs

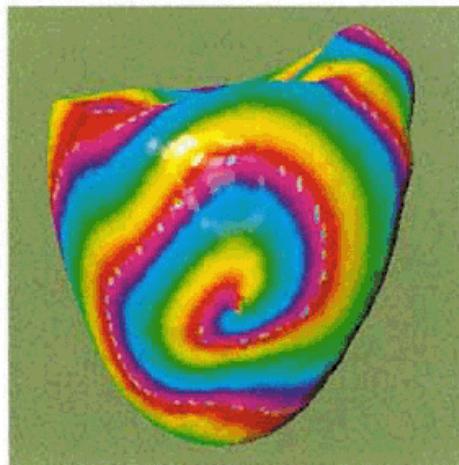
➤ La physiologie multicellulaire est aussi affaire de motifs

- ✓ motifs dynamiques fonctionnels

Aggregating slime mold
B. Goodwin, Schumacher College, UK

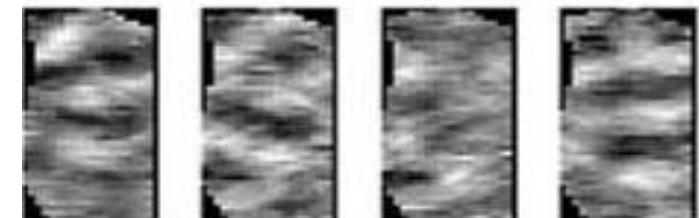


Model of dog heart
J. Keener, University of Utah



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

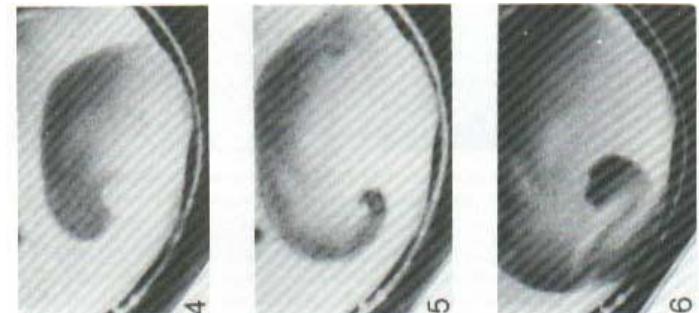
Spontaneous VC activity
Grinvald



Olfactory bulb phase pattern
W. Freeman



Chicken retina waves
Gorelova & Bures, 1983



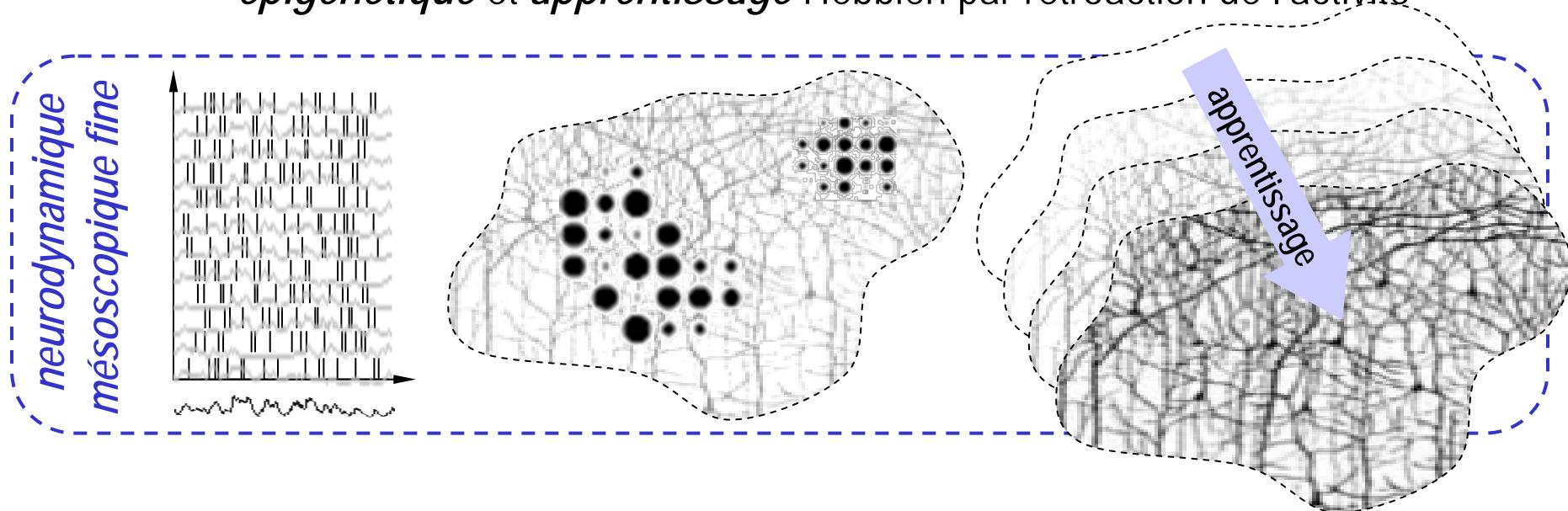
Cognition mésoscopique

- Hypothèse 1 : la neurodynamique mésoscopique est faite de motifs spatio-temporels (STP) fins de spikes
- Hypothèse 2 : ces STP mésoscopiques sont des entités individuées, formant un “jeu de construction”
 - (i) produites de façon *endogène* par le substrat neuronal,
 - (ii) *évoquées* et *perturbées* sous l'influence de stimuli,
 - (iii) dynamiquement *composables* (dissociables) les unes aux (des) autres.

Cognition mésoscopique

(i) STP produites de façon endogène par le substrat neuronal

- ✓ à connectivité donnée, une assemblée cellulaire peut montrer différents *régimes dynamiques*, ou motifs, d'activité spontanée
- ✓ la connectivité sous-jacente est elle-même le produit d'un développement *épigénétique* et *apprentissage* Hebbien par rétroaction de l'activité

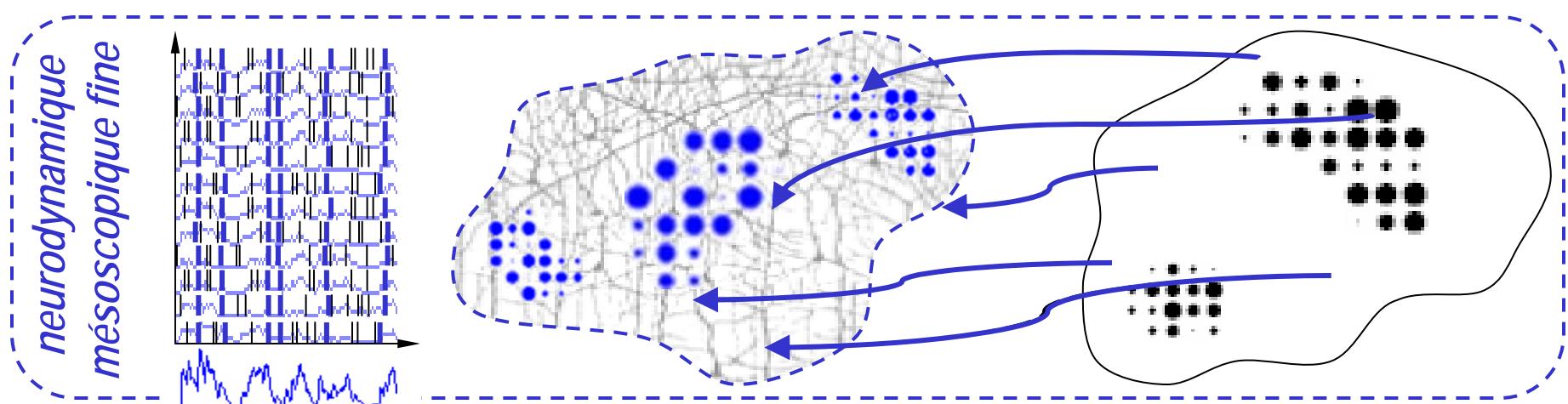


→ *l'identité, la spécificité et/ou la sélectivité aux stimuli d'une STP sont déterminées par sa structure interne de ses connexions*

Cognition mésoscopique

(ii) STP évoquées et perturbées sous l'influence de stimuli

- ✓ les stimuli extérieurs peuvent *évoquer et influencer* des STP préexistantes dynamiquement, pas les créer
- ✓ c'est un mécanisme indirect de *perturbation*, pas un mécanisme direct d'activation

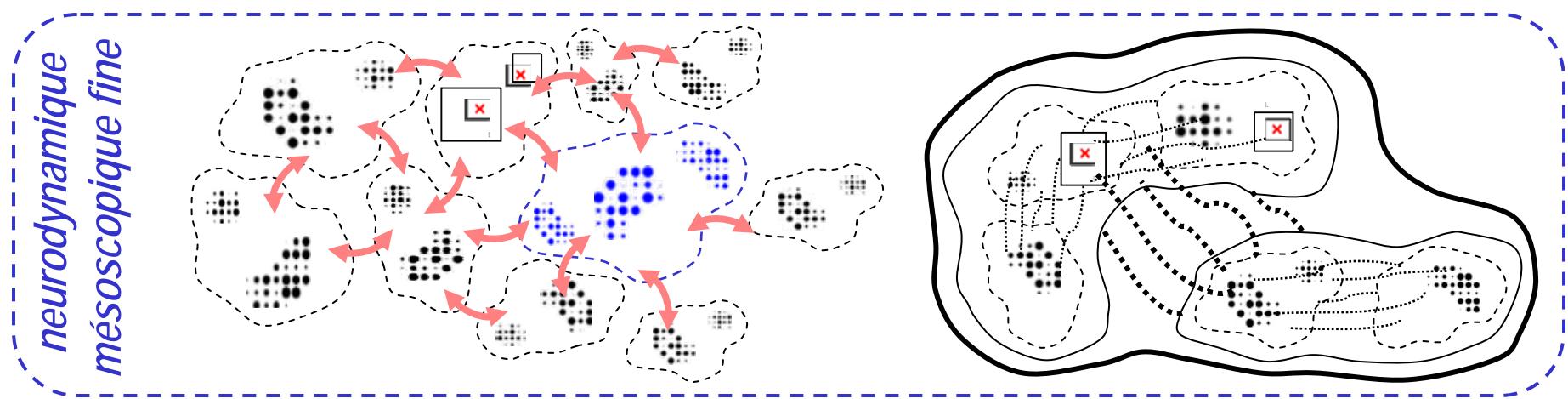


- ✓ capacités de reconnaissance ou représentation sans nécessairement ressemblance directe avec stimuli (STP pas forcément "templates" ou attracteurs)

Cognition mésoscopique

(iii) STP dynamiquement composables et/ou dissociables

- ✓ des populations de STP en *concurrence et différentiation* pour créer des unités fonctionnelles spécialisées
- ✓ et se *liant* les uns aux autres par cohérence temporelle (synchronie, plasticité rapide) pour créer des objets composés



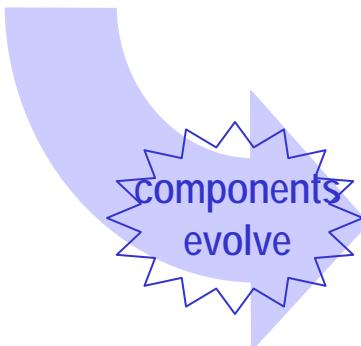
paradigme de population de STP évolutionnaire

paradigme de compositionnalité "moléculaire" entre STP

Systems that are *self-organized* and *architectured*



free self-organization



self-organized architecture / architectured self-organization

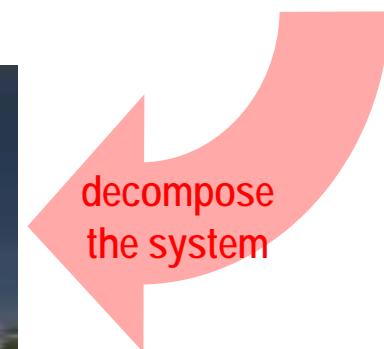
the scientific challenge of complex systems: how can they integrate a true *architecture*?



