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Of Tapestries, Ponds and RAIN:

Toward Fine-Grain Mesoscopic Neurodynamics in Excitable Media

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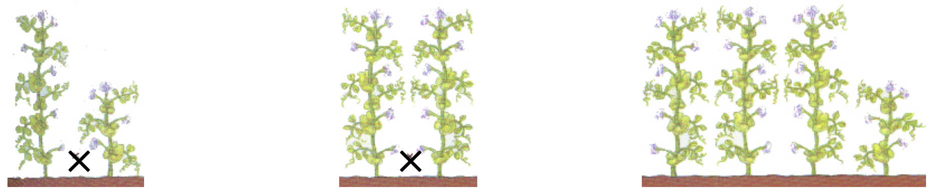
Toward a Fine-Grain Mesoscopic Neurodynamics

1. The Missing Mesoscopic Level of Cognition
2. Three Viewpoints on Fine-Grain Neurodynamics
   a. The self-made tapestry of synfire chains
   b. Waves in a morphodynamic pond
   c. Lock-and-key coherence in Recurrent Asynchronous Irregular Networks (RAIN)
3. A Multiscale Perspective on Neural Causality

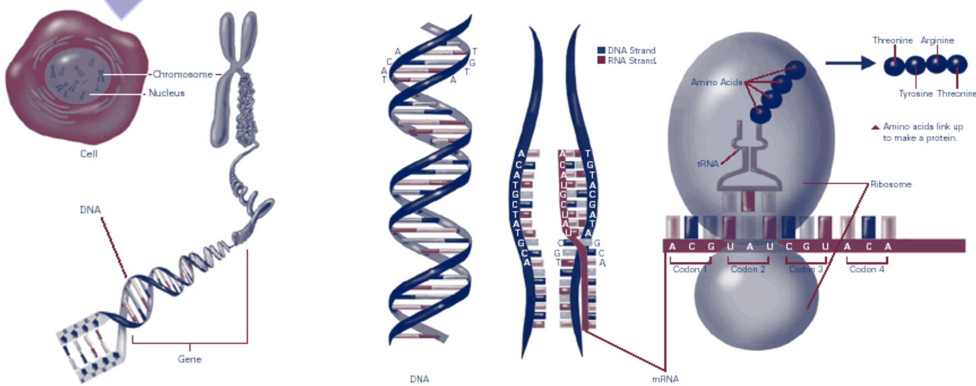
1. Mesoscopic Cognition

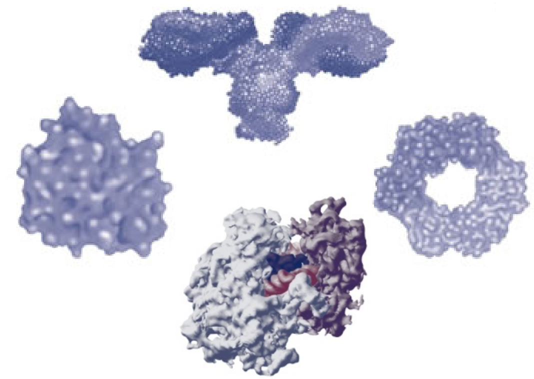
macrolevel:
genetics

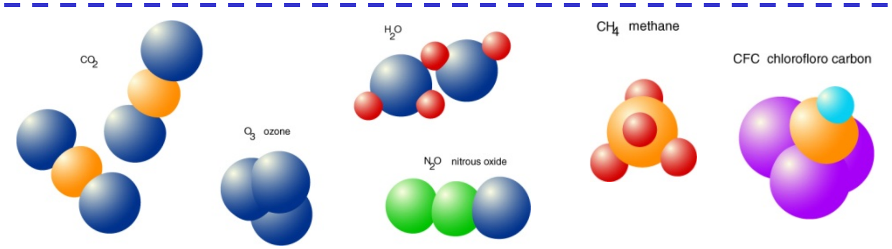


TT × Tt → Tt × Tt → TT, Tt, tT, tt

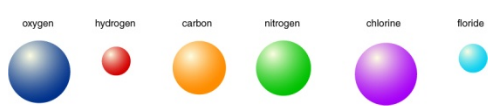
mesolevel:
molec. biology







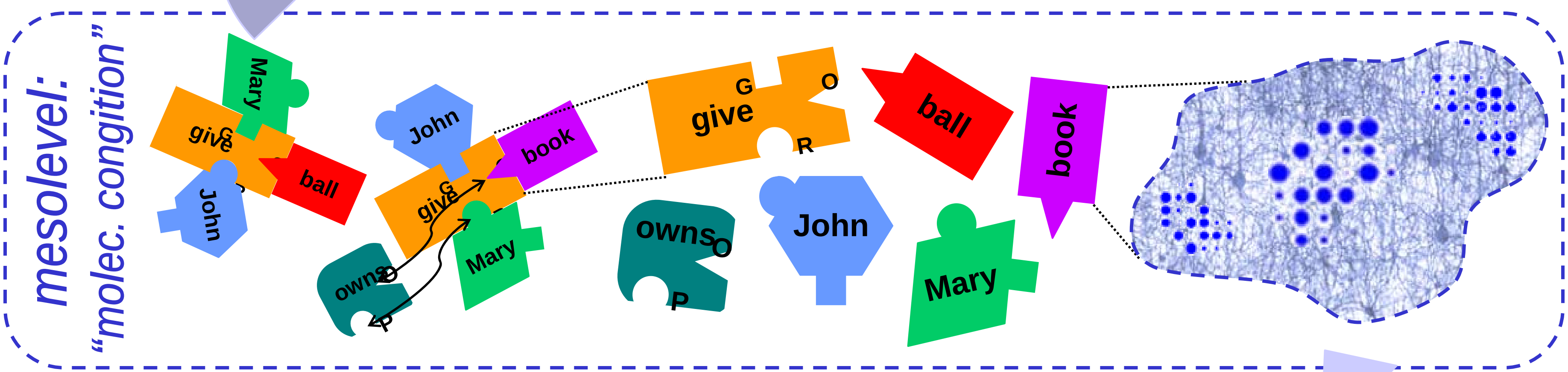
microlevel:
atoms



1. Mesoscopic Cognition

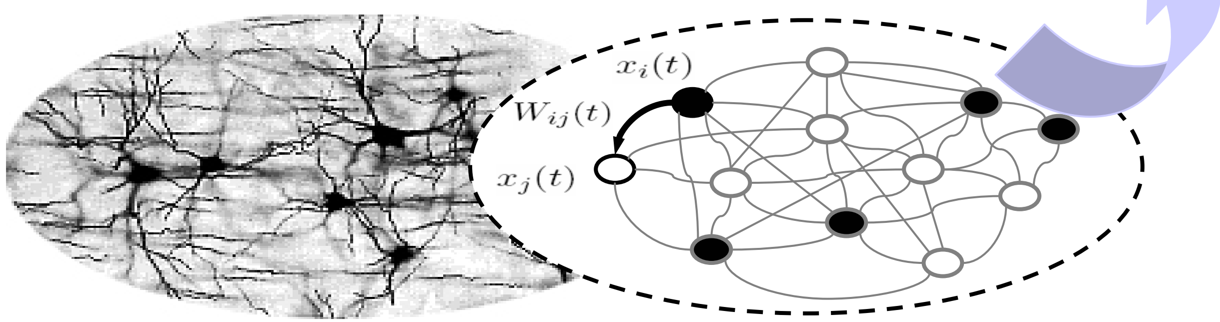
macrolevel:
symbols

“John gives a book to Mary” → **“Mary is the owner of the book”**



after Elie Bienenstock (1995, 1996)

microlevel:
neurons



1. Mesoscopic Cognition

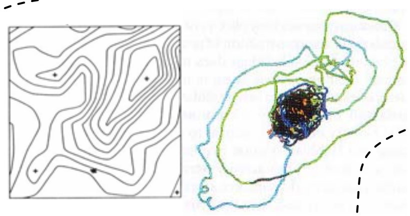
- AI: symbols, syntax → production rules
  - ✓ *logical systems* define high-level *symbols* that can be *composed* together in a generative way
  - → *they are lacking a "microstructure" needed to explain the fuzzy complexity of perception, categorization, motor control, learning*
- Missing link: "mesoscopic" level of description
  - ✓ cognitive phenomena emerge from the underlying *complex systems* neurodynamics, via intermediate *spatiotemporal patterns*
- Neural networks: neurons, links → activation rules
  - ✓ in neurally inspired *dynamical systems*, the *nodes* of a network *activate* each other by association
  - → *they are lacking a "macrostructure" needed to explain the systematic compositionality of language, reasoning, cognition*

1. Mesoscopic Cognition

➢ Populating the mesoscopic level: neural field models

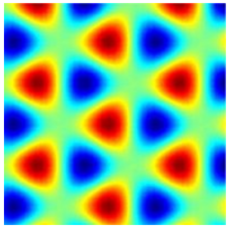
field mesolevel

spatial EEGs, chaotic attractors



Freeman (1994)

bumps, blobs, bubbles



Amari (1975, 1977)

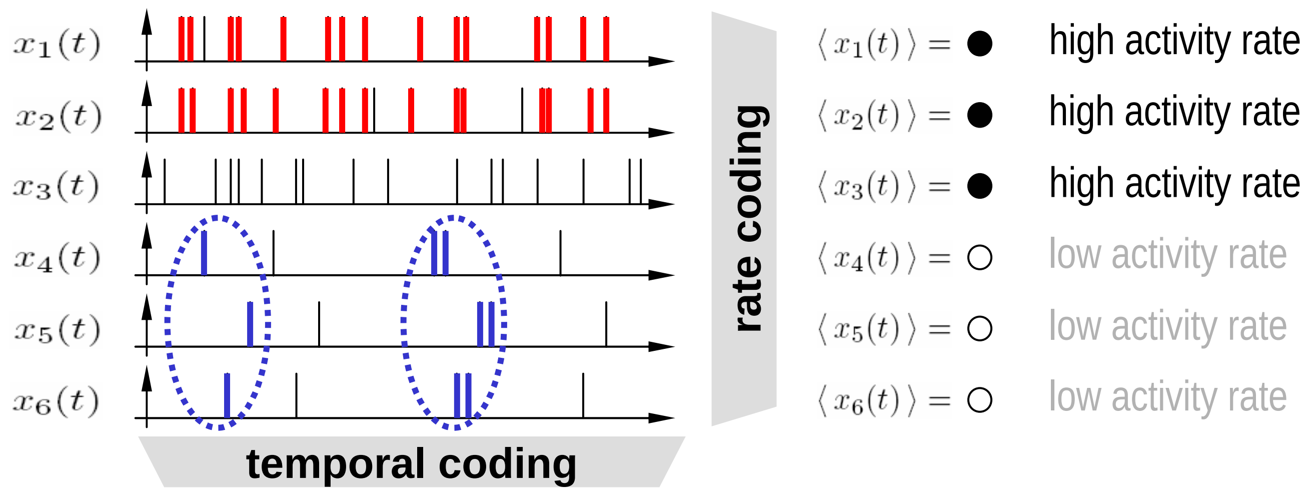
✓ neural ensembles characterized by ***mean field variables***, continuous in time and space, e.g.

- local field potentials
- firing rates (spike densities)
- neurotransmitter densities, etc.

