The Self-Organized Growth of Synfire Patterns

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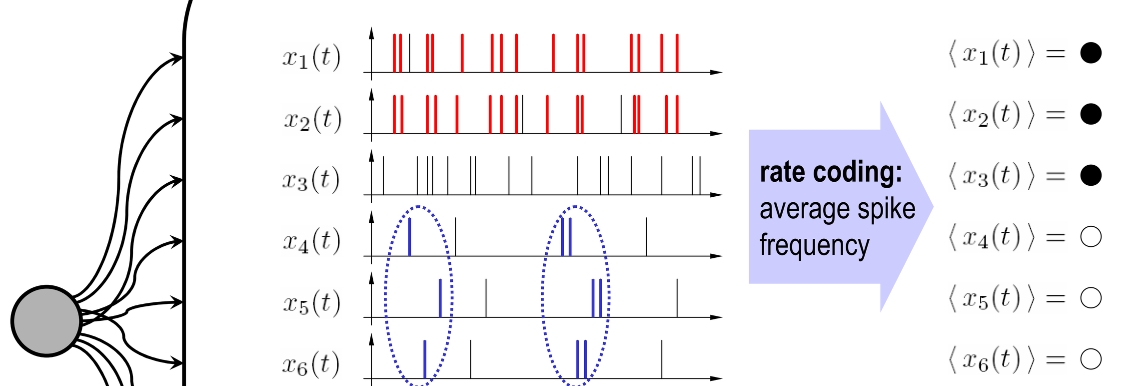
MOTIVATION

1. Rate vs. Temporal Coding



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

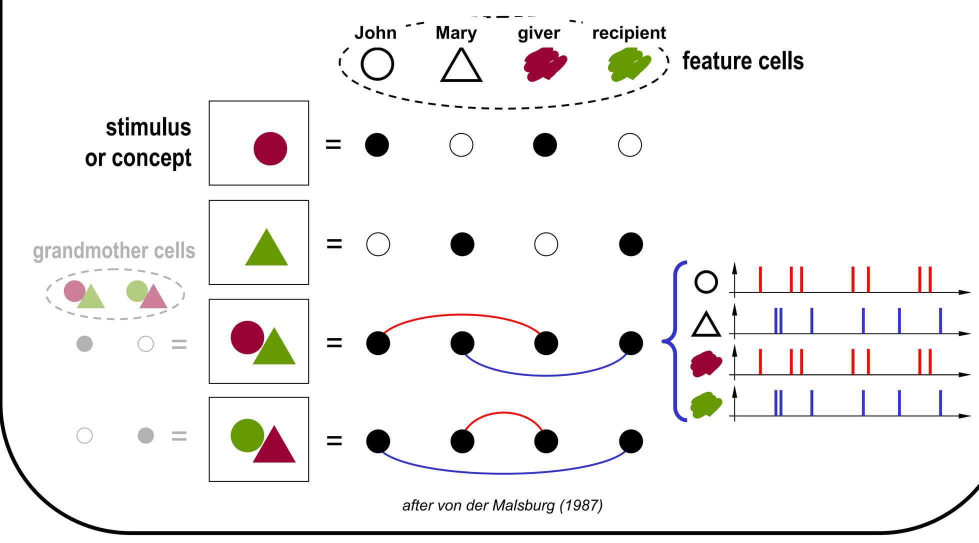
$\langle x_4(t)\,x_5(t-\tau_{4,5})\,x_6(t-\tau_{4,6})\rangle$

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

- ✓ there is more to neural signals than mean activity rates—***synchronization*** and ***delayed correlations*** among spikes (but not necessarily oscillatory)