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

Peugeot Picasso

deliberate design



Beyond “patterns”: structured forms

➤ Self-organized (complex) systems

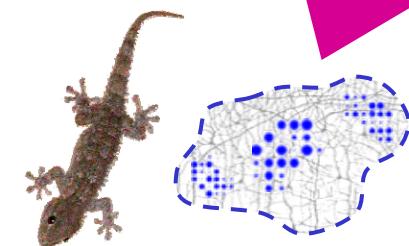
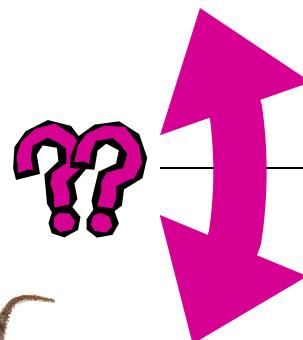
- ✓ a myriad of self-positioning, self-assembling agents
- ✓ collective order is not imposed from outside (only influenced)
- ✓ comes from purely *local* information & interaction around each agent
- ✓ no agent possesses the global map or goal of the system
- ✓ but every agent may contain all the *rules* that contribute to it



➤ Structured systems

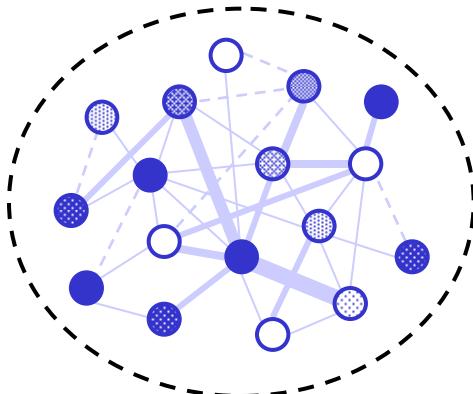
- ✓ true *architecture*: non-trivial, complicated morphology
 - *hierarchical*, multi-scale: regions, parts, details, agents
 - *modular*: reuse, quasi-repetition
 - *heterogeneous*: differentiation & divergence in the repetition
- ✓ *random* at the microscopic level, *but reproducible* (quasi deterministic) at the mesoscopic and macroscopic levels

multicellular organisms and (in higher animals' brains) neural states of activity are two examples of self-organized *and* structured systems



Self-organized and structured systems

➤ Natural and human-made complex systems everywhere



- large number of elementary agents interacting locally
- simple individual behaviors creating a complex emergent collective behavior
- *decentralized dynamics: no master blueprint or grand architect*

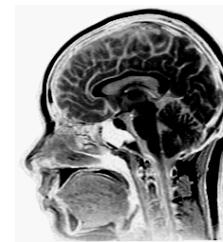
✓ **physical, biological, technical, social** systems (natural or artificial)



pattern formation
○ = matter



biological development
○ = cell



the brain & cognition
○ = neuron



insect colonies
○ = ant



Internet & Web
○ = host/page



social networks
○ = person

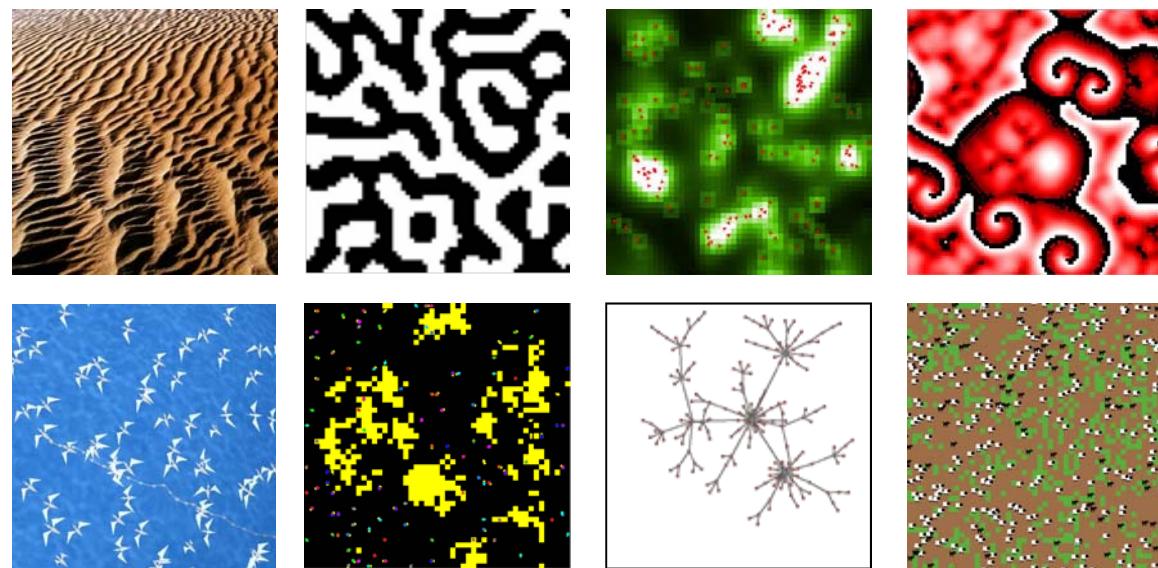
“Statistical” vs. “morphological” complex systems

➤ A brief taxonomy of systems

Category	<i>Agents / Parts</i>	<i>Local Rules</i>	<i>Emergent Behavior</i>	<i>A “Complex System”?</i>
 2-body problem	<i>few</i>	<i>simple</i>	<i>simple</i>	<i>NO</i>
 3-body problem, low-D chaos	<i>few</i>	<i>simple</i>	<i>complex</i>	<i>NO – too small</i>
 crystal, gas	<i>many</i>	<i>simple</i>	<i>simple</i>	<i>NO – few params suffice to describe it</i>
 patterns, swarms, complex networks	<i>many</i>	<i>simple</i>	<i>“complex”</i>	<i>YES – but mostly random and uniform</i>
 embryogenesis	<i>many</i>	<i>sophisticated</i>	<i>complex</i>	<i>YES – reproducible and heterogeneous</i>
 machines, crowds with leaders	<i>many</i>	<i>sophisticated</i>	<i>“simple”</i>	<i>COMPLICATED – not self-organized</i>

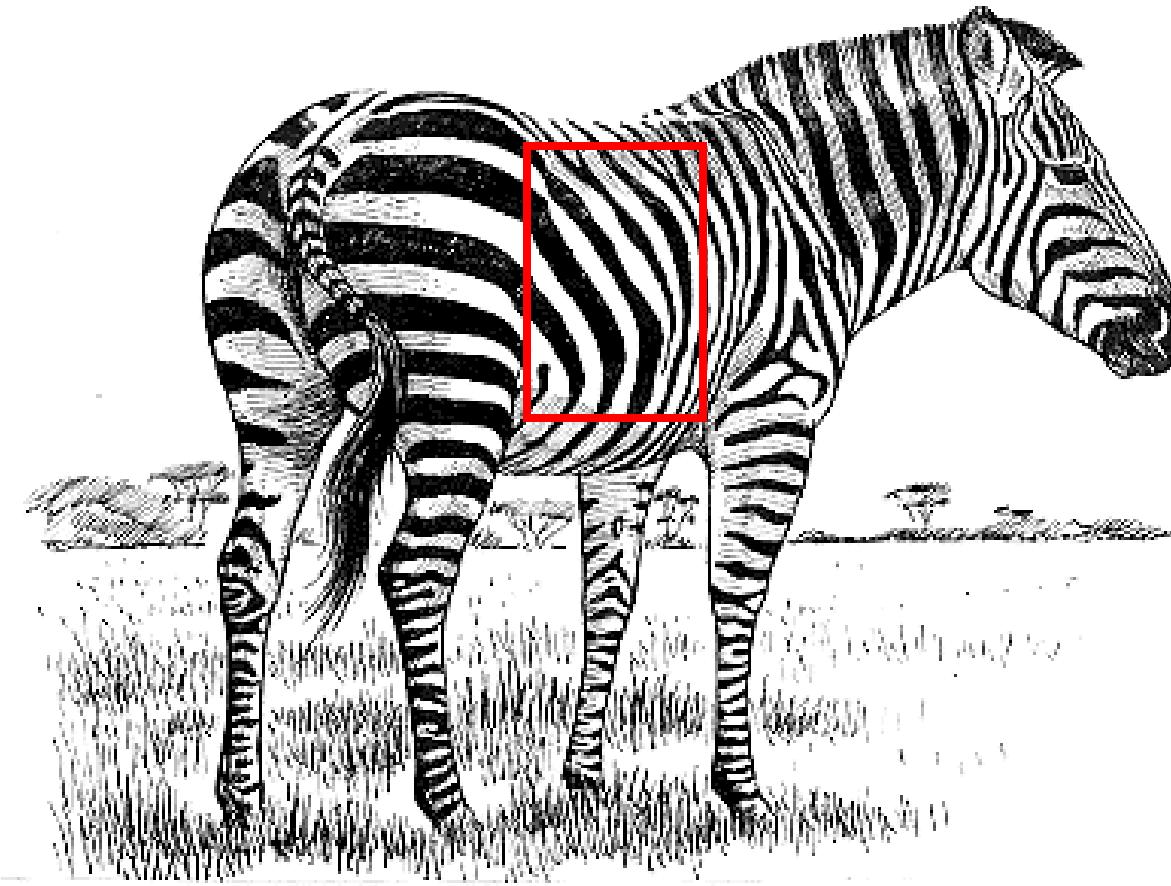
Statistical (self-similar) systems

- Many agents, simple rules, “complex” emergent behavior
 - the “clichés” of complex systems: diversity of pattern formation (spots, stripes), swarms (clusters, flocks), complex networks, etc.



- ✓ yet, often like “textures”: repetitive, statistically *uniform*, information-poor
- ✓ spontaneous order arising from amplification of *random* fluctuations
- ✓ *unpredictable* number and position of mesoscopic entities (spots, groups)

Morphological (self-dissimilar) systems compositional systems: pattern formation \neq morphogenesis



*“I have the stripes, but where is the zebra?” OR
“The stripes are easy, it’s the horse part that troubles me”*

—attributed to A. Turing, after his 1952 paper on morphogenesis

Morphological (self-dissimilar) systems

- Many agents, sophisticated rules, complex emergence
 - natural ex: organisms (cells)



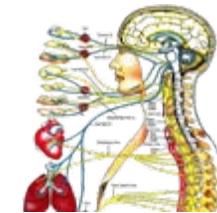
plants



vertebrates



arthropods



humans

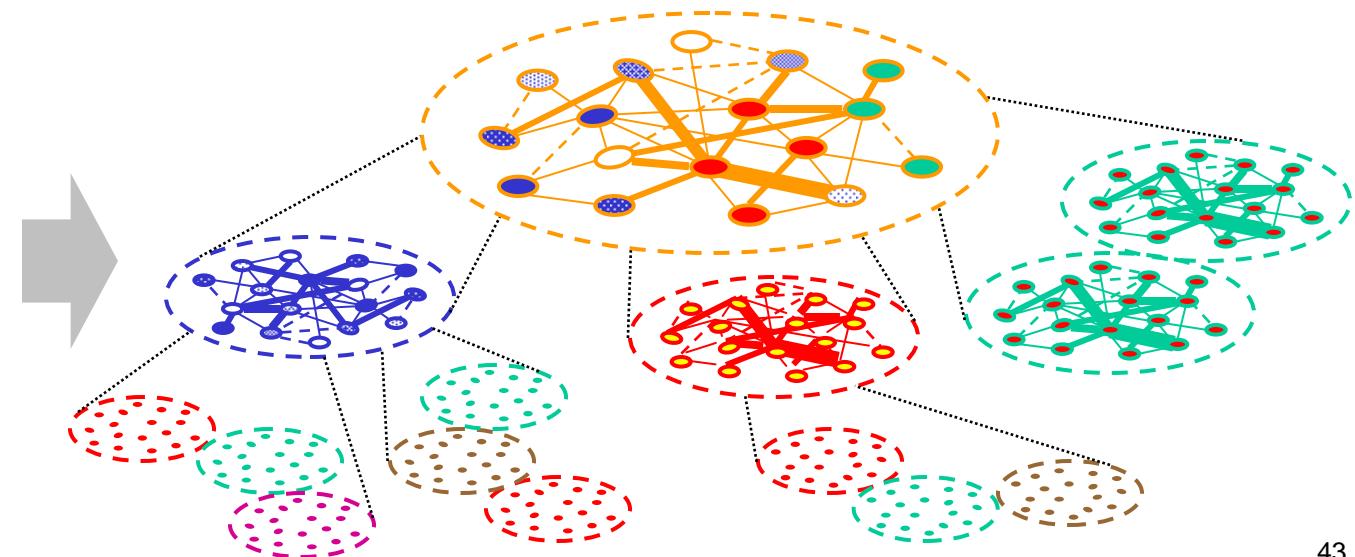
- ✓ mesoscopic organs and limbs have intricate, *nonrandom* morphologies
- ✓ development is highly *reproducible* in number and position of body parts
- ✓ *heterogeneous* elements arise under information-rich genetic control

- Biological organisms are self-organized and structured

- ✓ because the pieces of the puzzle (agent rules) are more “sophisticated” (than inert matter): depend on agent’s *type* and/or *position* in the system
- ✓ the outcome (development) is truly complex but, paradoxically, can also be more *controllable* and *programmable*