1. Mesoscopic Cognition

➢ Below mean firing-rate coding: precise temporal coding

- more than mean rates → *temporal correlations* among spikes
- zero delays: synchrony
- nonzero delays: rhythms

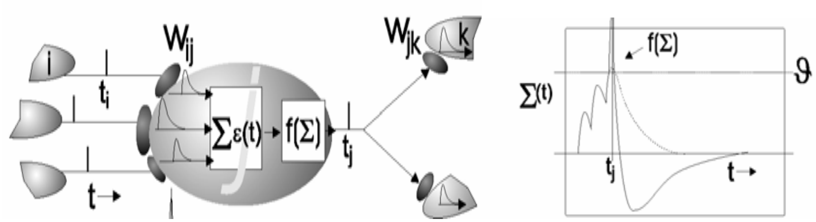


$\boxed{\langle\, x_1(t)\, x_2(t) \,\rangle \gg \langle\, x_1(t)\, x_3(t) \,\rangle}$ ➢ 1 and 2 more in sync than 1 and 3

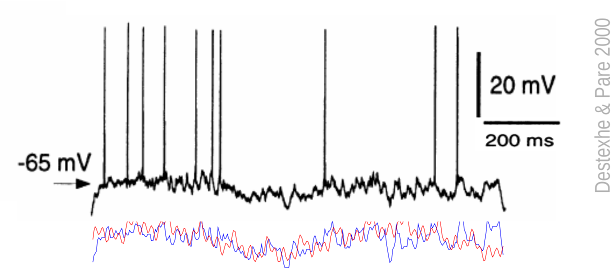
$\boxed{\langle\, x_4(t)\, x_5(t-\tau_{4,5})\, x_6(t-\tau_{4,6}) \,\rangle}$ ➢ 4, 5 and 6 correlated through delays

➢ Below digital temporal coding: analog temporal coding

- more than spikes → *membrane potential*



S. M. Bohte, 2003



1. Mesoscopic Cognition

➢ Populating the mesoscopic level: spiking neural models

✓ large-scale, localized dynamic cell assemblies that display complex, *reproducible* digital-analog regimes of neuronal activity

→ fine-grain *spatiotemporal patterns* (STPs)

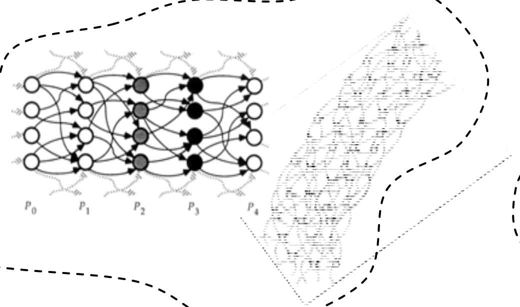

tapestries


ponds


RAIN

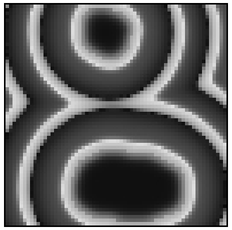
spiking mesolevel

synfire chains & braids



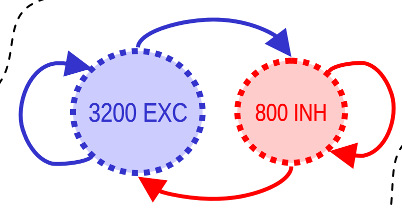
Abeles (1982),
Doursat (1991), Bienenstock (1995), D & B (2006)

morphodynamic waves



Doursat & Petitot (1997, 2005)

RAIN lock-&-key coherence

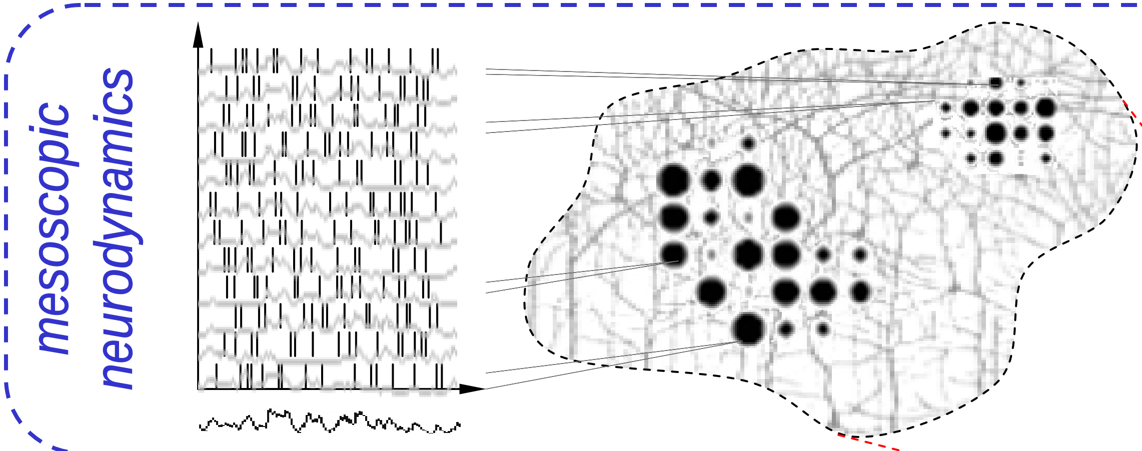


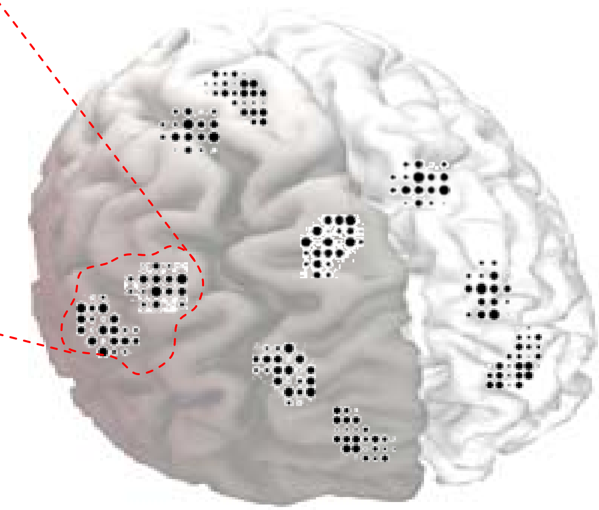
Vogels & Abbott (2006)
Doursat & Goodman (2006)

1. Mesoscopic Cognition

➢ The dynamic richness of spatiotemporal patterns (STPs)

- ✓ large-scale, localized dynamic cell assemblies that display complex, *reproducible* digital-analog regimes of neuronal activity
- ✓ these regimes of activity are supported by specific, *ordered* patterns of recurrent synaptic connectivity





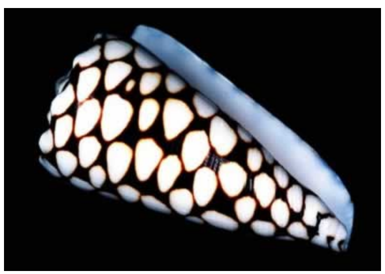
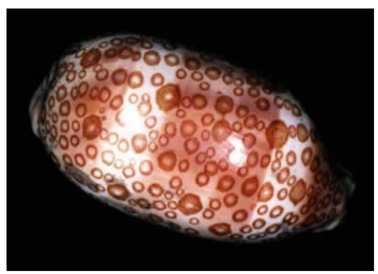
- ✓ mesoscopic neurodynamics: construing the brain as a (spatio-temporal) *pattern formation machine*

1. Mesoscopic Cognition

➢ Biological development is all about pattern formation

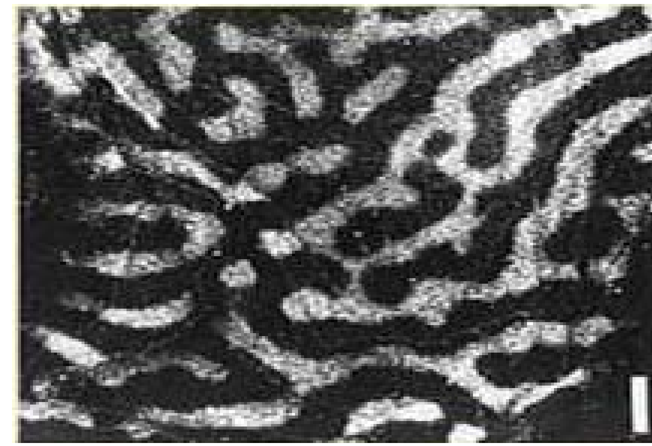
✓ static, structural patterning



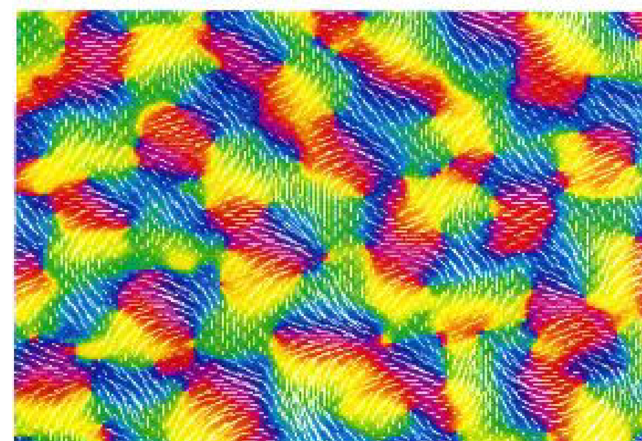



Scott Camazine, http://www.scottcamazine.com

✓ why would the brain be different?



ocular dominance stripes Hubel & Wiesel, 1970



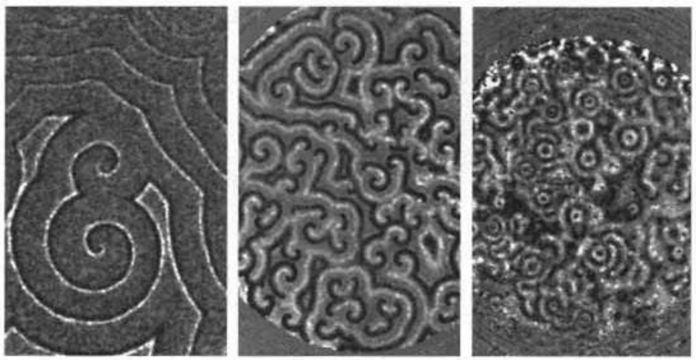
orientation column "pinwheels" Blasdel, 1992

1. Mesoscopic Cognition

➢ Tissue physiology is also about pattern formation

✓ dynamic, functional pattng

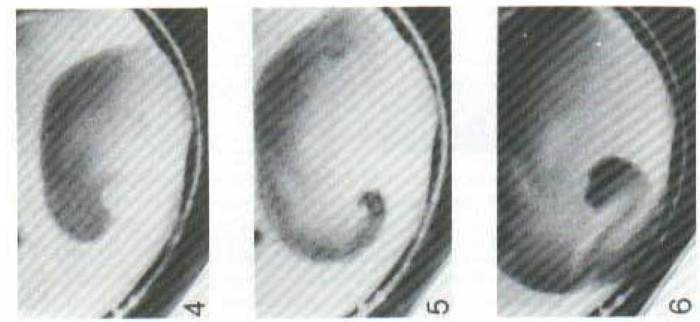
Aggregating slime mold
B. Goodwin, Schumacher College, UK



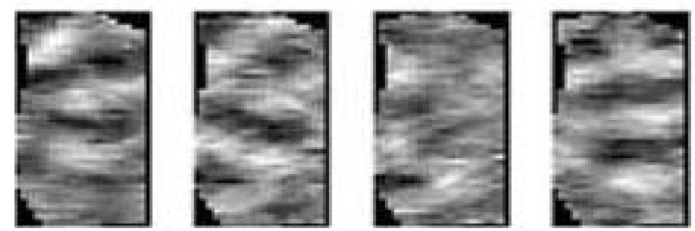
Model of dog heart
J. Keener, University of Utah

✓ why would the brain be different?