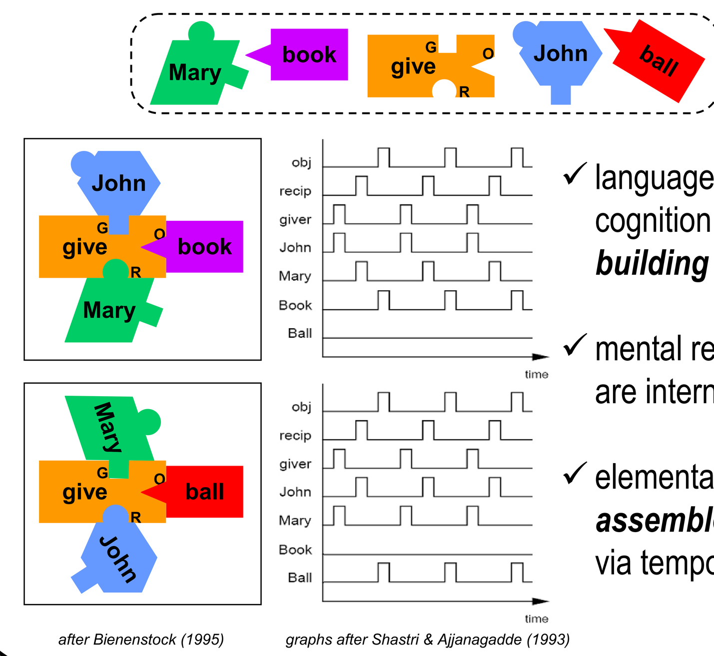
2. The Binding Problem

- ✓ ***superposition catastrophe***: no relational information in rate coding
- ✓ but rather than creating more "grandmother" cells to fix the problem, feature combinations are better coded ***temporally***, e.g., by synchrony



after von der Malsburg (1987)

3. The Compositionality of Cognition

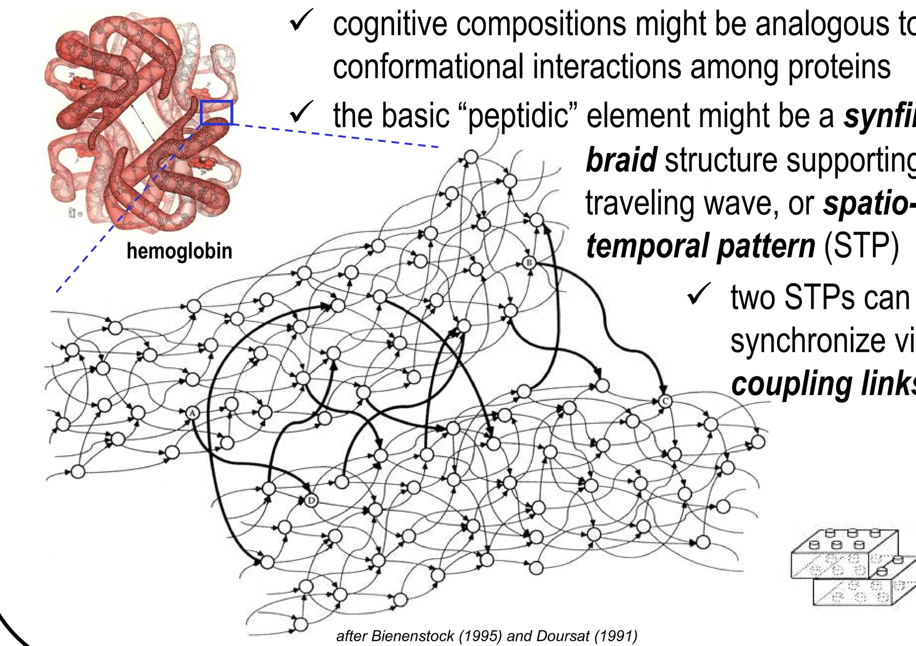


- ✓ language, perception, cognition are a game of ***building blocks***
- ✓ mental representations are internally ***structured***
- ✓ elementary components ***assemble dynamically*** via temporal binding

after Bienenstock (1995) — graphs after Shastri & Ajjanagadde (1993)

4. Spatiotemporal Pattern Binding

- ✓ cognitive compositions might be analogous to conformational interactions among proteins
- ✓ the basic "peptidic" element might be a ***synfire braid*** structure supporting a traveling wave, or ***spatiotemporal pattern*** (STP)
  - ✓ two STPs can synchronize via ***coupling links***



after Bienenstock (1995) and Doursat (1991)

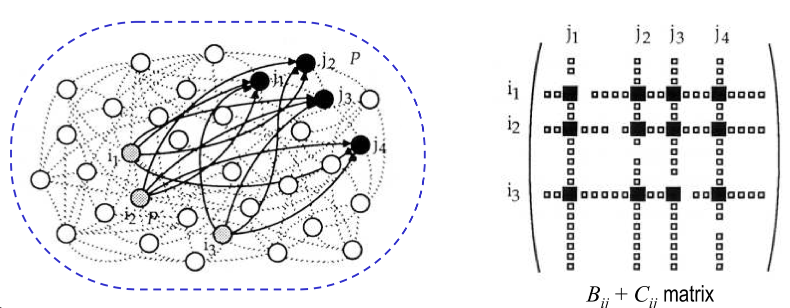
MODEL

8. Rule C – Synaptic Competition

- ✓ to offset the positive feedback between correlations and connections, a constraint ***preserves weight sums*** at s_0 (efferent) and s'_0 (afferent)