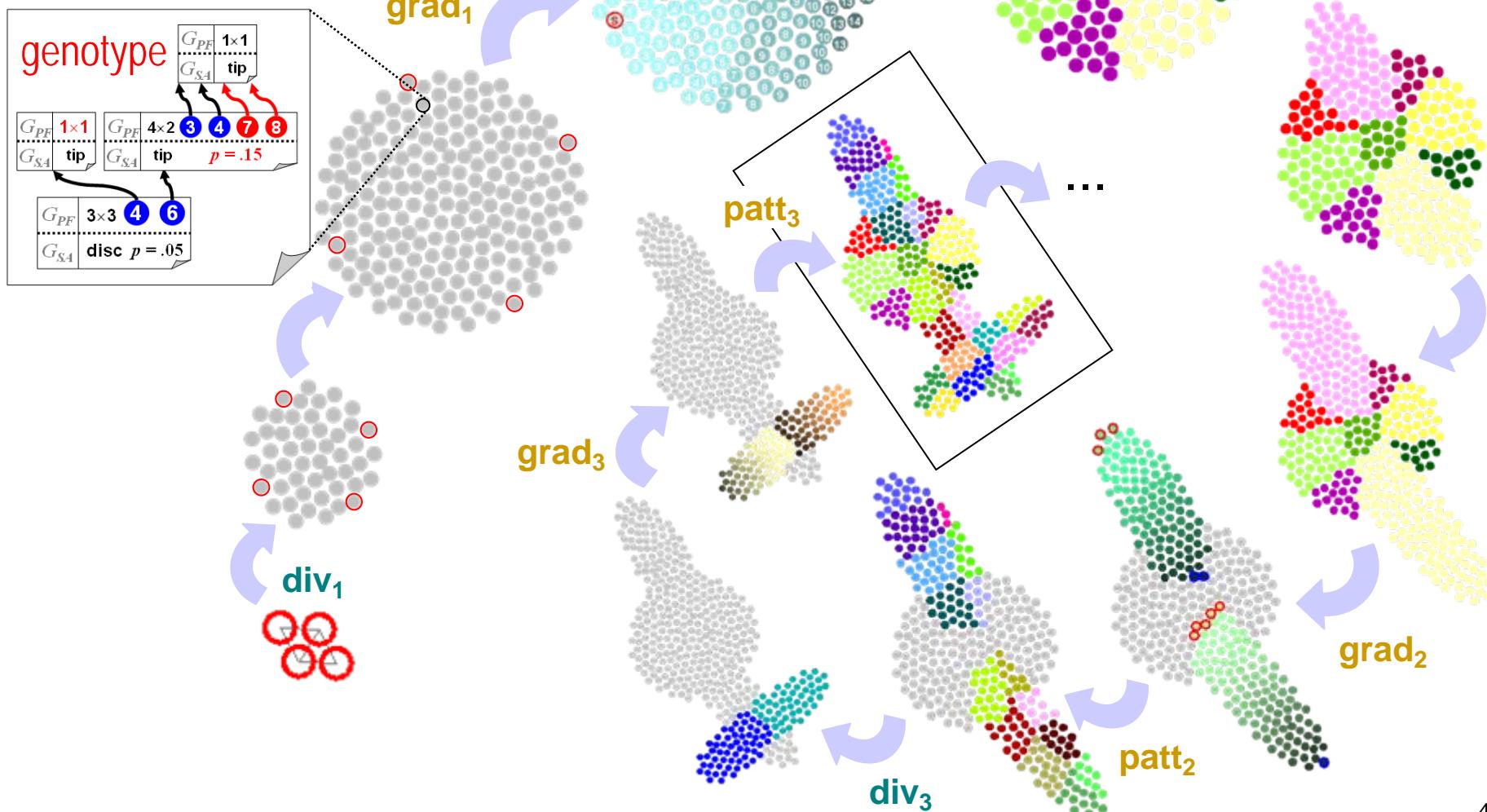
Beyond statistics: heterogeneity, modularity, reproducibility

- Complex systems can be much more than a “soup”
 - ✓ “complex” doesn’t necessarily imply “homogeneous”...
→ *heterogeneous agents and diverse patterns, via positions*
 - ✓ “complex” doesn’t necessarily imply “flat” (or “scale-free”)...
→ *modular, hierarchical, detailed architecture (at specific scales)*
 - ✓ “complex” doesn’t necessarily imply “random”...
→ *reproducible patterns relying on programmable agents*



Example from artificial development

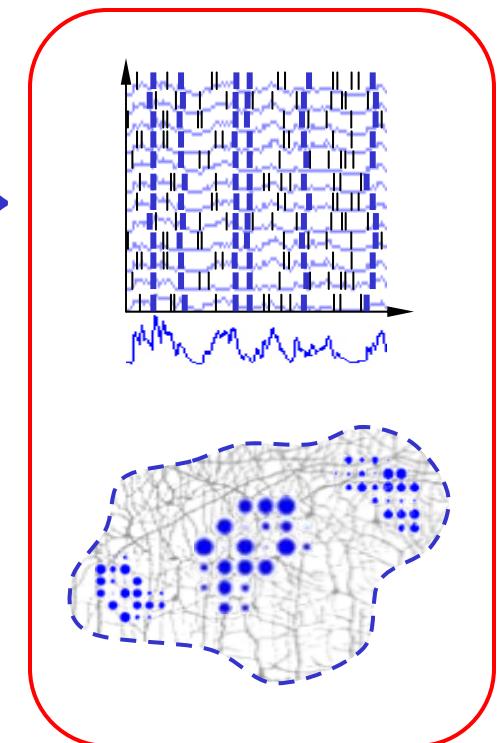
➤ Recursive morphogenesis



Le cerveau comme machine morphogénétique

➤ Vers des nuages de spikes “architecturés” ?

- ✓ STP non triviales, douées d'une structure



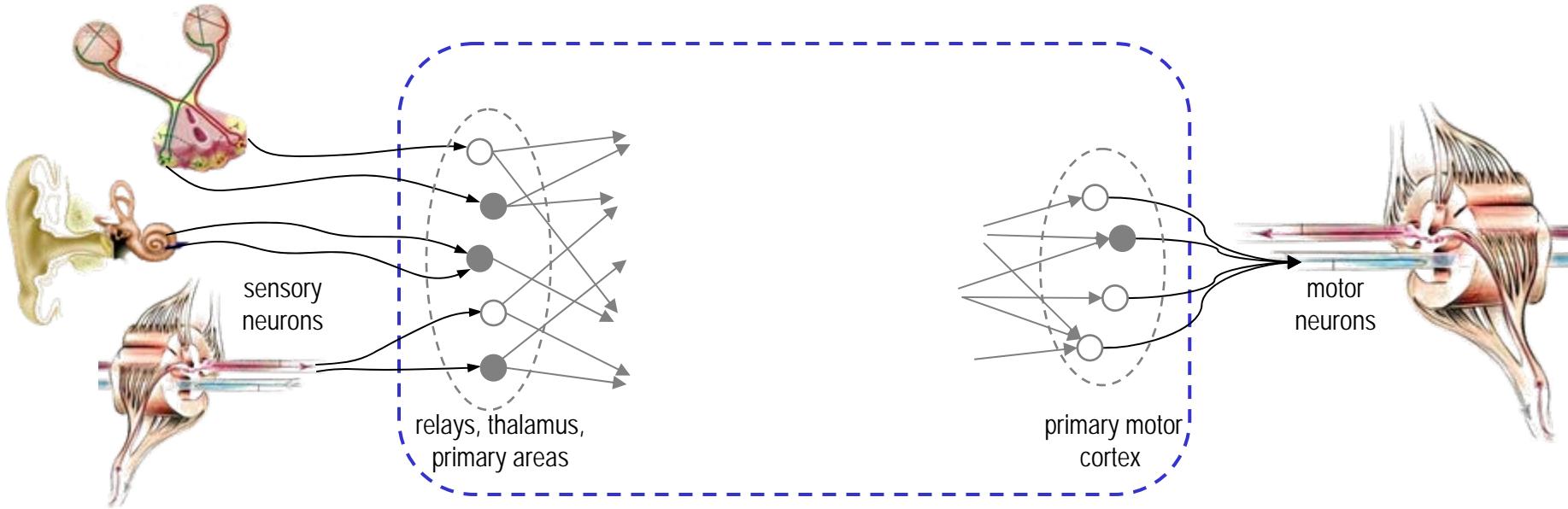
Entre neurodynamique complexe et cognition

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

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

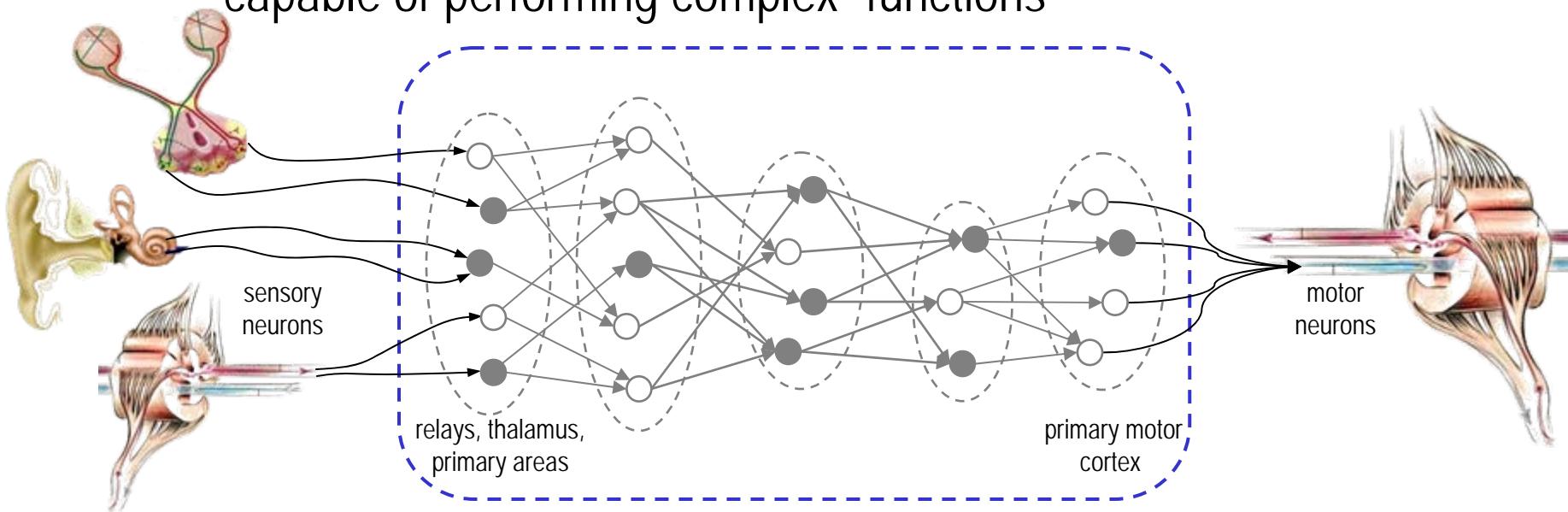
The litteral informational paradigm



The litteral informational paradigm

➤ Old, unfit engineering metaphor: “signal processing”

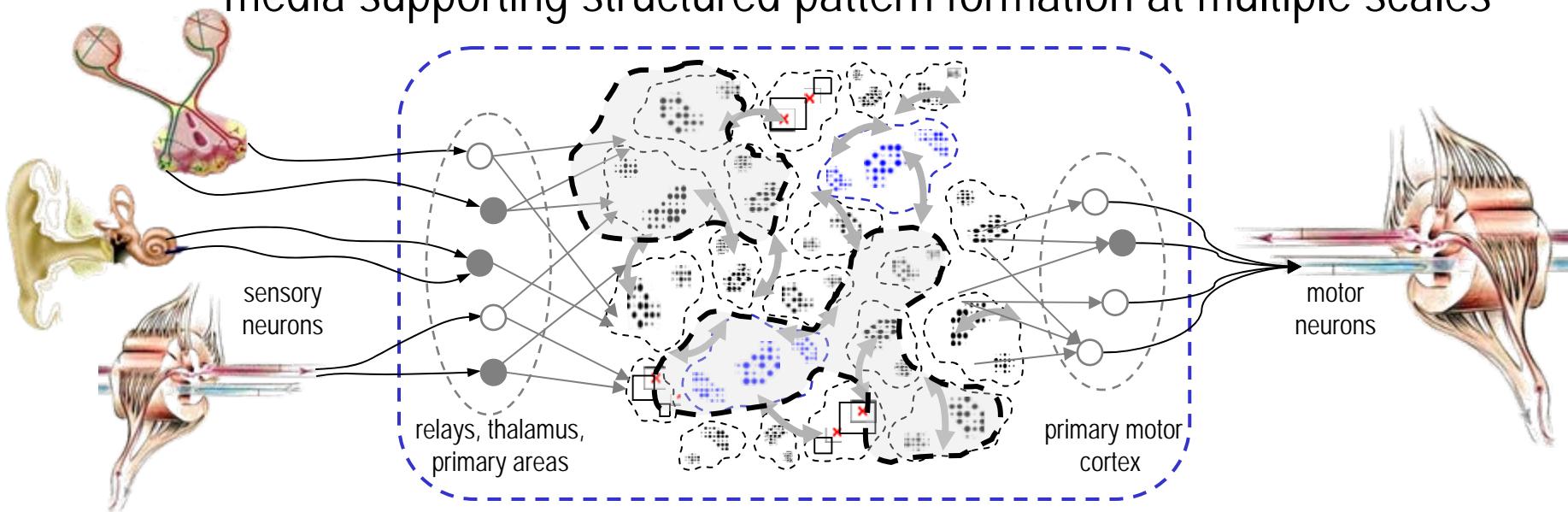
- ✓ *feed-forward* structure – activity literally “moves” from one corner to another, from the input (problem) to the output (solution)
- ✓ *activation* paradigm – neural layers are initially silent and are literally “activated” by potentials transmitted from external stimuli
- ✓ *coarse-grain* scale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



The emergent dynamical paradigm

➤ A “Cognitive Neurodynamics” journal

- ✓ Springer journal: “CN is a trend to study cognition from a dynamic view that has emerged as a result of the rapid developments taking place in nonlinear dynamics and cognitive science.”
 - focus on the spatiotemporal dynamics of neural activity in describing brain function
 - contemporary theoretical neurobiology that integrates nonlinear dynamics, complex systems and statistical physics
 - often contrasted with computational and modular approaches of cognitive neuroscience

The emergent dynamical paradigm

➤ Field neurodynamics vs. spiking neurodynamics

- ✓ CN also distinguishes three levels of organization (W. Freeman):
 - microscopic – multiple spike activity (MSA)
 - “mesoscopic” – local field potentials (LFP), electrocorticograms (ECoG)
 - macroscopic – brain imaging; metabolic (PET, fMRI), spatiotemporal (EEG)
 - ✓ but here, the mesoscopic level is based on *neural fields*:
 - continuum approximation of discrete neural activity by spatial and temporal integration of lower levels → loss of spatial and temporal resolution
- *at a finer-grain mesoscopic level of description, details of spiking (and subthreshold) patterns should be retained: what matters are the spatiotemporal “shapes” of mesoscopic objects*