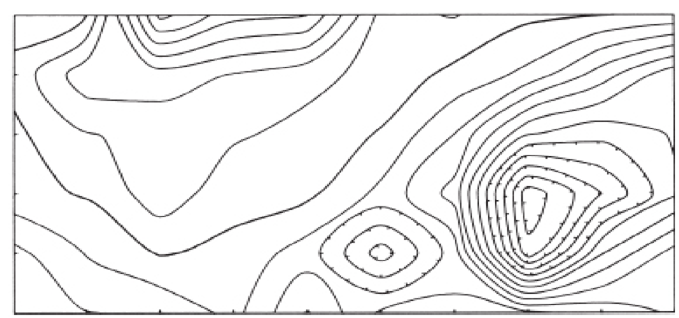
Chicken retina waves
Gorelova & Bures, 1983



Spontaneous VC activity Grinvald



Olfactory bulb phase pattern W. Freeman



1. Mesoscopic Cognition

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

  a) endogenously produced by the neuronal substrate,

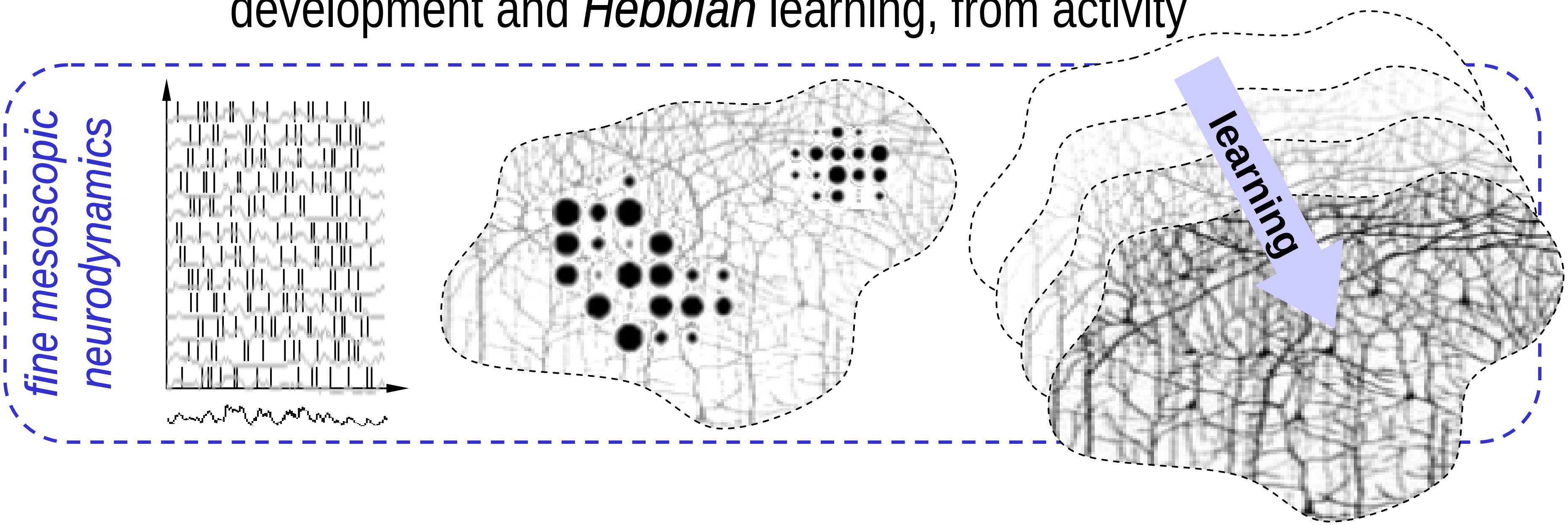
  b) exogenously evoked & perturbed under the influence of stimuli,

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

1. Mesoscopic Cognition

a) Mesoscopic patterns are endogenously produced

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

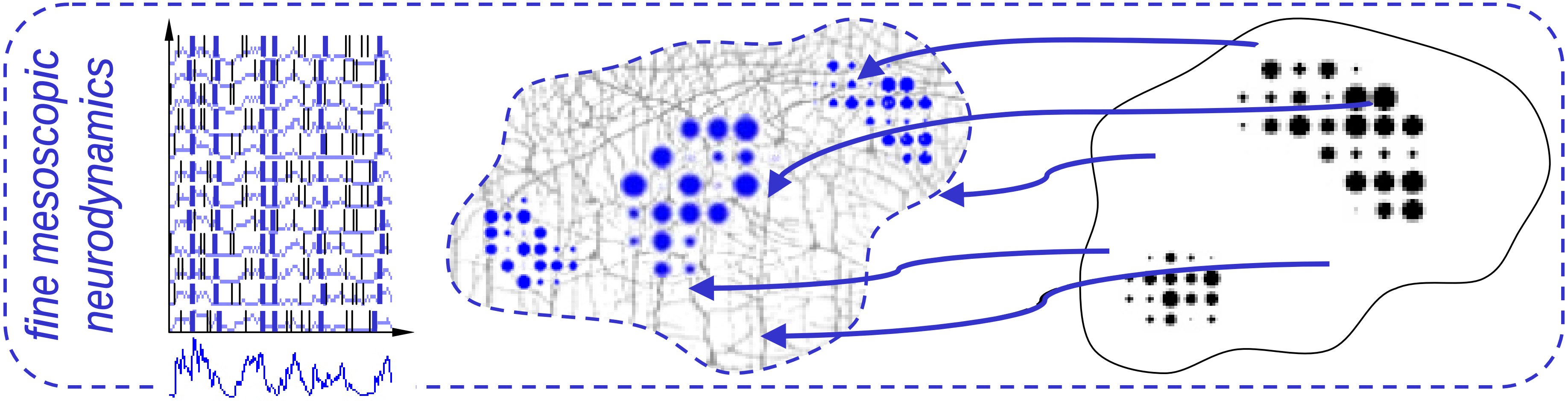


→ *the identity, specificity or stimulus-selectiveness of a mesoscopic entity is largely determined by its internal pattern of connections*

1. Mesoscopic Cognition

b) Mesoscopic patterns are exogenously influenced

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

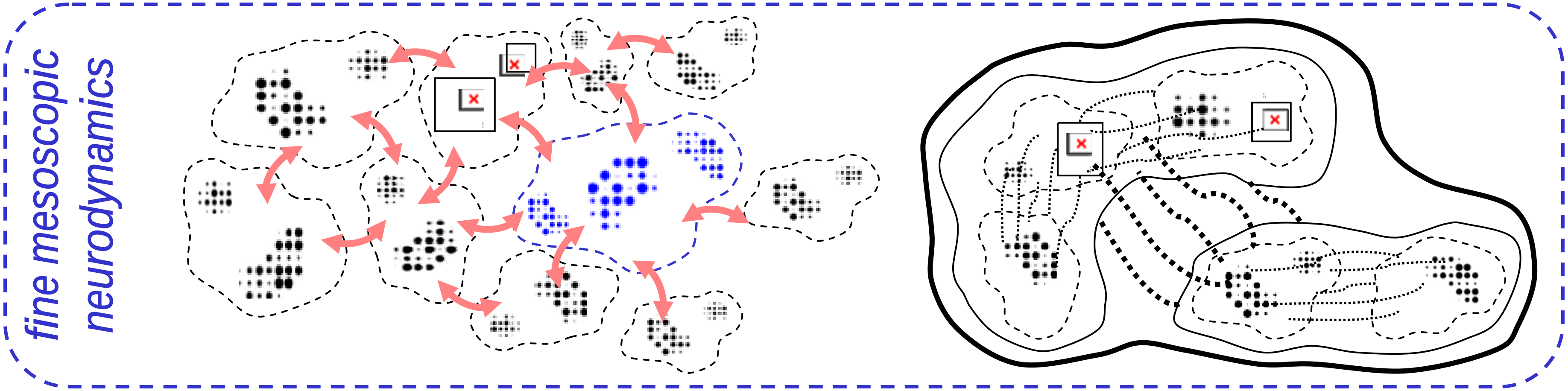


- ✓ mesoscopic entities may have stimulus-specific ***recognition or "representation"*** abilities, without being "templates" or "attractors" (no resemblance to stimulus)

1. Mesoscopic Cognition

c) Mesoscopic patterns interact with each other

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



evolutionary population paradigm

molecular compositionality paradigm

Toward a Fine-Grain Mesoscopic Neurodynamics

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2. Three Viewpoints on Fine-Grain Neurodynamics

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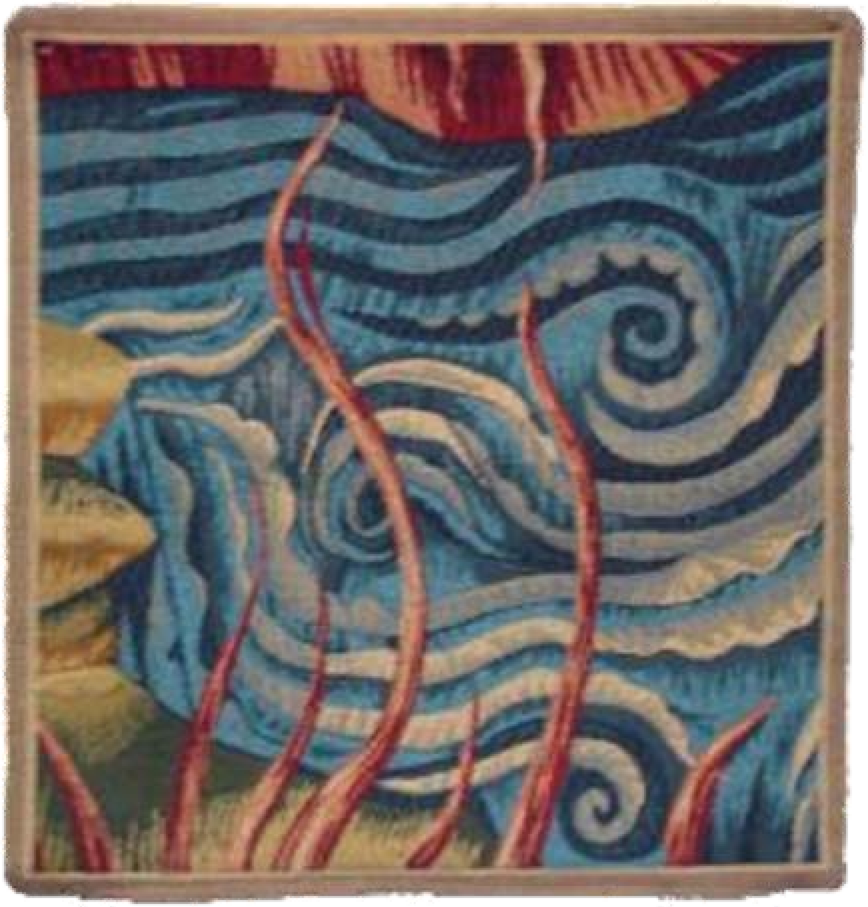
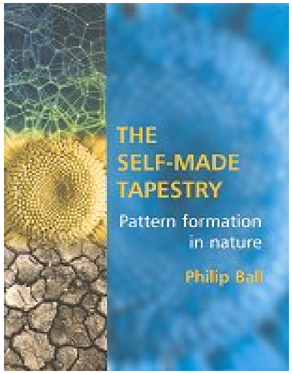
2. Fine-Grain Neurodynamics