$$W_{ij}(t) = W_{ij}(t-1) + B_{ij}(t) + C_{ij}(t) \quad \begin{cases} C_{ij}(t) = -\left(\dfrac{\partial H}{\partial W_{ij}}\right)_{\mathbf{W}(t-1)+\mathbf{B}(t)} \\ H(\mathbf{W}) = \gamma \sum_i \left(\sum_j W_{ij} - s_0\right)^2 + \gamma' \sum_j \left(\sum_i W_{ij} - s'_0\right)^2 \end{cases}$$

- ✓ sum preservation ***redistributes*** synaptic contacts: a rewarded link slightly "depresses" other links sharing its pre- or postsynaptic cell



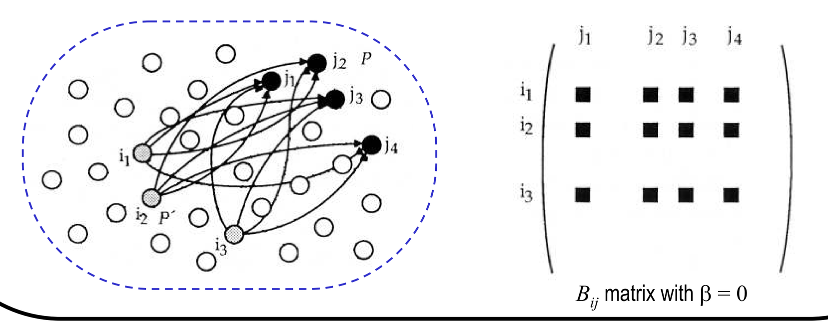
$B_{ij} + C_{ij}$ matrix

7. Rule B – Synaptic Cooperation

- ✓ the weight variation depends on the ***temporal correlation*** between pre and post neurons, in a Hebbian or "binary STDP" fashion

$$W_{ij}(t) = W_{ij}(t-1) + B_{ij}(t) \quad \begin{cases} x_i(t-\tau_{ij}) = 1,\ x_j(t) = 1 & \Rightarrow \quad B_{ij}(t) = +\alpha \\ x_i(t-\tau_{ij}) = 1,\ x_j(t) = 0 & \Rightarrow \quad B_{ij}(t) = -\beta \\ x_i(t-\tau_{ij}) = 0,\ x_j(t) = 1 & \Rightarrow \quad B_{ij}(t) = -\beta \\ x_i(t-\tau_{ij}) = 0,\ x_j(t) = 0 & \Rightarrow \quad B_{ij}(t) = 0 \end{cases}$$

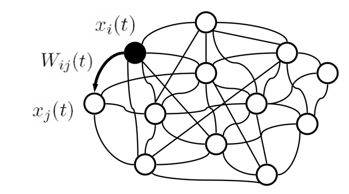
- ✓ successful spike transmission events 1→1 are rewarded, thus connectivity "builds up" in the wake of the propagation of activity



B_{ij} matrix with β = 0

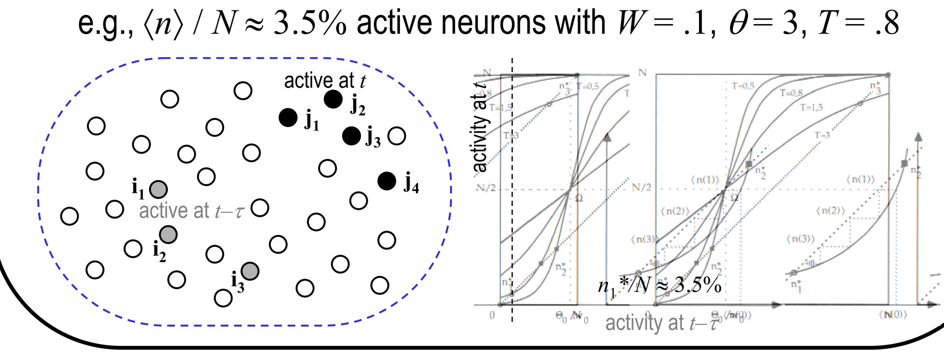
6. Rule A – Neuronal Activation

- ✓ we consider a network of simple binary units obeying a ***LNP spiking dynamics*** on the 1ms time scale (similar to "fast McCulloch & Pitts")