Entre neurodynamique complexe et cognition

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“Tapestry, ponds and RAIN” : synfire chains, ondes et résonance

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

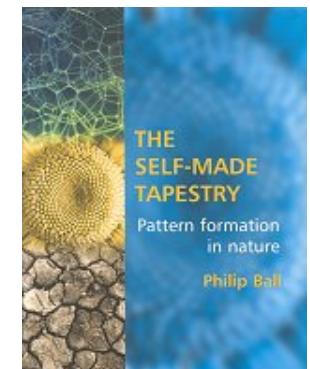
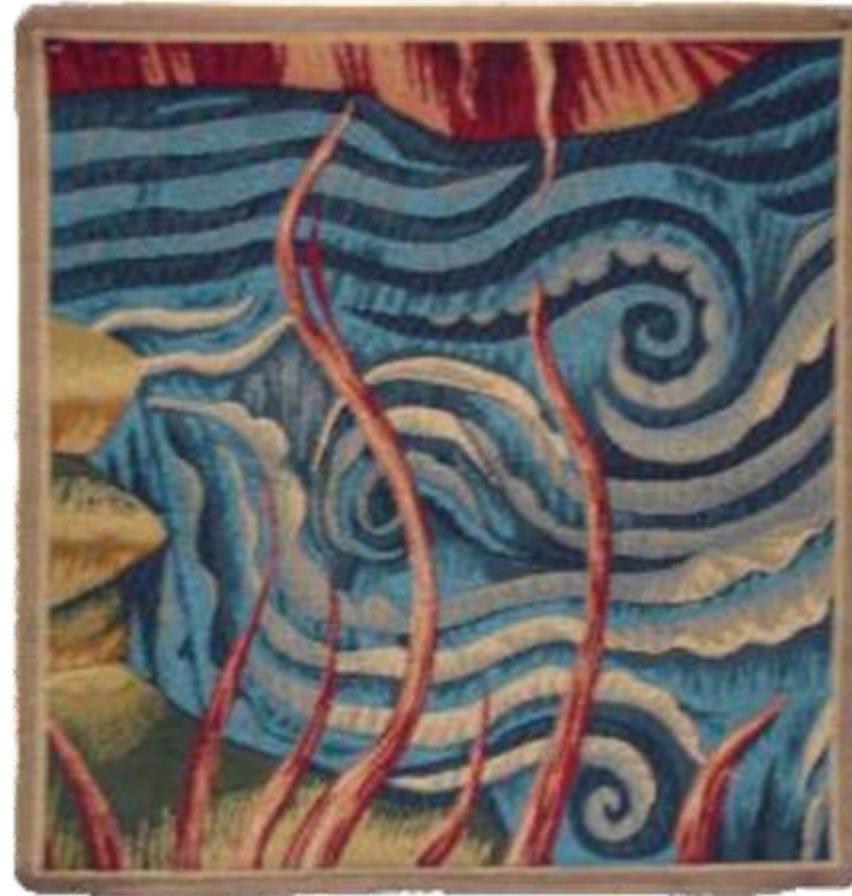


c. Résonance clé-serrure dans des "Recurrent Asynchronous Irregular Networks" (RAIN)

3. Une vue multi-échelle de la causalité neuronale

Tapestries

- a) Une tapisserie auto-tressée de synfire chains
→ *constructing the architecture of STPs*

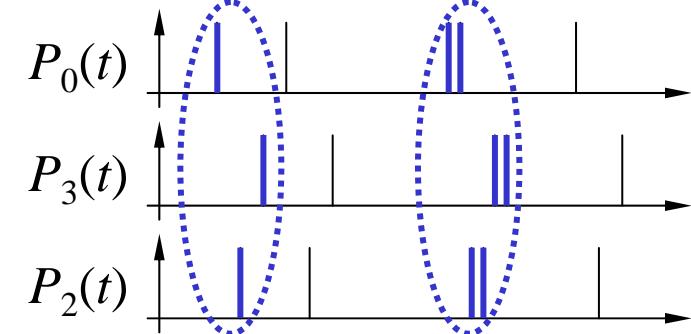
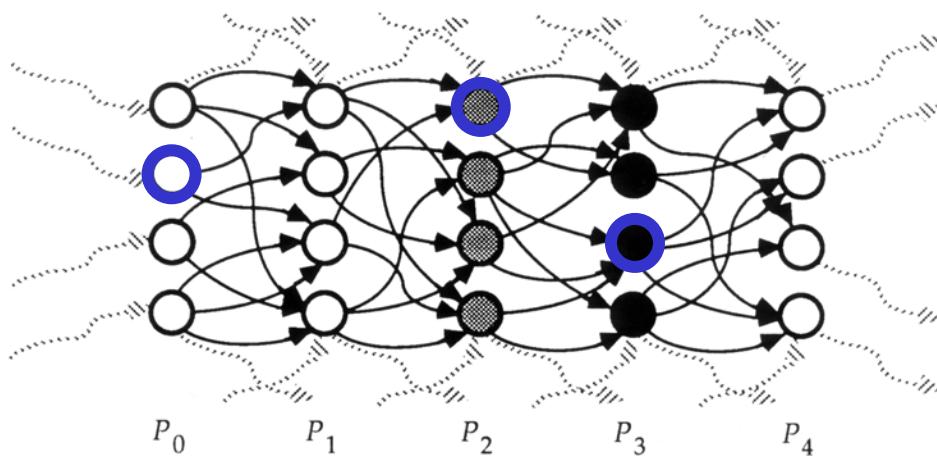


Doursat (1991), Bienenstock (1995), Doursat & Bienenstock (2005)

Tapestries

➤ What is a synfire chain?

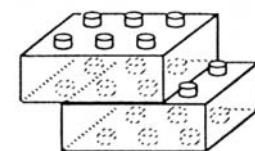
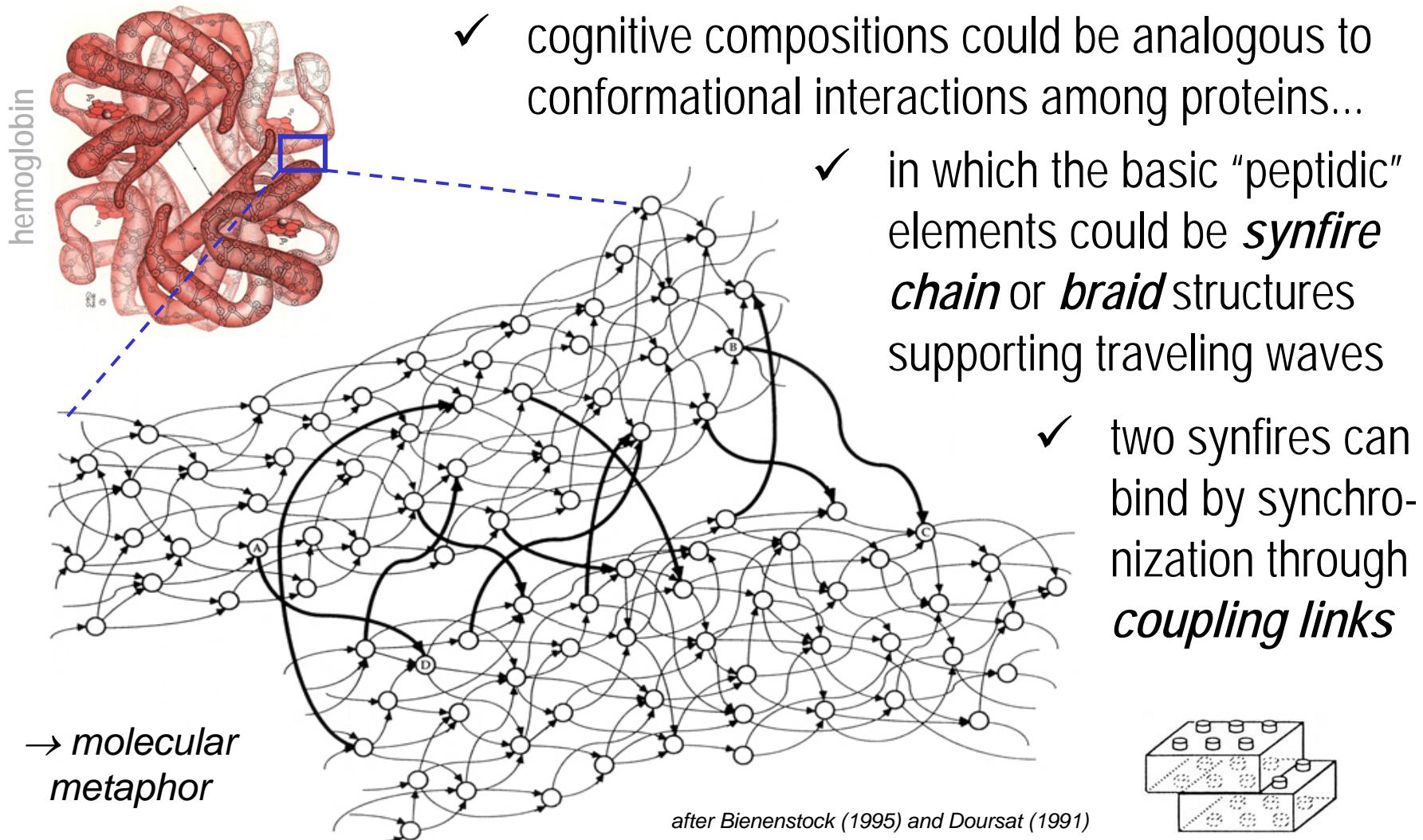
- ✓ a synfire chain (Abeles 1982) is a sequence of synchronous neuron groups $P_0 \rightarrow P_1 \rightarrow P_2 \dots$ linked by feedforward connections that can support the propagation of waves of activity (action potentials)



- ✓ 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

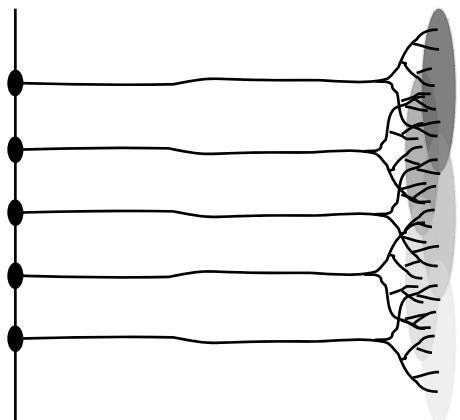
- Synfire patterns can *bind*, thus support compositionality



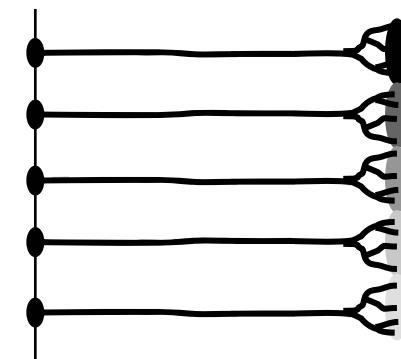
Tapestries

➤ A model of synfire growth: tuning connectivity by activity

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

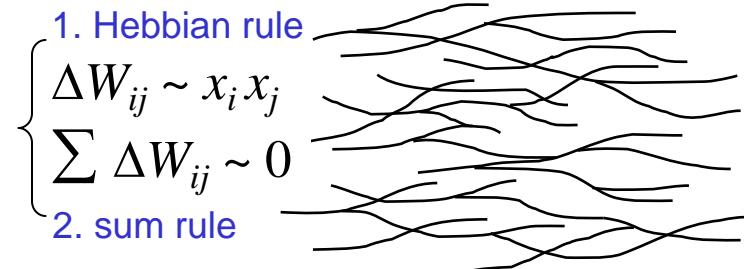


focusing of
innervation
in the retinotopic
projection

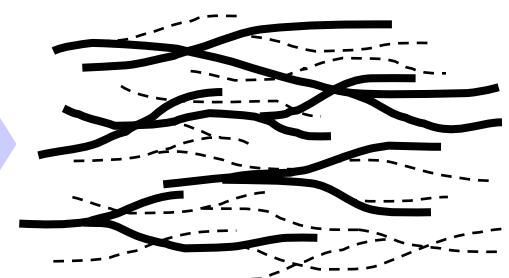


after Willshaw & von der Malsburg (1976)

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



“selective
stabilization” by
activity/connectivity
feedback

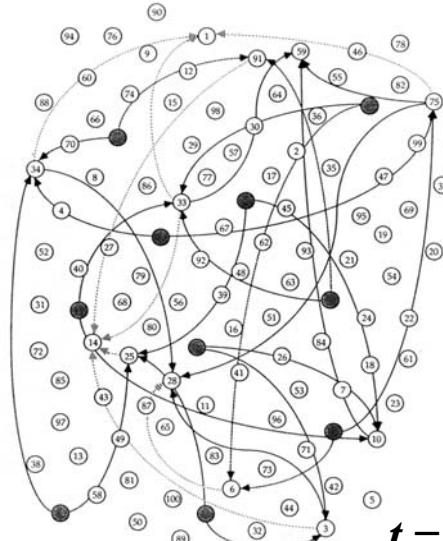


after Changeux & Danchin (1976)