a) The self-made tapestry of synfire chains

→ *constructing the architecture of STPs*



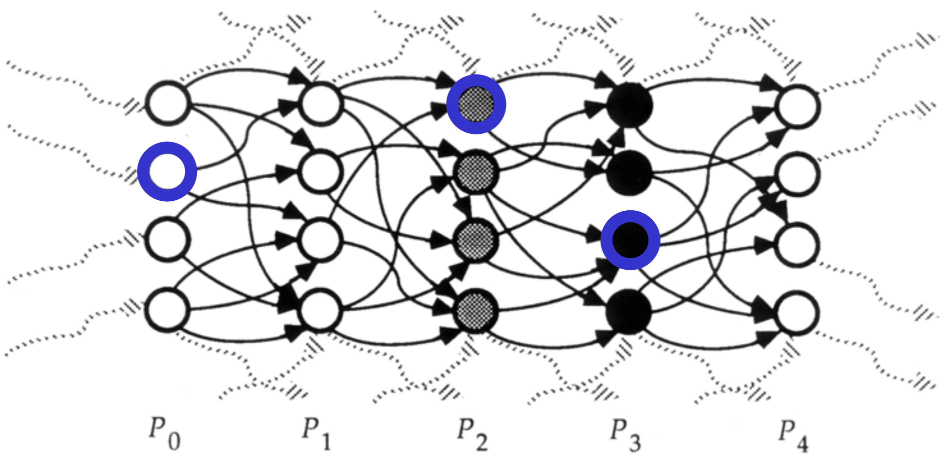


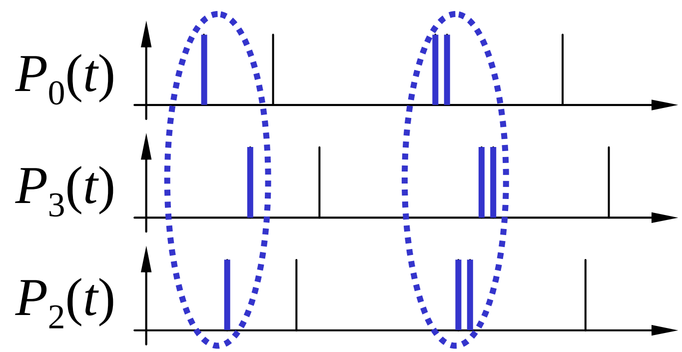
Doursat (1991), Bienenstock (1995), Doursat & Bienenstock (2005)

2. Fine-Grain Neurodynamics

➢ 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)

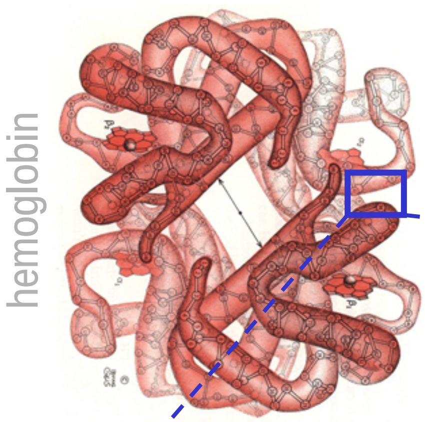




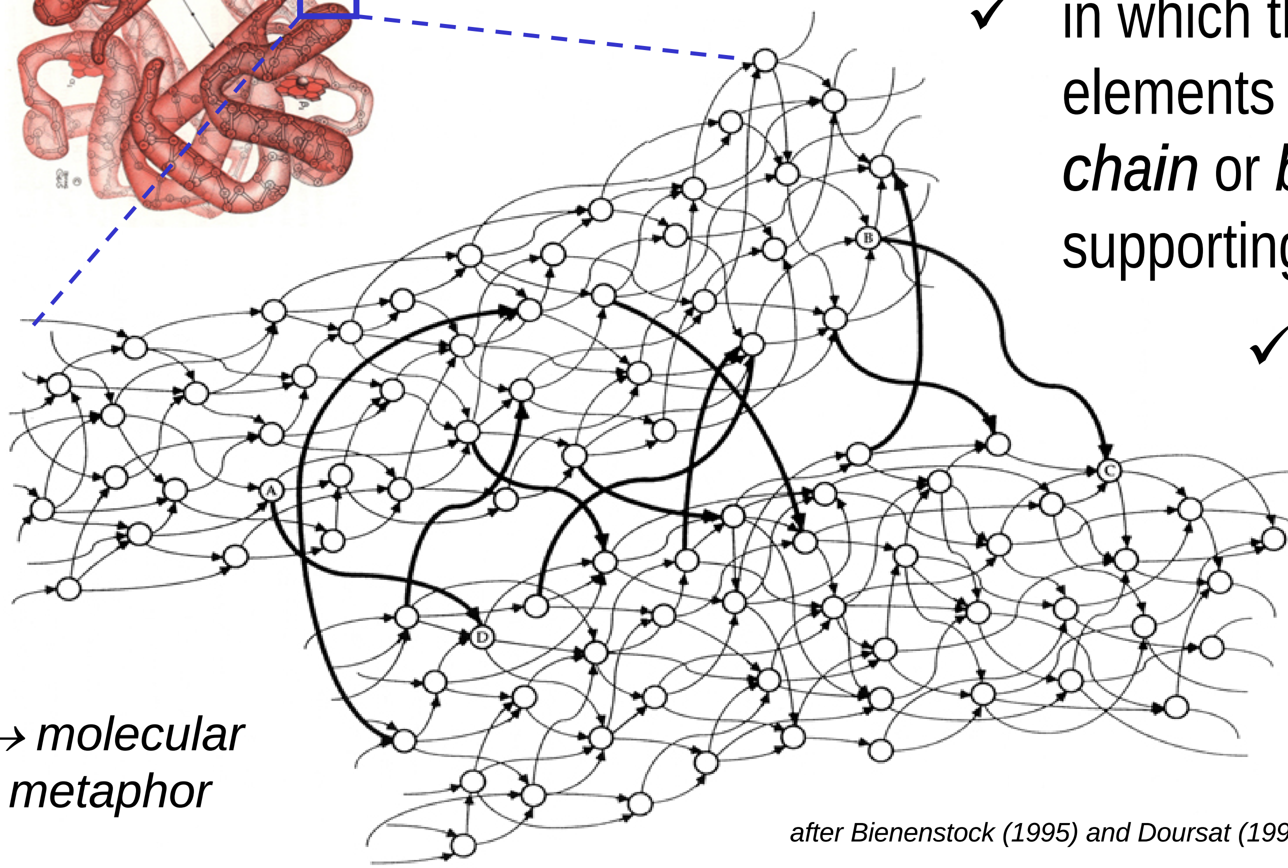
- ✓ synfire chains have been hypothesized to explain neurophysiological recordings containing statistically significant delayed correlations
- ✓ the redundant divergent/convergent connectivity of synfire chains can preserve accurately synchronized action potentials, even under noise

2. Fine-Grain Neurodynamics

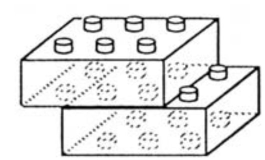
➢ Synfire patterns can *bind*, thus support compositionality



- ✓ 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 synchronization through ***coupling links***



after Bienenstock (1995) and Doursat (1991)

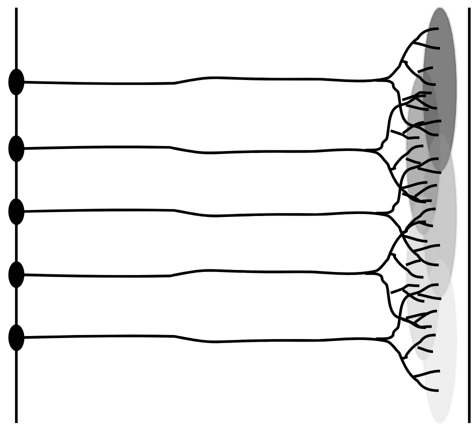


→ molecular metaphor

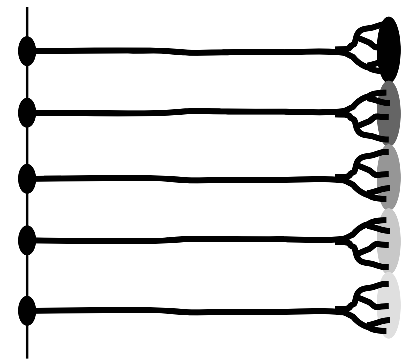
2. Fine-Grain Neurodynamics

➢ 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



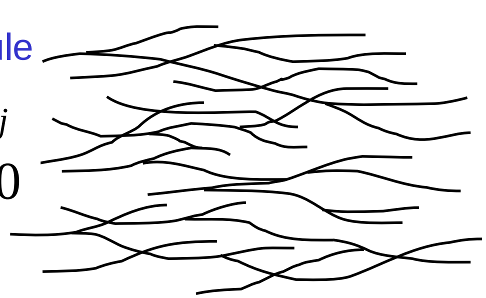
after Willshaw & von der Malsburg (1976)

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

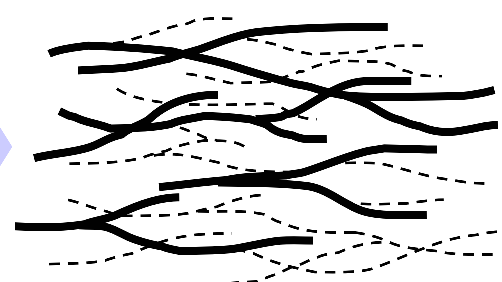
1. Hebbian rule

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

2. sum rule



"selective stabilization" by activity/connectivity feedback

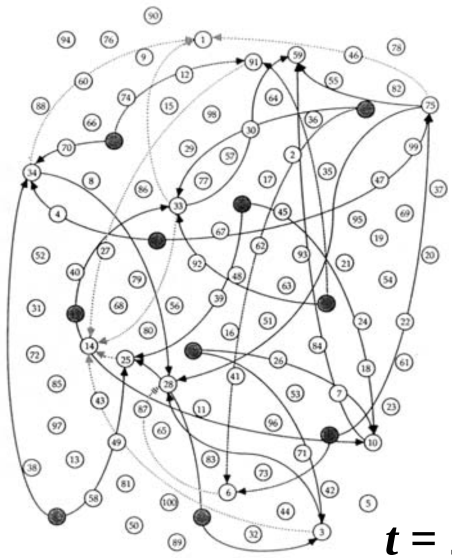


after Changeux & Danchin (1976)

2. Fine-Grain Neurodynamics

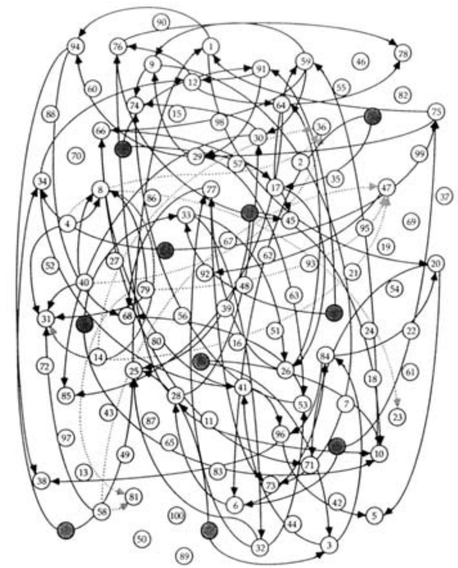
- Synfire chains develop recursively, adding groups 1 by 1