Tapestries

- Synfire chains develop recursively, adding groups 1 by 1

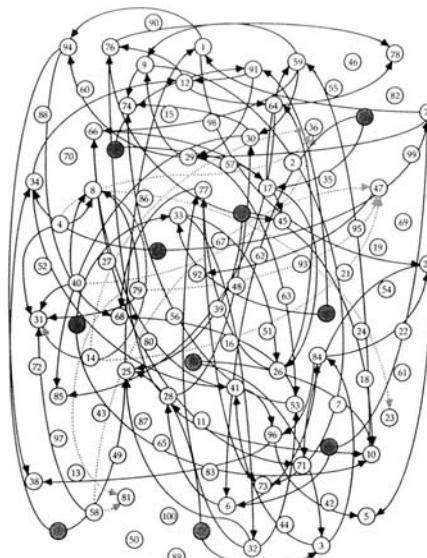
$$\begin{cases} \Delta W_{ij} \sim x_i x_j \\ \sum \Delta W_{ij} \sim 0 \end{cases}$$



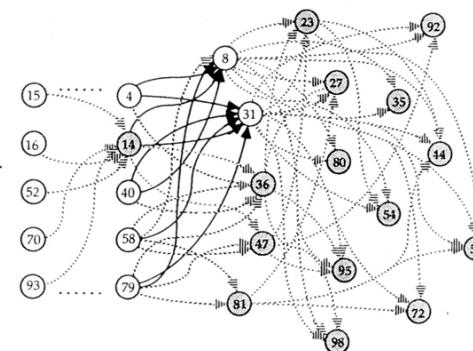
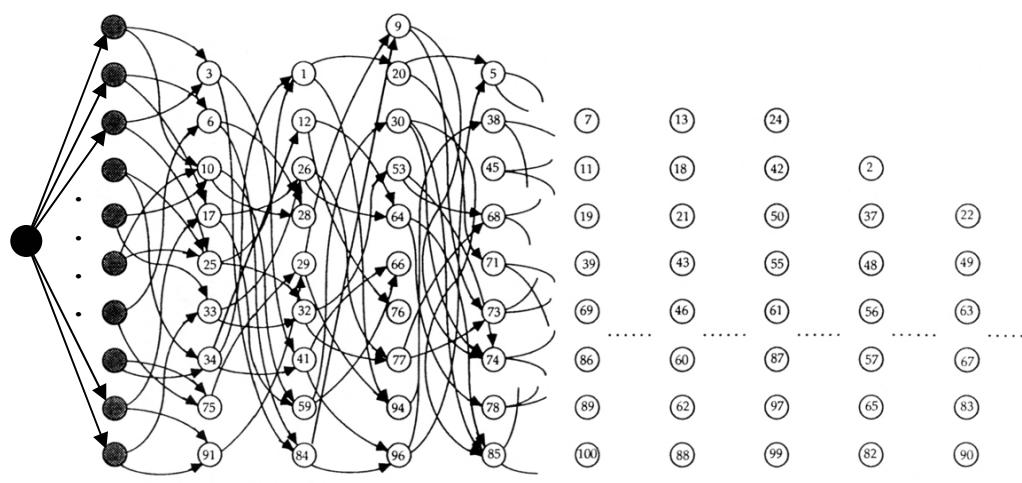
$t = 200$

network
structuration
by accretive
synfire growth

$t = 4000$



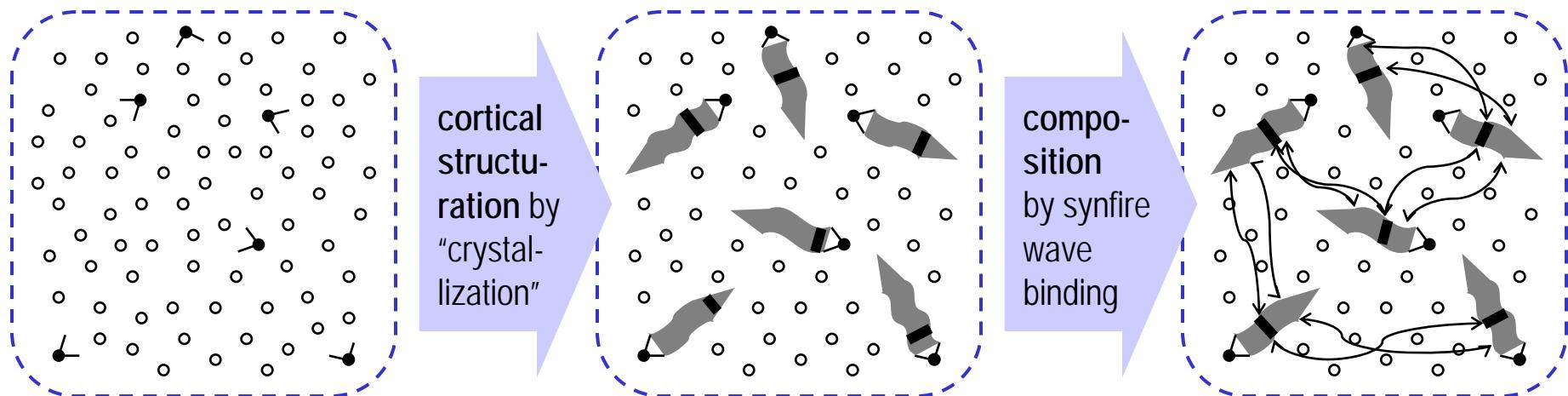
spatially
rearranged
view



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



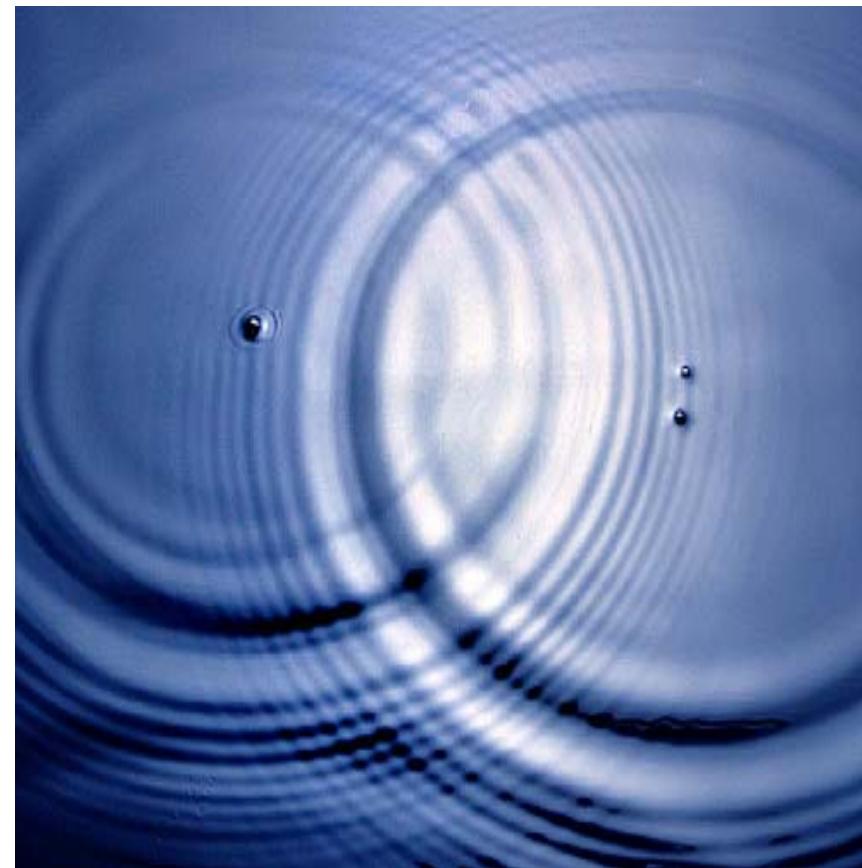
see Bienenstock (1995), Abeles, Hayon & Lehmann (2004), Trengrove (2005)

- ✓ 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

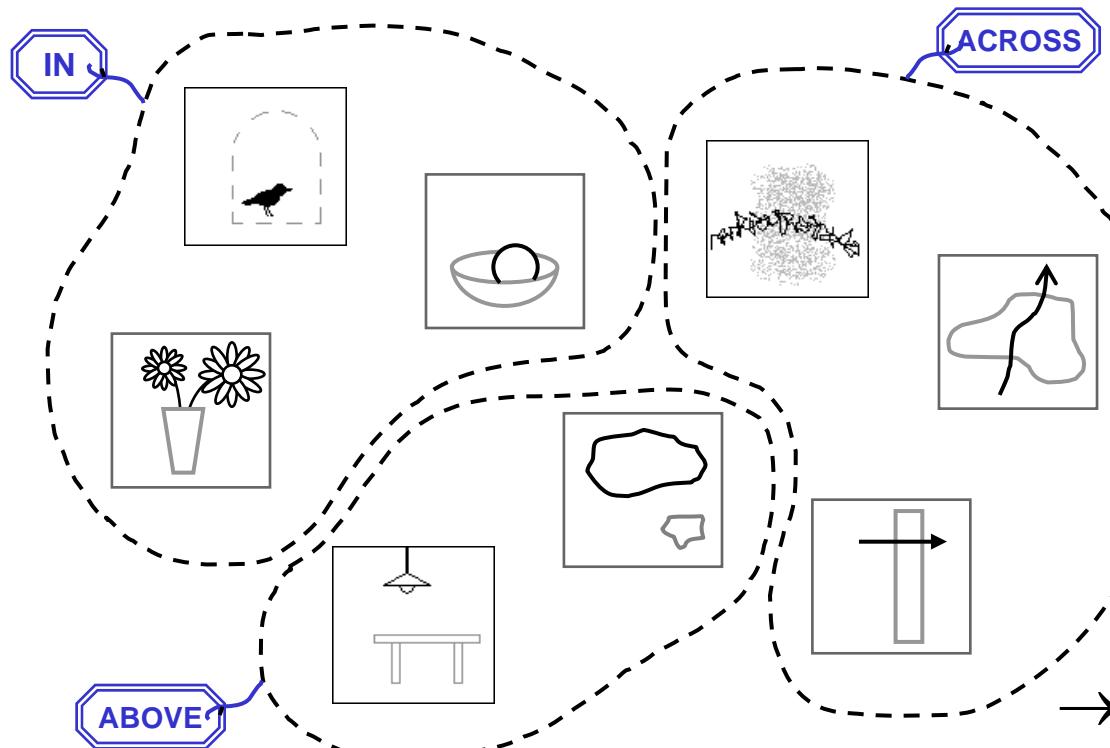
→ *STPs envisioned as excitable media, at criticality*



Doursat & Petitot (1997, 2005)

Ponds

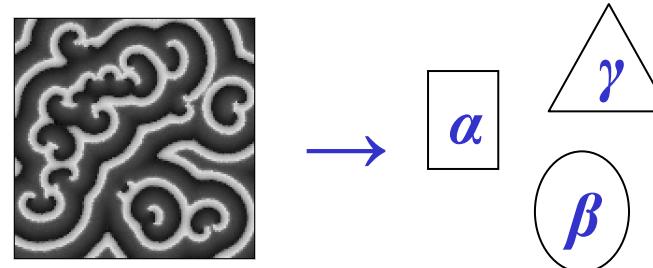
- Linguistic categories: the emergence of a symbolic level
 - ✓ we can map an infinite continuum of scenes to a few spatial labels



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

→ how are these transforms accomplished by the brain?

Embodied . . . computation?



schematization

+

categorization

=

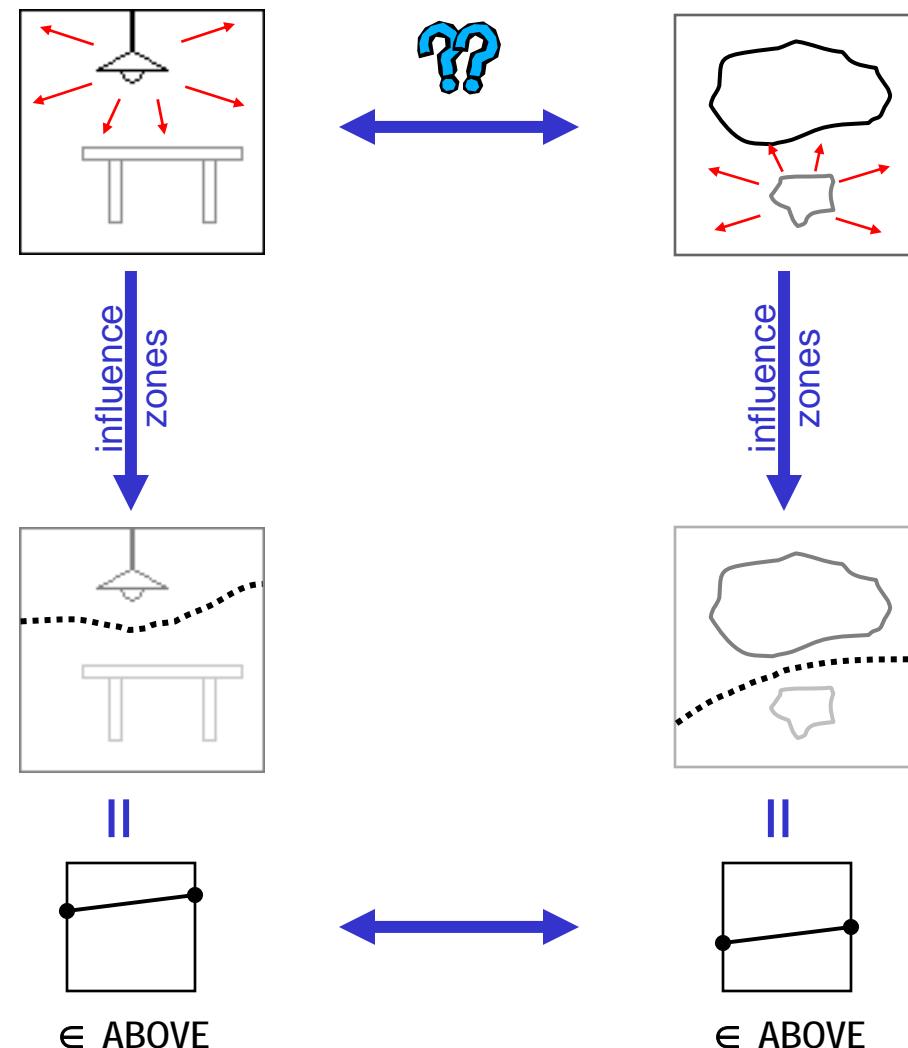
drastic reduction of information

- *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

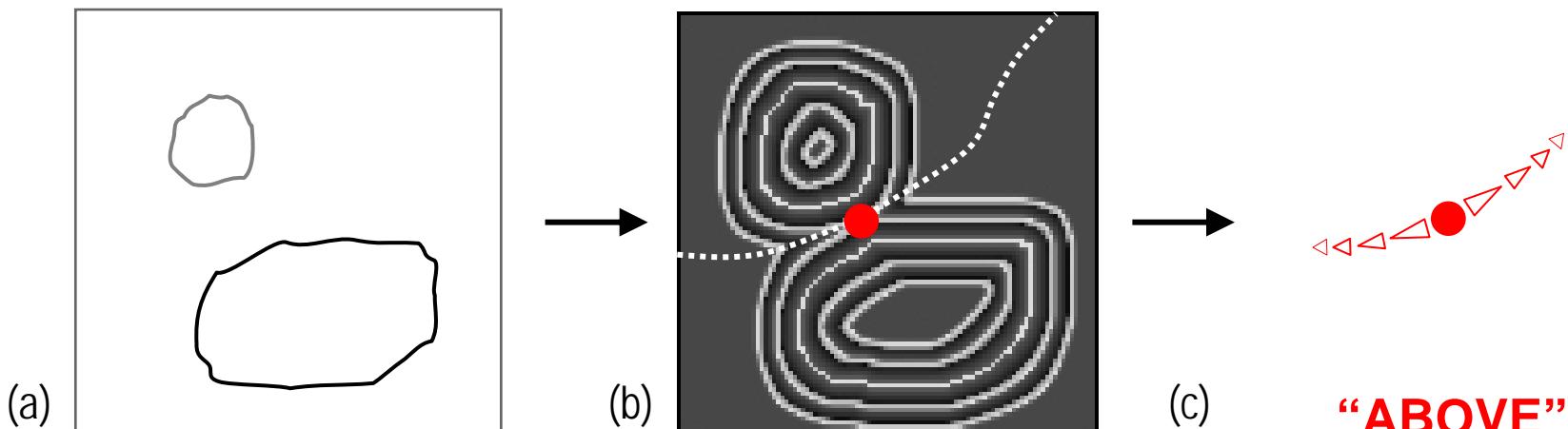


- ✓ what can be compared, however, are virtual structures generated by morphological transforms

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)

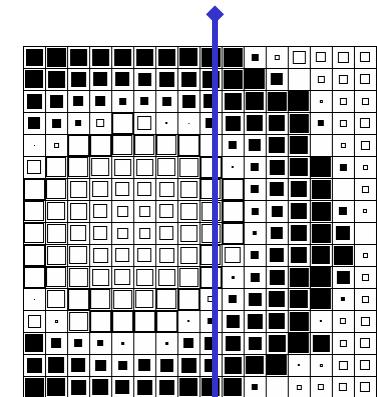
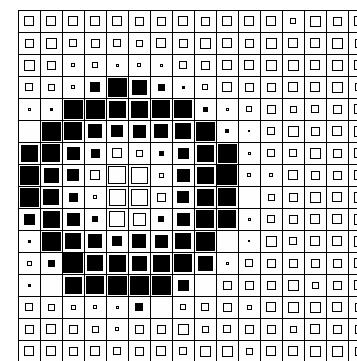
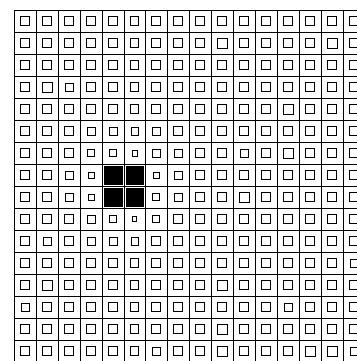
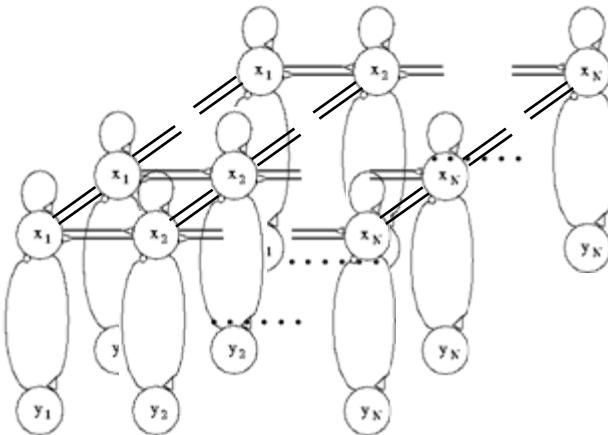


- ✓ for ex: in *traveling waves*, singularities are collision points
- ✓ (a) under the influence of an external input, (b) the internal dynamics of the system (c) spontaneously creates singularities that are characteristic of a symbolic category

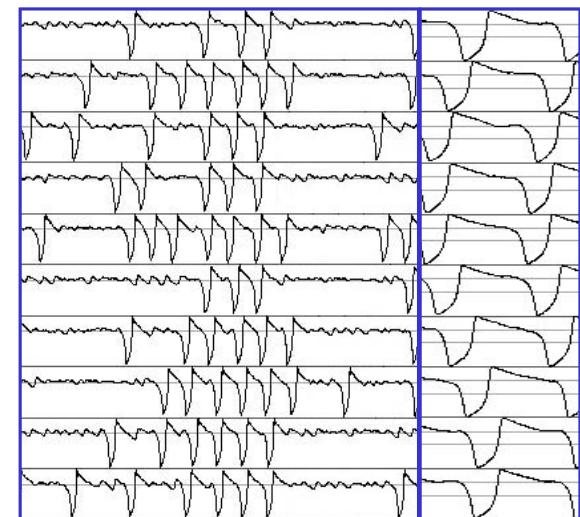
Ponds

➤ Spiking neural networks as excitable media

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

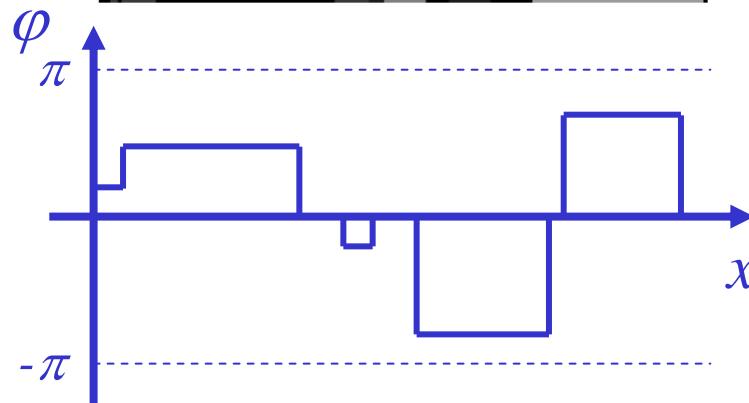
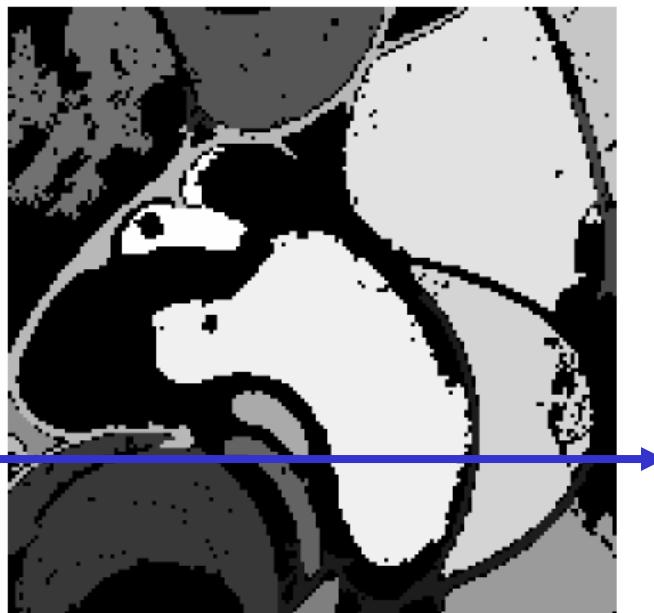


- ✓ *criticality* in neural dynamics: when slightly perturbed by an input, the network quickly transitions into a new regime of spatiotemporal order
- ✓ the structure and singularities of this regime are *influenced* by the input

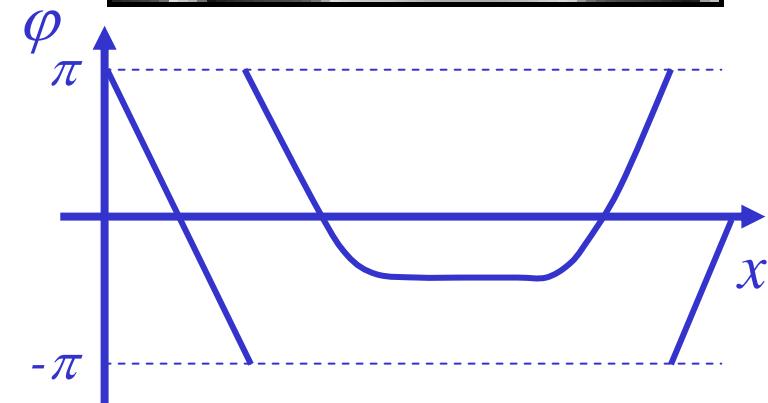
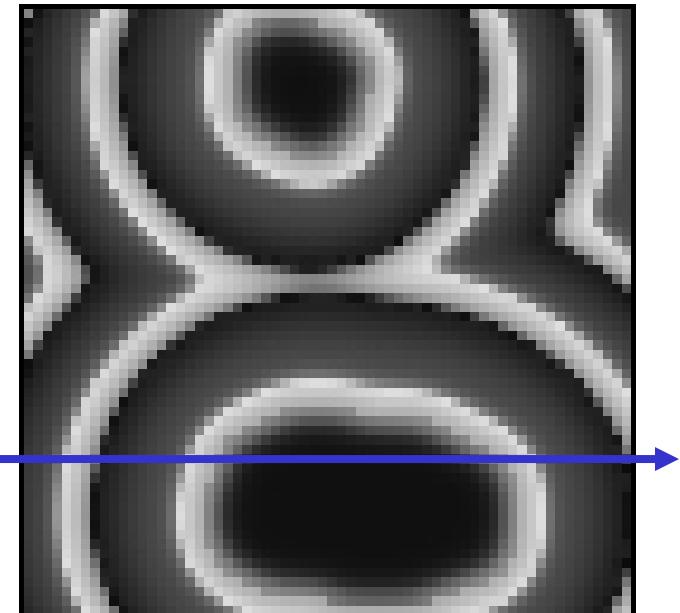