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



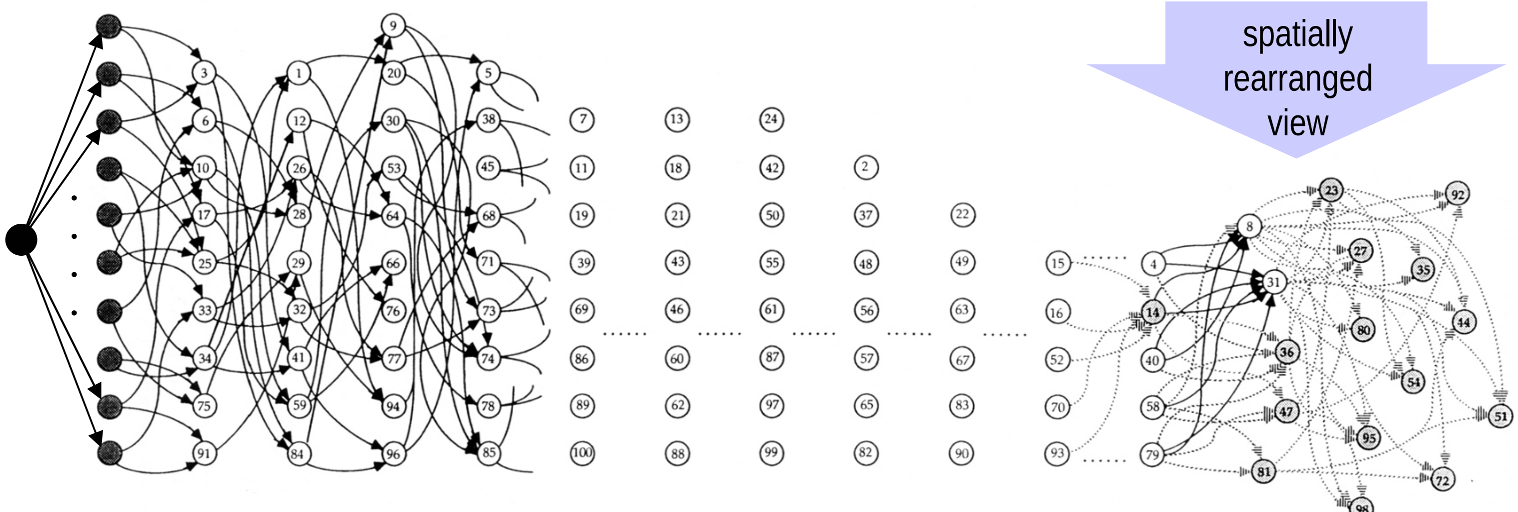
$t = 200$

network **structuration** by accretive synfire growth



$t = 4000$

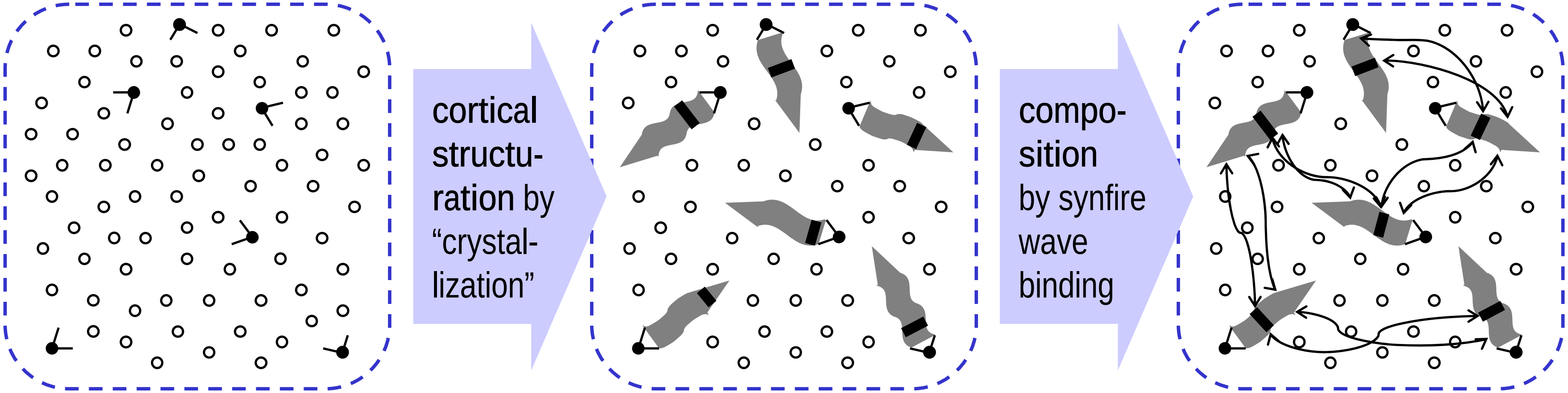
spatially rearranged view



2. Fine-Grain Neurodynamics

➢ 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



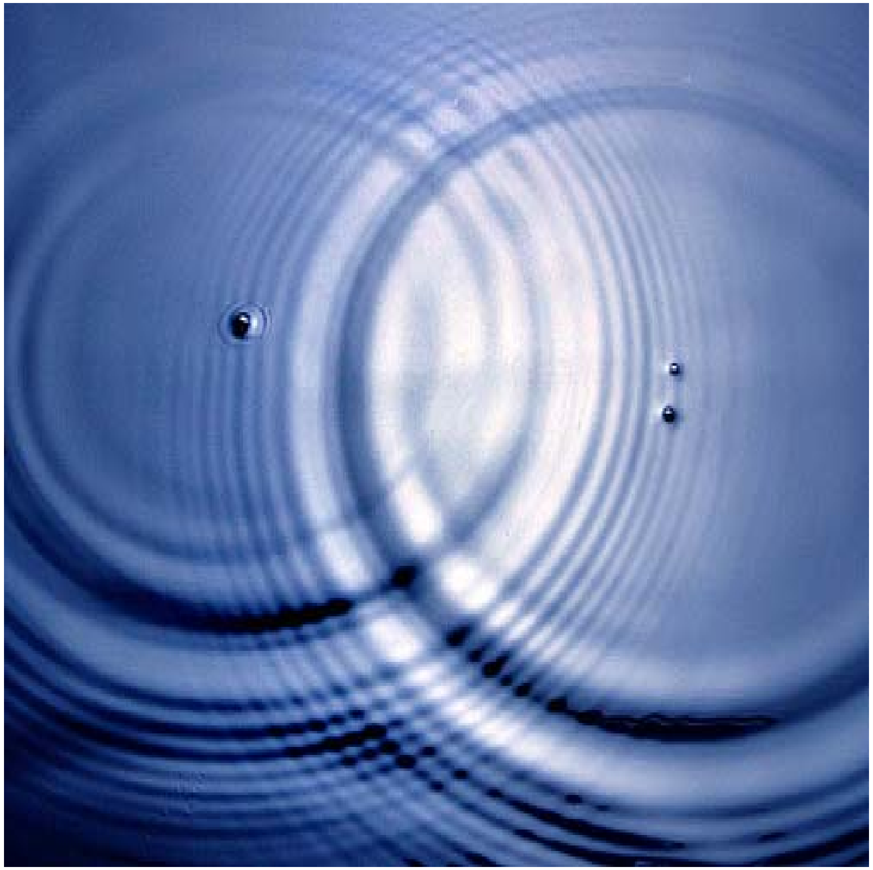
see Bienenstock (1995), Abeles, Hayon & Lehmann (2004), Trengrove (2005)

- ✓ 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

2. Fine-Grain Neurodynamics

b) Waves in a morphodynamic pond

→ *STPs envisionned as excitable media, at criticality*

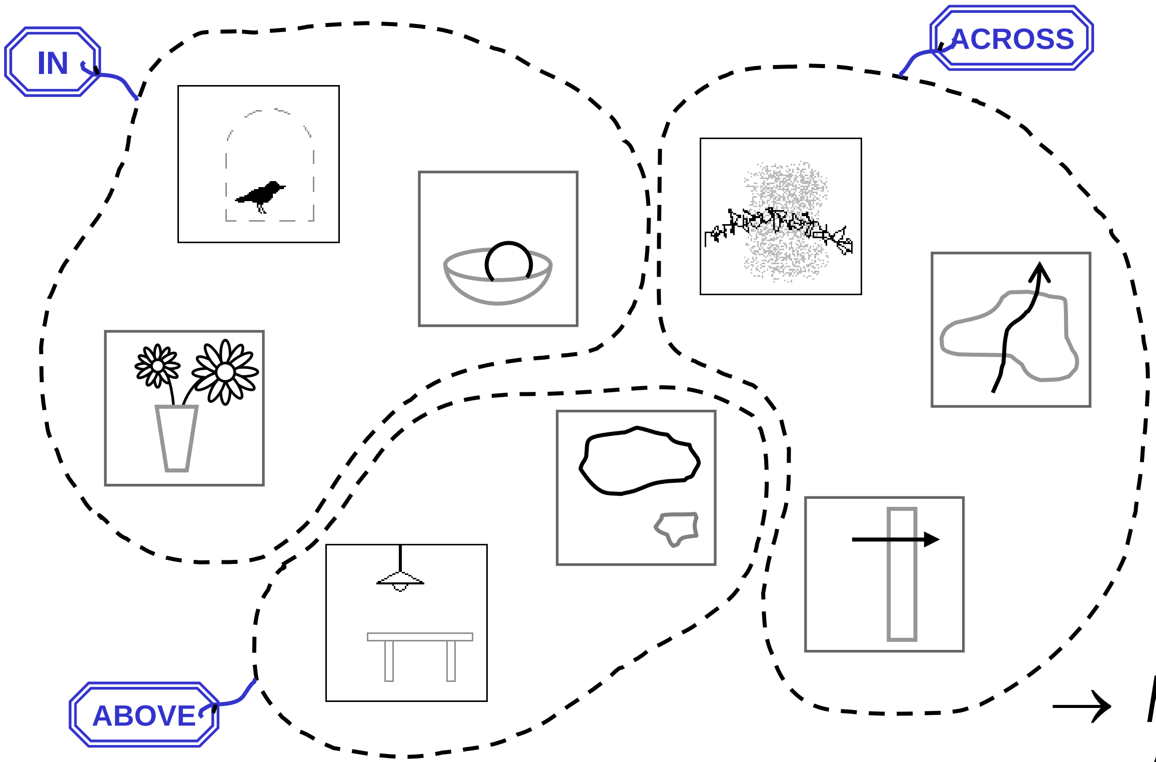


Doursat & Petitot (1997, 2005)

2. Fine-Grain Neurodynamics

➢ Linguistic categories: the emergence of a symbolic level

✓ we can map an infinite continuum of scenes to a few spatial labels



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

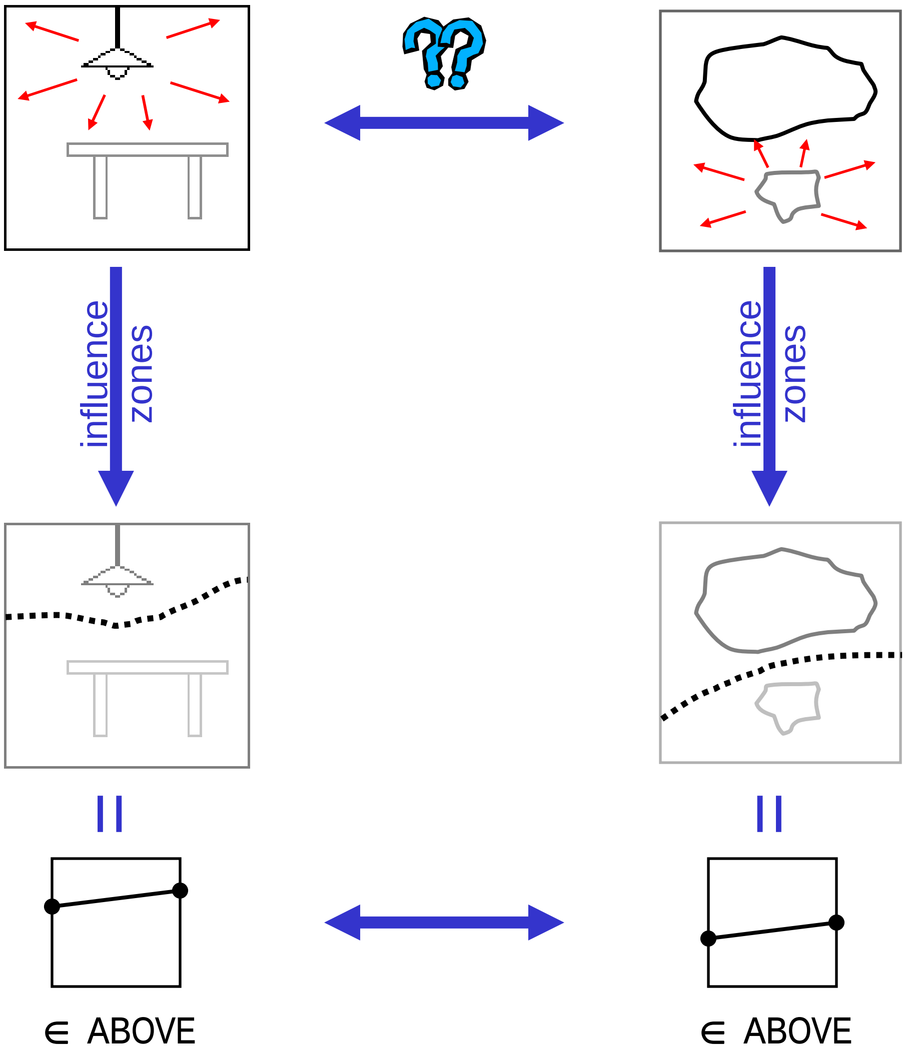
perception → language
continuous → discrete
physical, dynamical → symbolic, logic

2. Fine-Grain Neurodynamics

➢ The path to invariance: drastic morphological transforms

- ✓ scenes representing the same **spatial category** are not directly similar

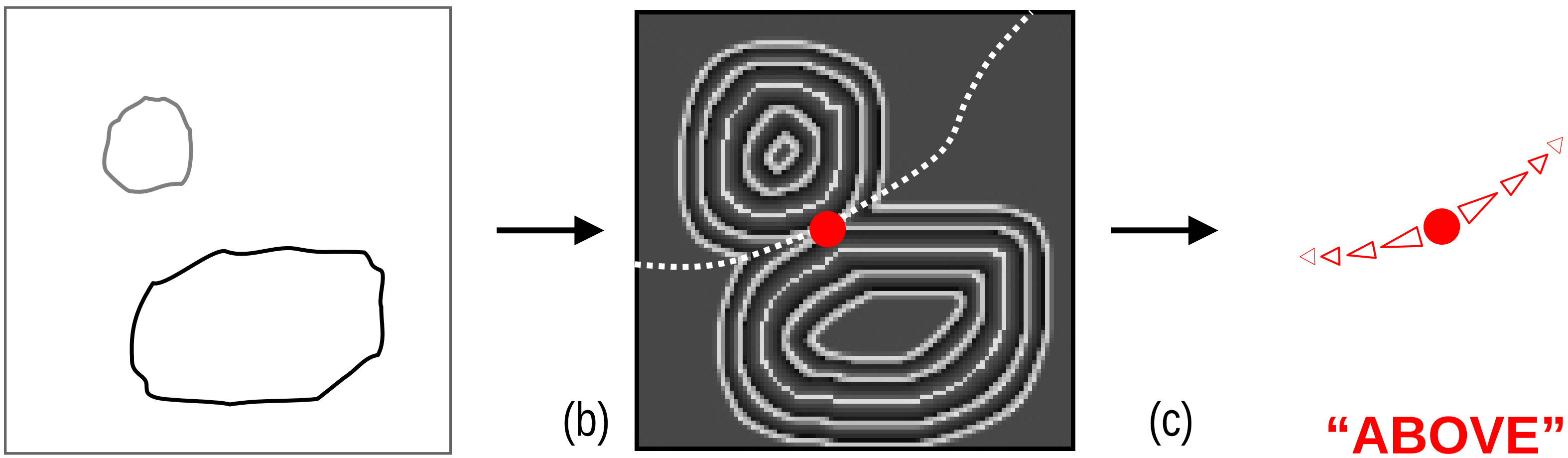
- ✓ what can be compared, however, are virtual structures generated by morphological transforms



2. Fine-Grain Neurodynamics

➢ 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)



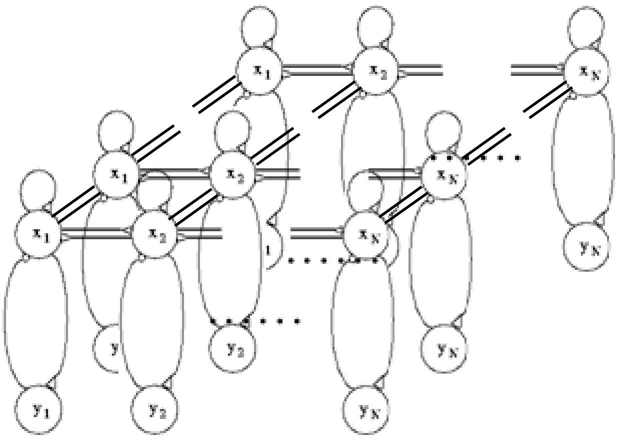
(a) (b) (c)

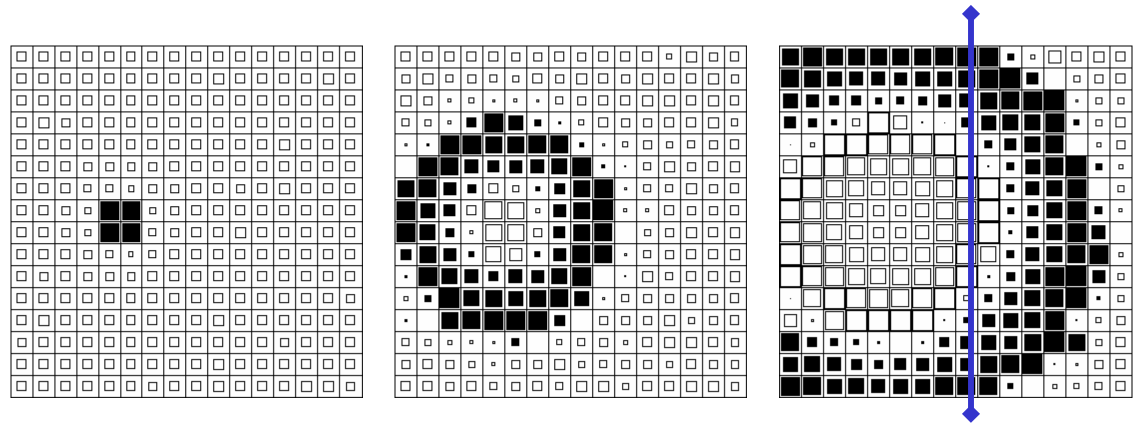
- ✓ for ex: in *traveling waves*, singularities are collision points
- ✓ (a) under the influence of an external input, (b) the internal dynamics of the system (c) spontaneously creates singularities that are characteristic of a symbolic category

2. Fine-Grain Neurodynamics

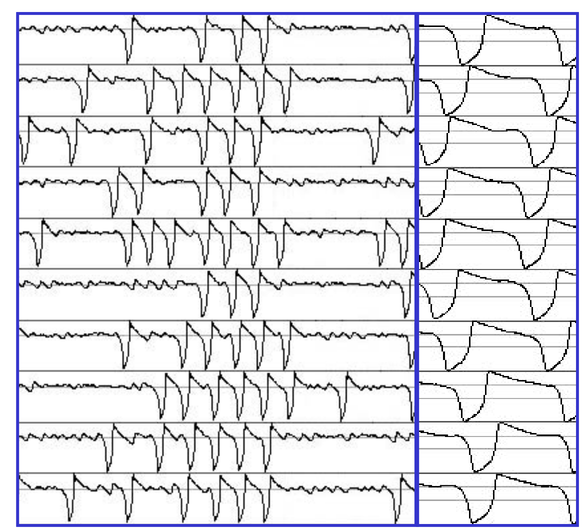
➢ Spiking neural networks as excitable media

- ✓ 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



2. Fine-Grain Neurodynamics

➢ 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*

2. Fine-Grain Neurodynamics

c) Lock-and-key coherence in RAIN Networks

→ *pattern recognition by specialized STPs*

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

2. Fine-Grain Neurodynamics

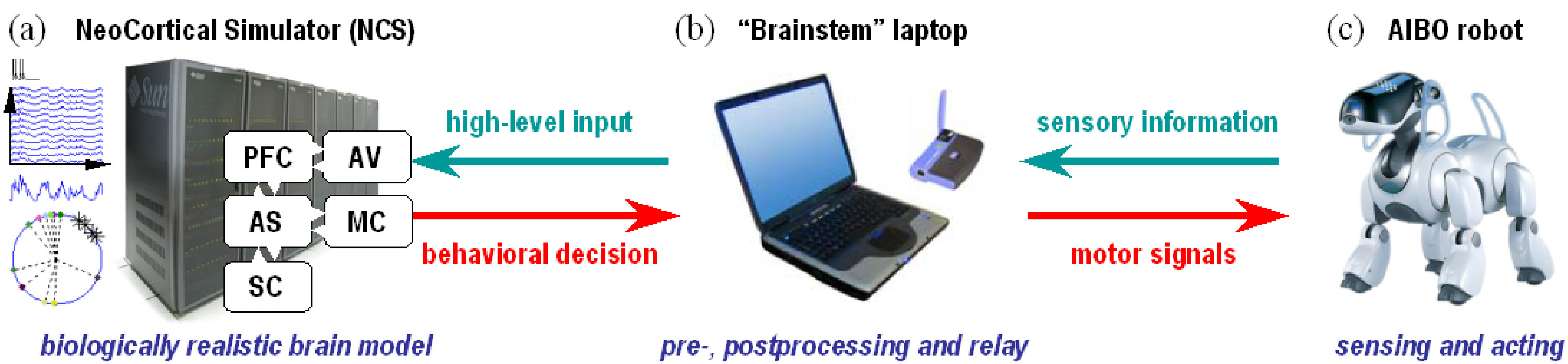
➢ Complete sensorimotor loop between cluster and robot

✓ 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

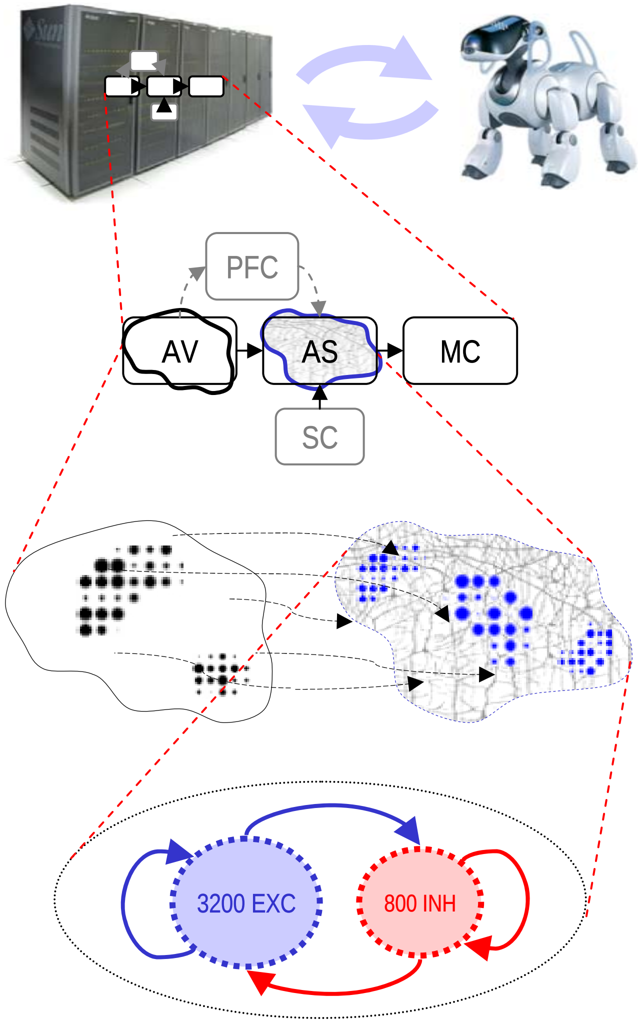
a) NeoCortical Simulator (NCS) software runs on computer cluster; contains the brain architecture for decision-making and learning

b) “brainstem” laptop brokers WiFi connection: transmits multimodal sensory signals to NCS; sends actuator commands to robot