Instead of group synchronization: traveling waves

Instead of phase plateaus: phase gradients



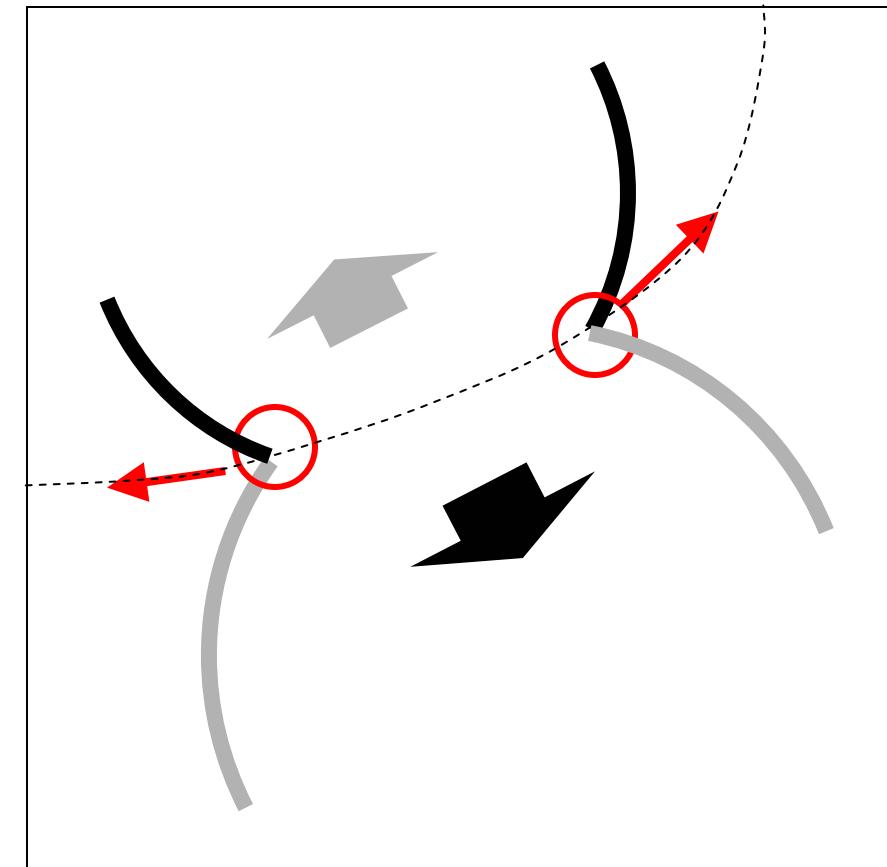
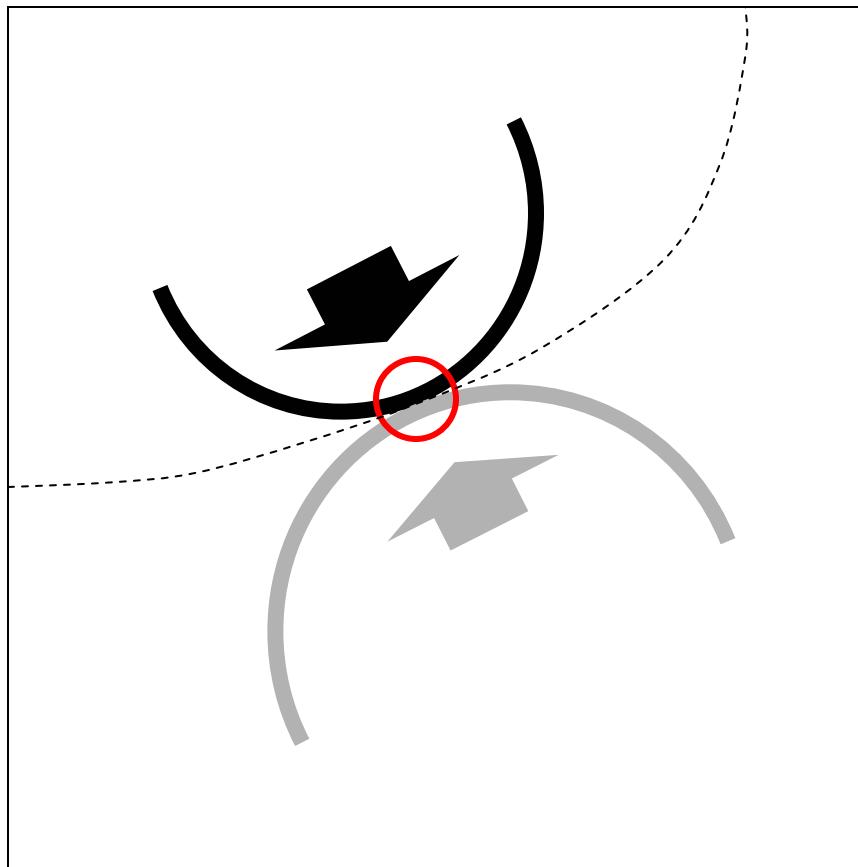
Wang, D. L. & Terman, D. (1997) Image segmentation based on oscillatory correlation. *Neural Computation*, 9: 805-836, 1997



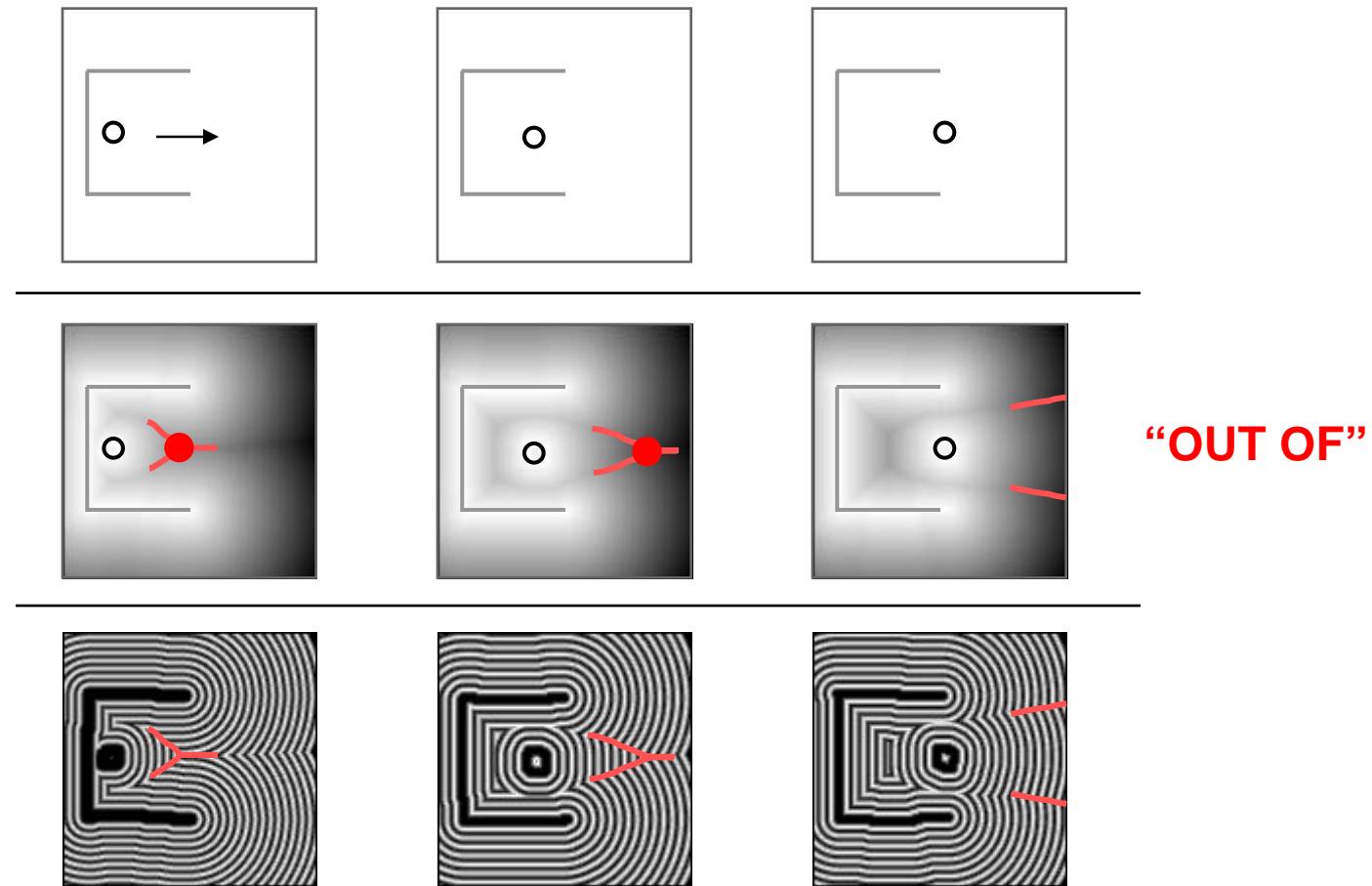
Doursat, R., & Petitot, J. (2005b) Dynamical models and cognitive linguistics: Toward an active morphodynamical semantics. To appear in *Neural Networks* (special issue on IJCNN 2005)

Spiking neural model supporting traveling waves

Detection of singular points



Dynamic evolution of singularities



- *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*

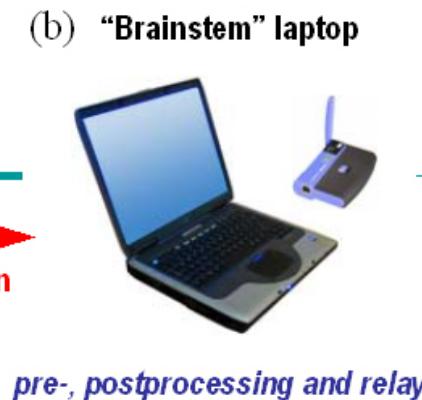
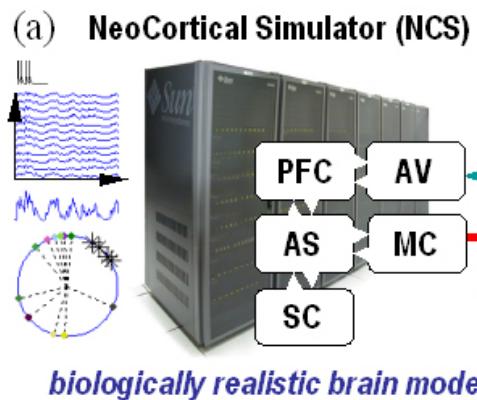


Doursat & Goodman (2006), Goodman, Doursat, Zou et al. (2007)

RAIN

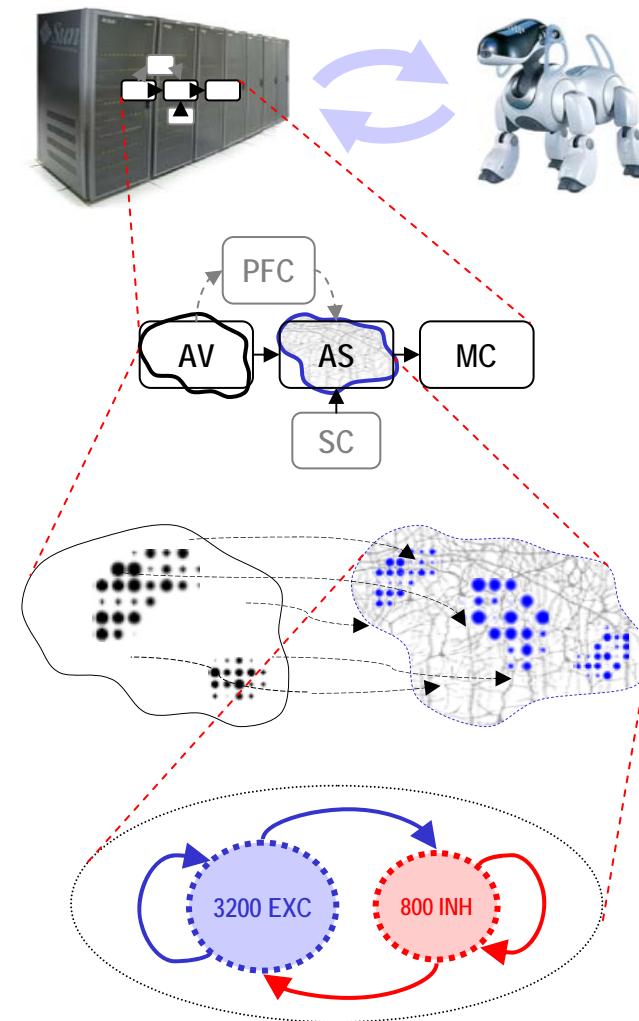
➤ Complete sensorimotor loop between cluster and robot

- ✓ 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

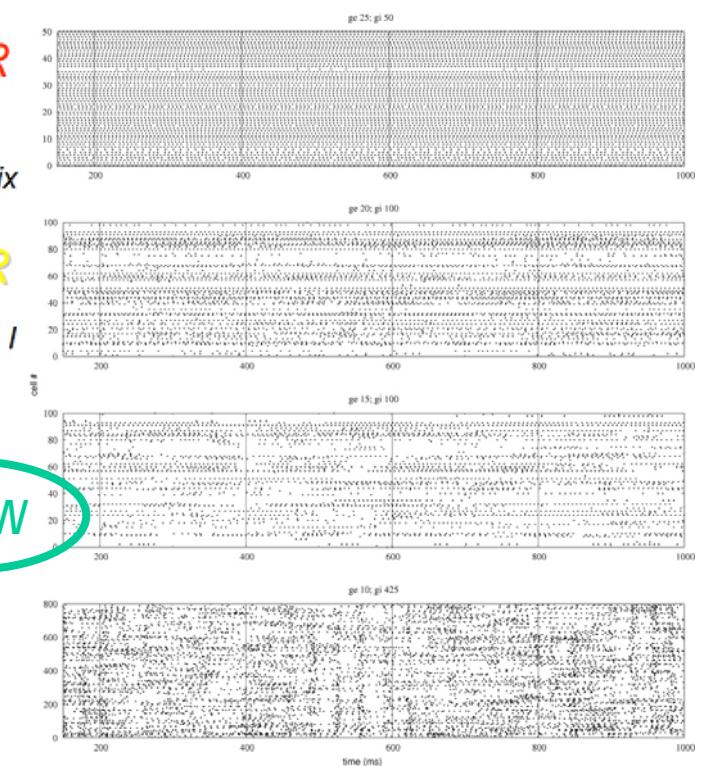
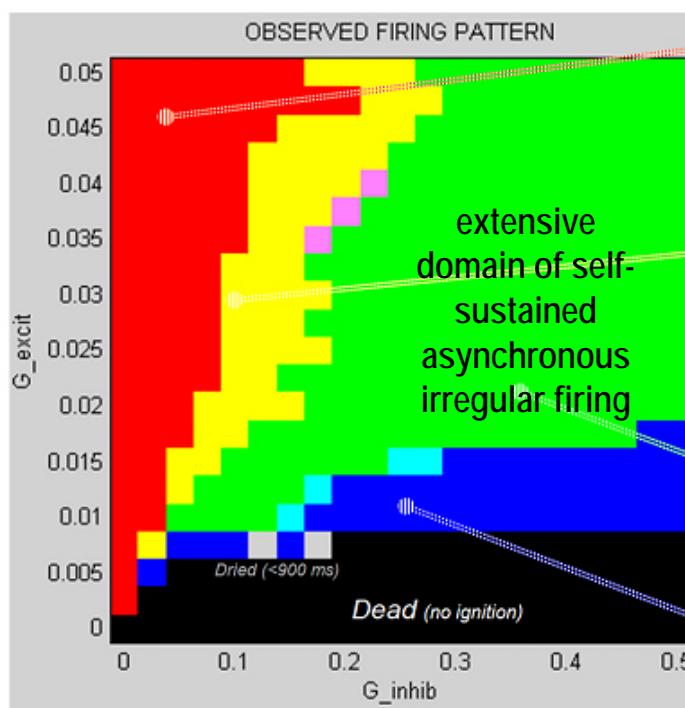
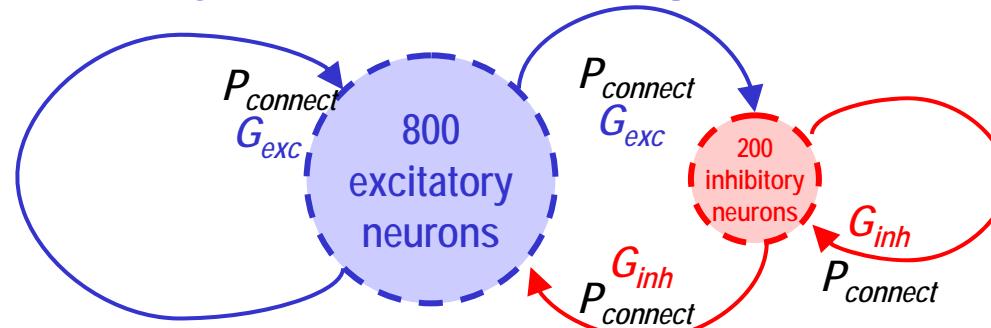
- Core of brain model: mesoscopic assemblies as RAINs



*RAIN: Recurrent Asynchronous
Irregular Network*

RAIN

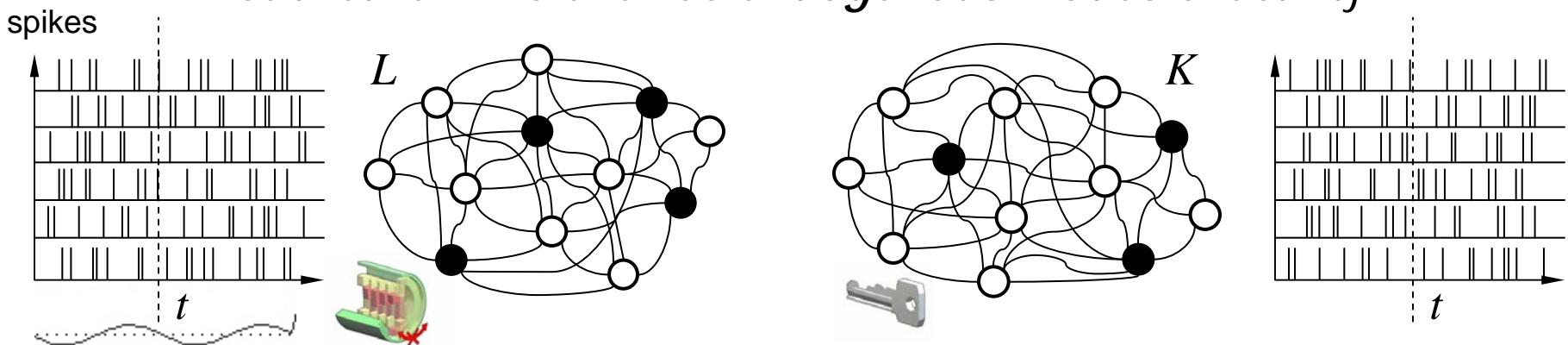
➤ Recurrent Asynchronous Irregular Network (RAIN)



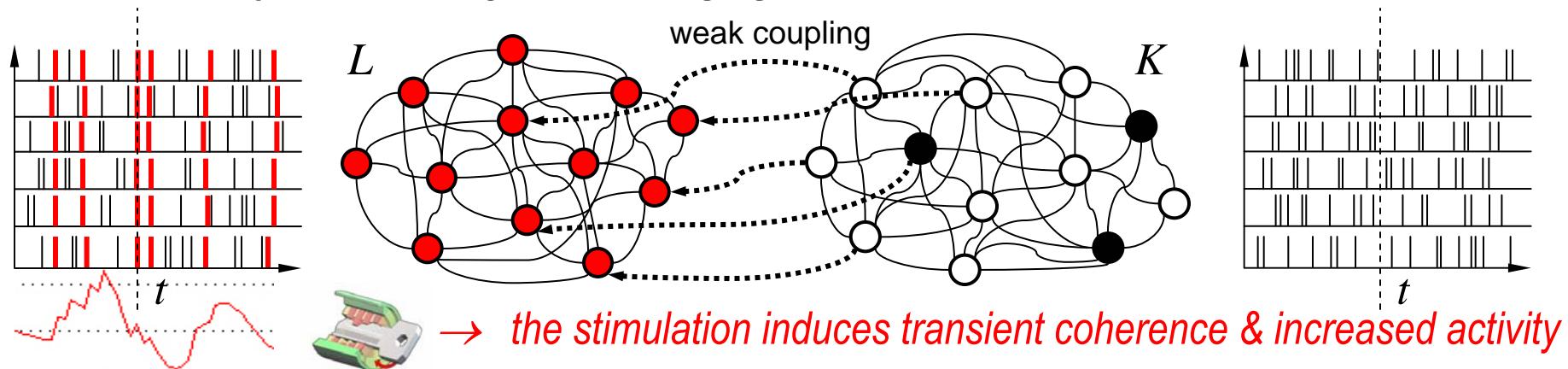
RAIN

➤ 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

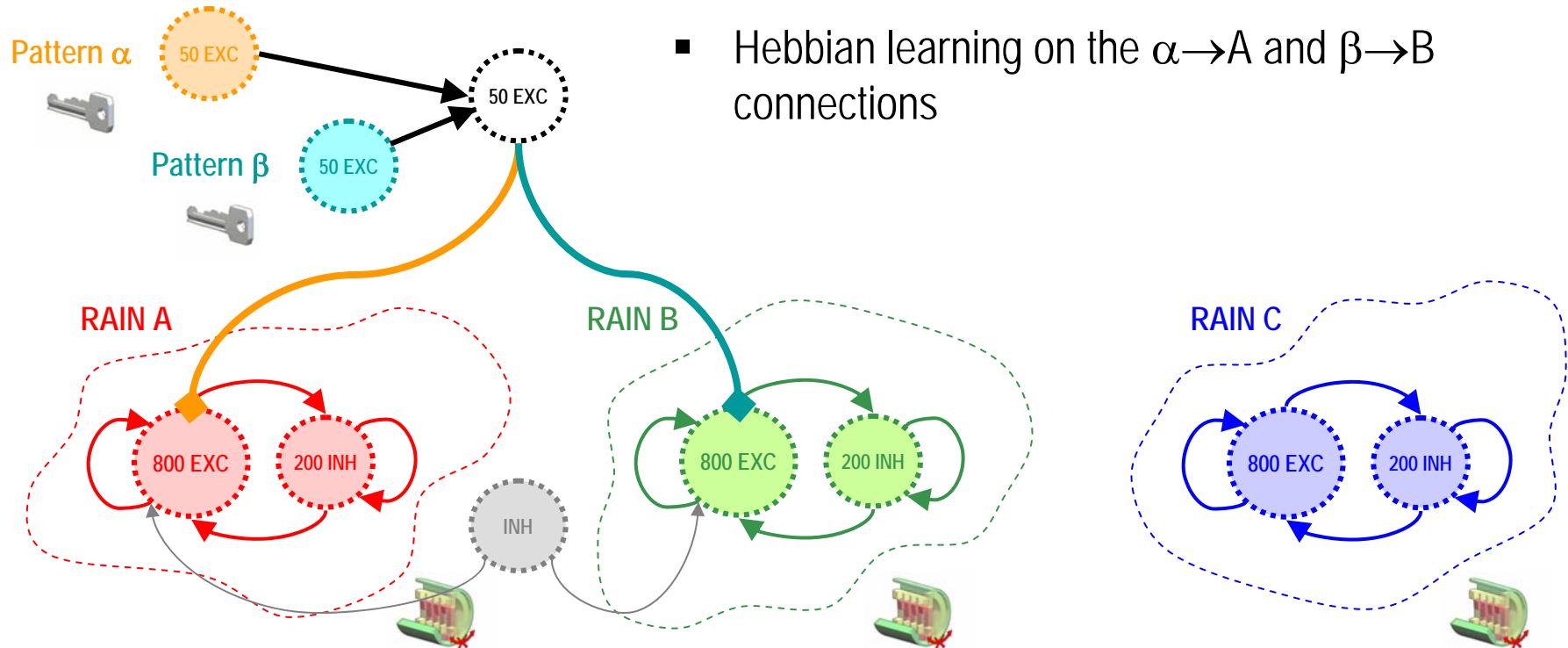


RAIN

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

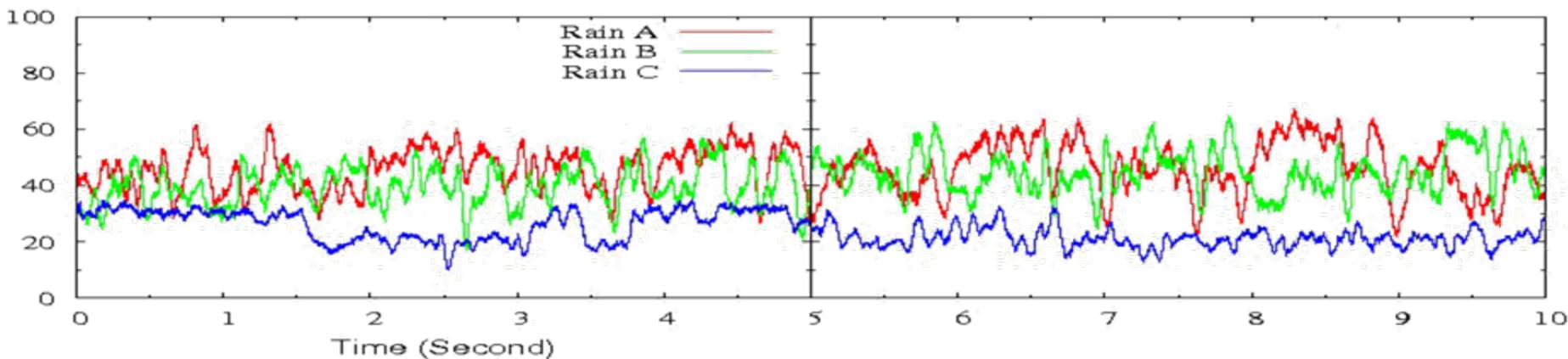
✓ numerical experiment involving

- 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

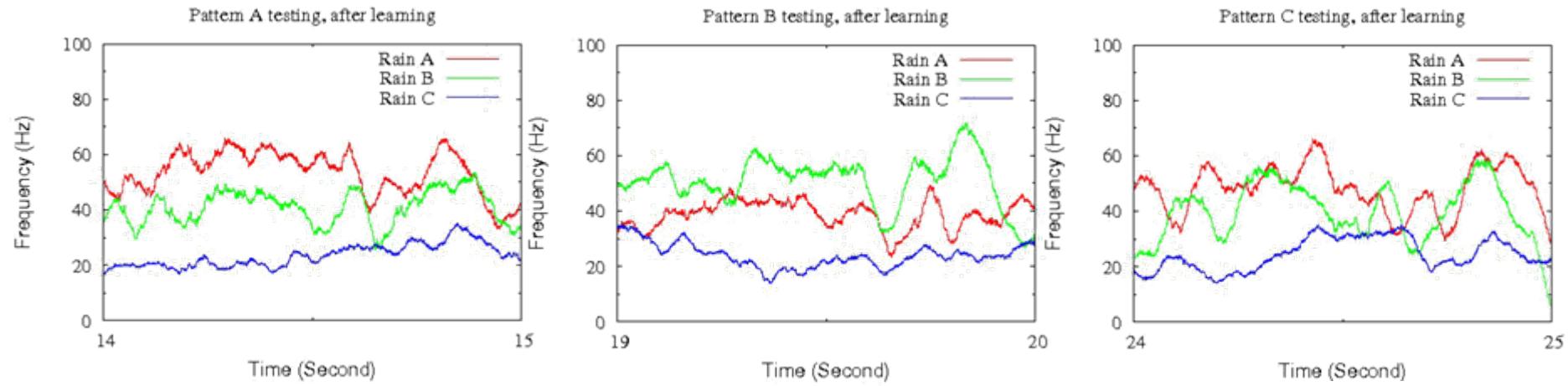


RAIN

- 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, compositionnalité
5. Trois études mésoscopiques
“Tapestry, ponds and RAIN” : synfire chains, ondes et résonance