2. Fine-Grain Neurodynamics

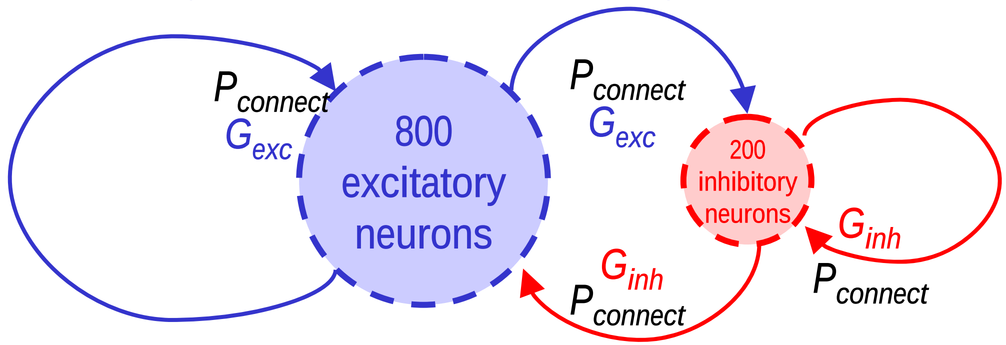
➢ Core of brain model: mesoscopic assemblies as RAINs

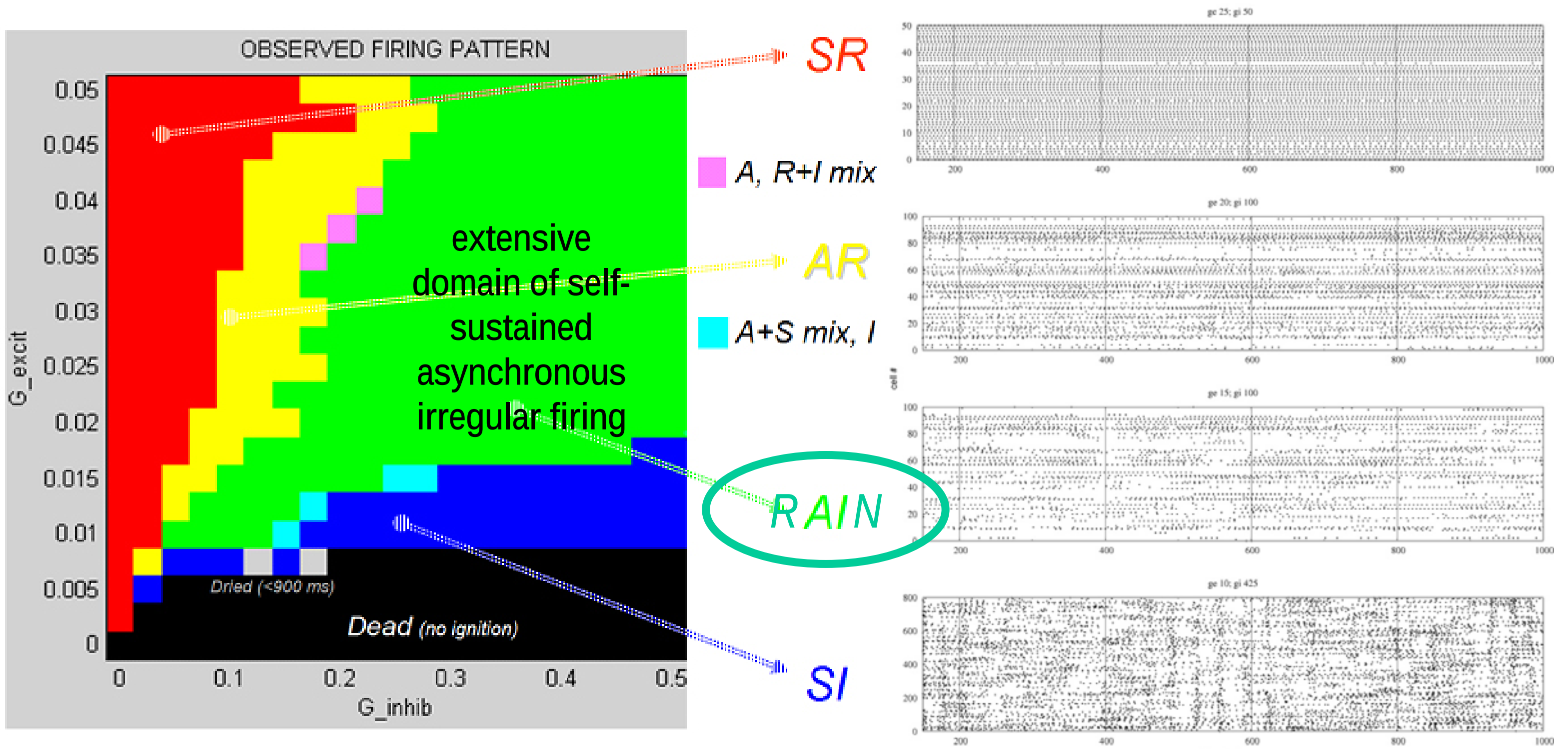


RAIN: Recurrent Asynchronous Irregular Network

2. Fine-Grain Neurodynamics

➢ Recurrent Asynchronous Irregular Network (RAIN)

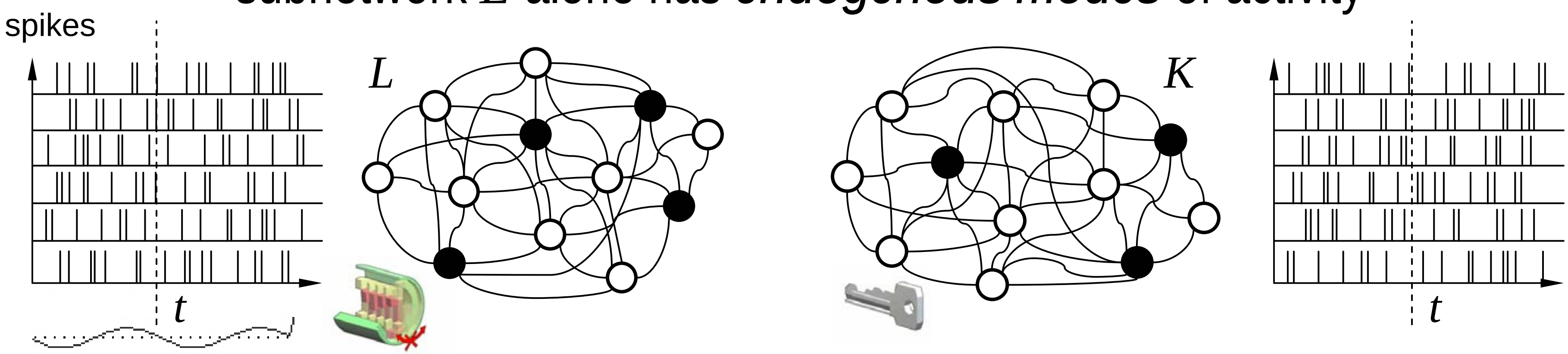




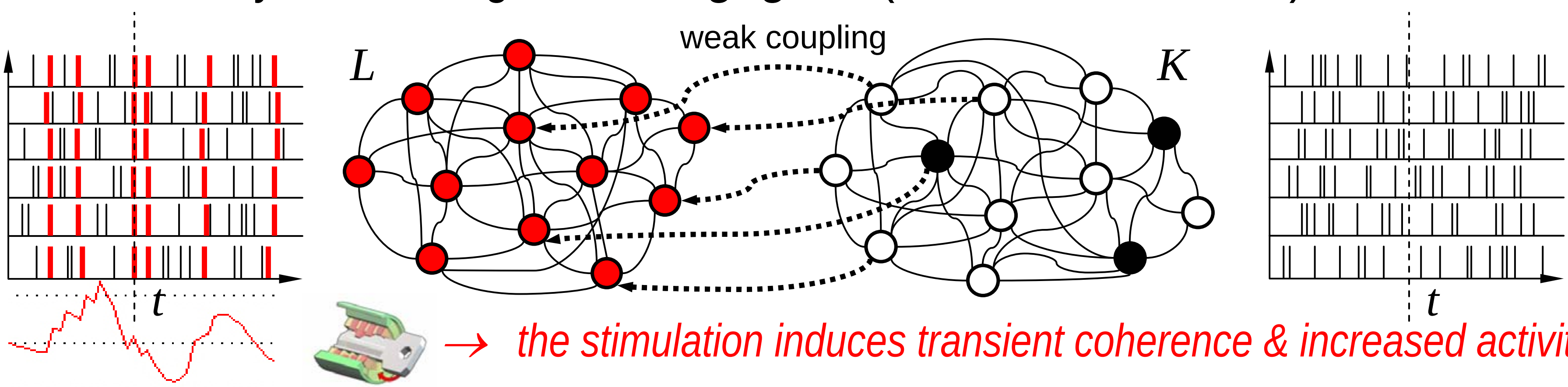
2. Fine-Grain Neurodynamics

➢ 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



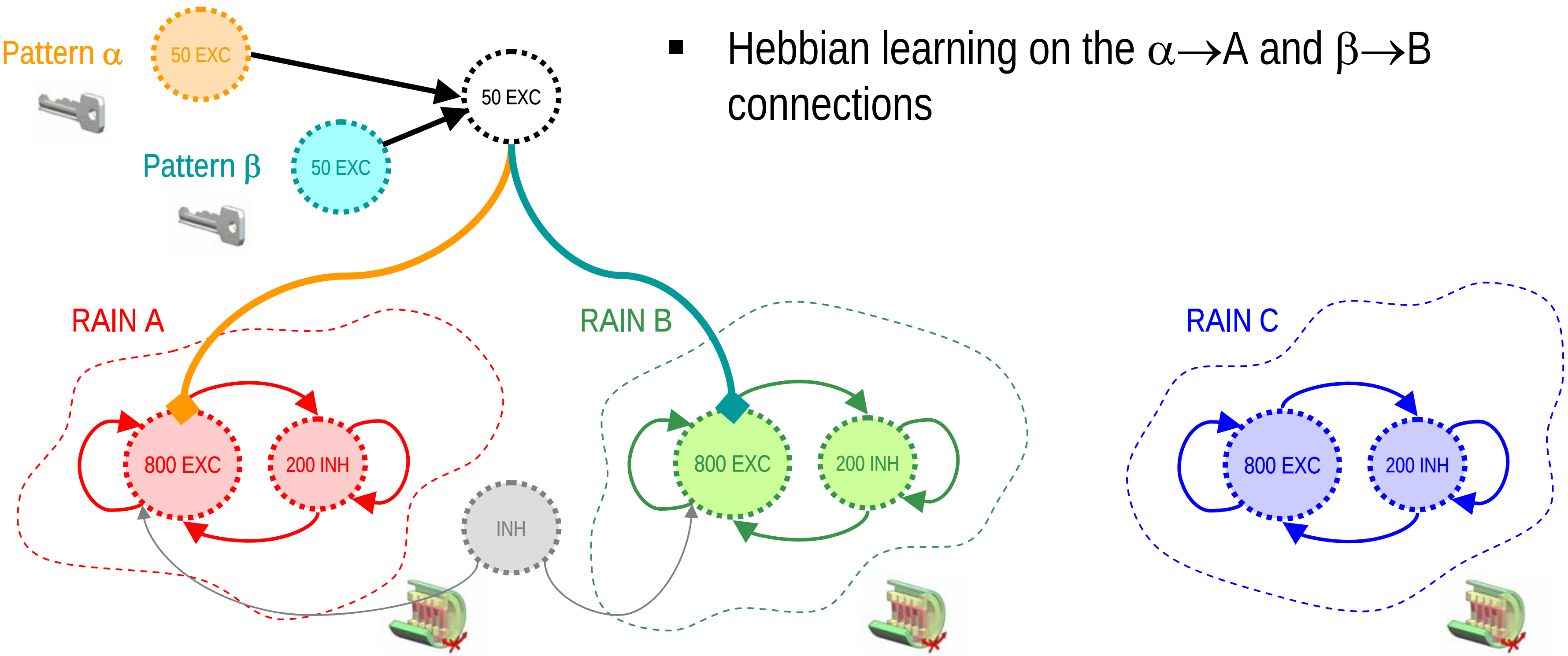
→ *the stimulation induces transient coherence & increased activity*

2. Fine-Grain Neurodynamics

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

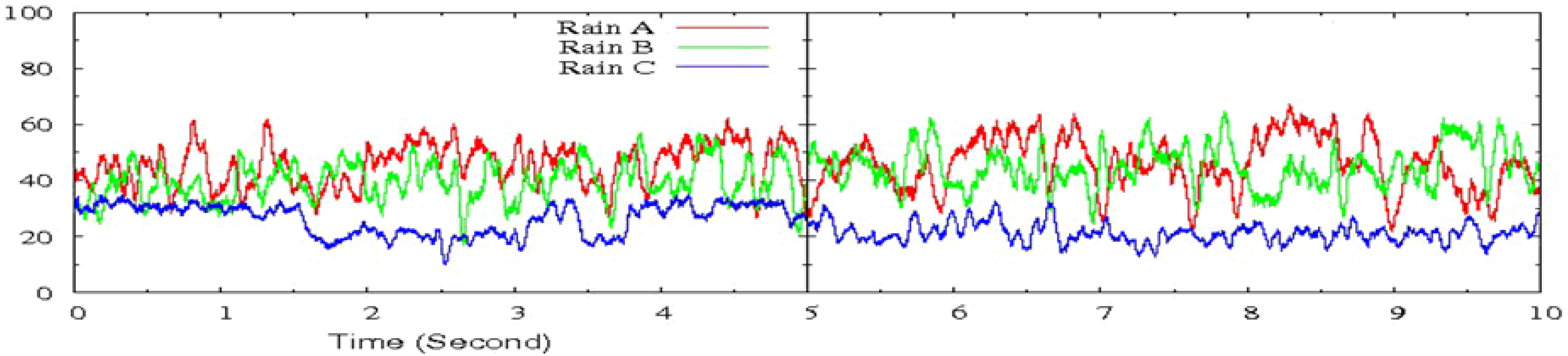
✓ numerical experiment involving

- 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

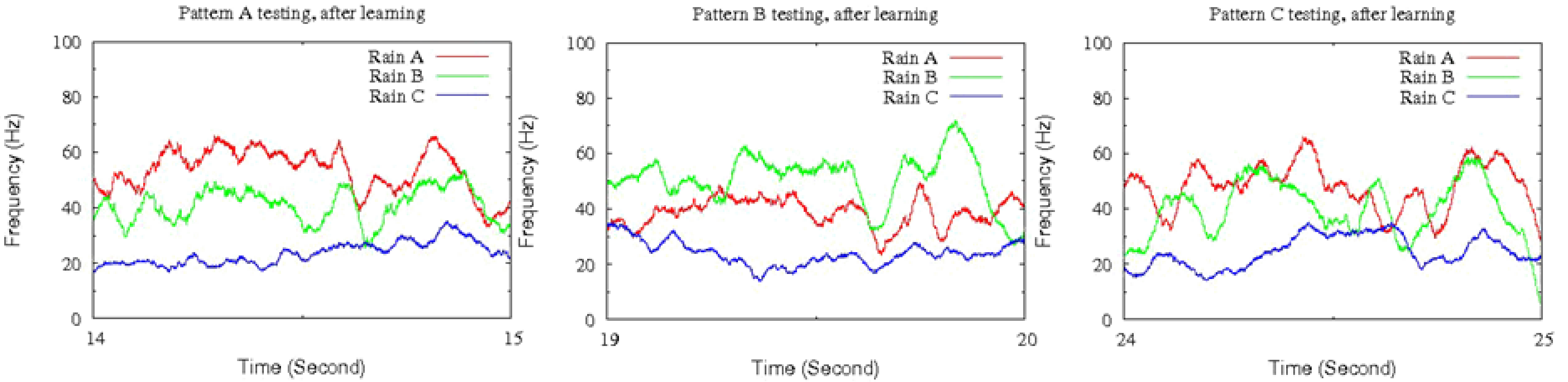


2. Fine-Grain Neurodynamics

- 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



Toward a Fine-Grain Mesoscopic Neurodynamics

1. The Missing Mesoscopic Level of Cognition

2. Three Viewpoints on Fine-Grain Neurodynamics

   a. The self-made tapestry of synfire chains

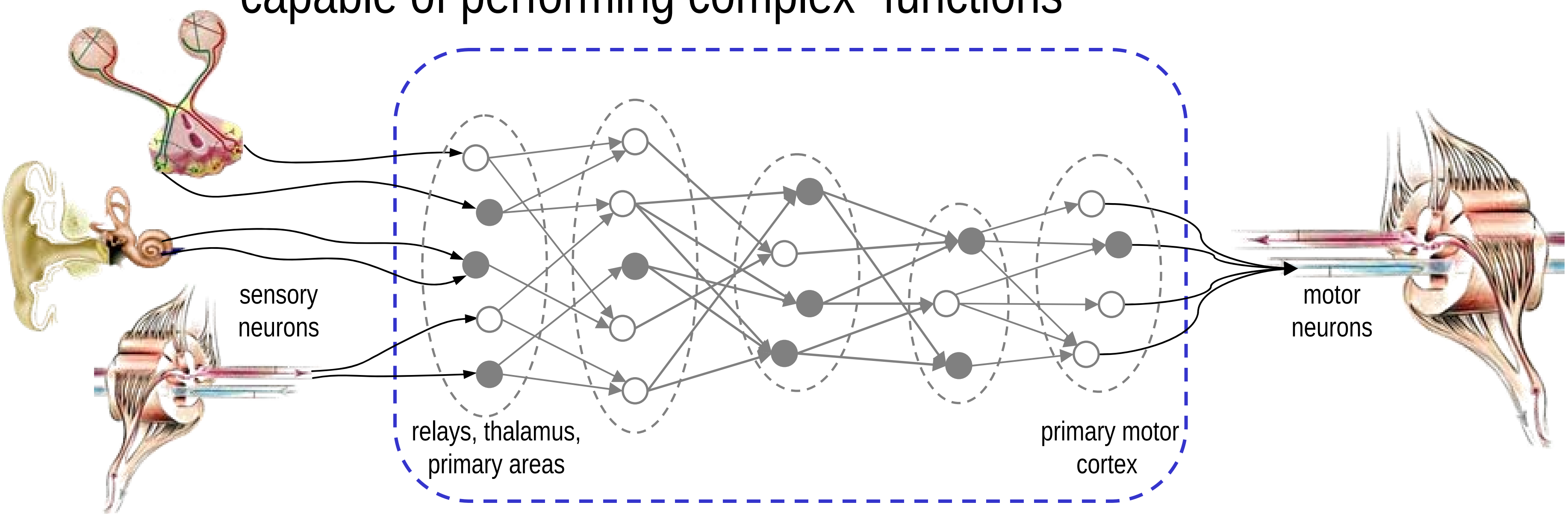
   b. Waves in a morphodynamic pond

   c. Lock-and-key coherence in Recurrent Asynchronous Irregular Networks (RAIN)

3. A Multiscale Perspective on Neural Causality

3. Multiscale Neural Causality

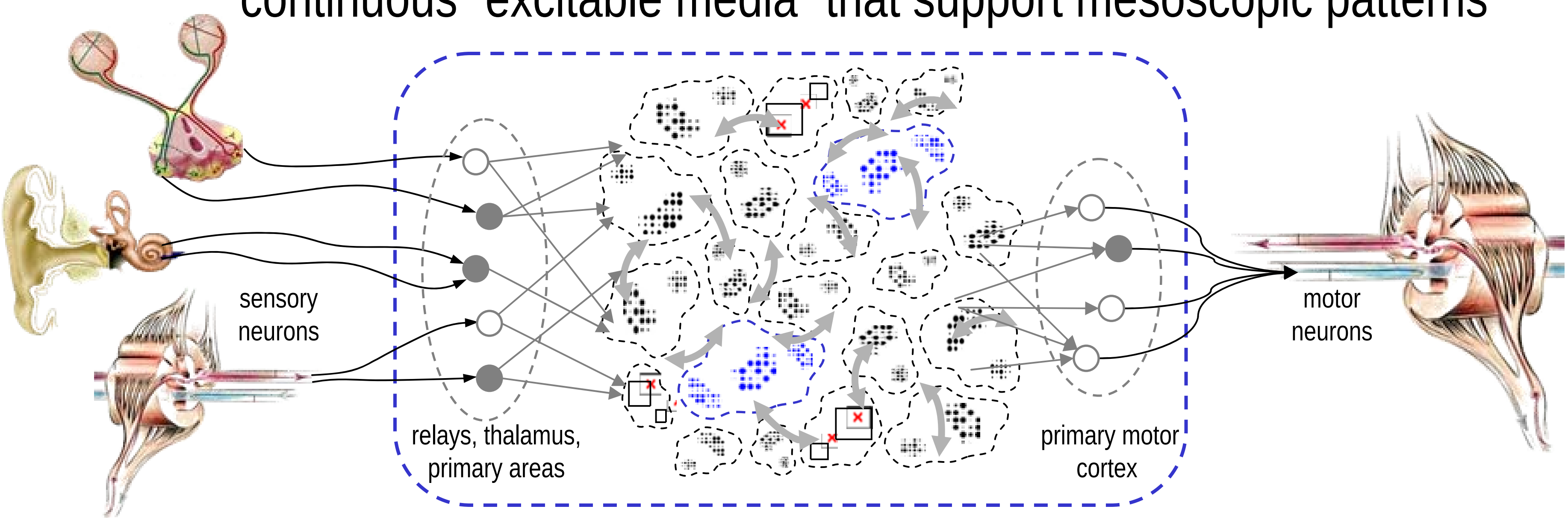
- Old, unfit engineering metaphor: "signal processing"
  - ✓ *feed-forward* structure – activity literally "moves" from one corner to another, from the input (problem) to the output (solution)
  - ✓ *activation* paradigm – neural layers are initially silent and are literally "activated" by potentials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



3. Multiscale Neural Causality

➢ 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 neuron are the substrate of quasi-continuous “excitable media” that support mesoscopic patterns



3. Multiscale Neural Causality

- Cognitive neurodynamics
  - ✓ 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

3. Multiscale Neural Causality

➢ 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)
- ✓ 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 are retained: what matters are the spatiotemporal **"shapes"** of mesoscopic objects*

Toward a Fine-Grain Mesoscopic Neurodynamics

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