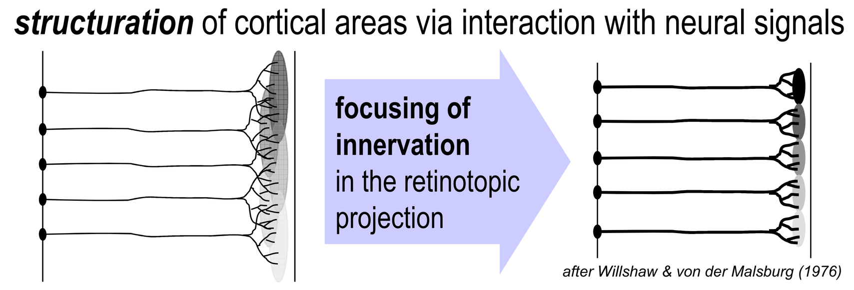
$$P[x_j(t) = 1] = \frac{1}{1 + e^{-(V_j(t)-\theta_j)/T}} \qquad V_j(t) = \sum_i W_{ij}(t)\, x_i(t-\tau_{ij})$$

- ✓ initial activity mode is stochastic at a low, stable average firing rate, e.g., $\langle n\rangle / N \approx 3.5\%$ active neurons with $W = .1$, $\theta = 3$, $T = .8$



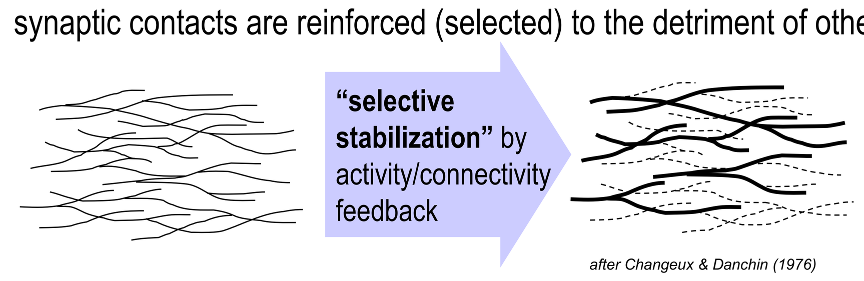
5. Neocortical Growth by Focusing

- ✓ we propose a model of synfire pattern growth akin to the ***epigenetic structuration*** of cortical areas via interaction with neural signals



after Willshaw & von der Malsburg (1976)

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

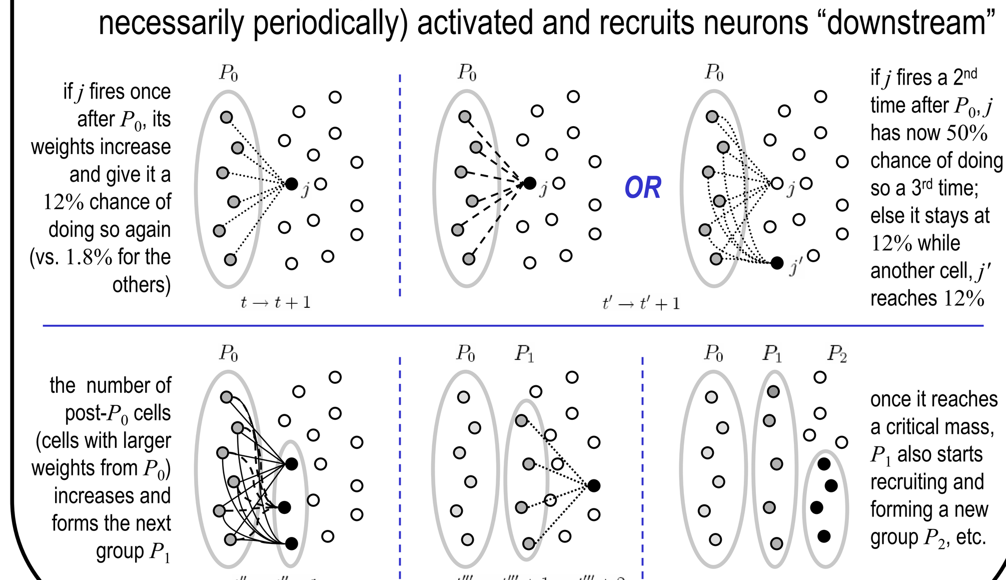


after Changeux & Danchin (1976)

NUMERICAL SIMULATIONS

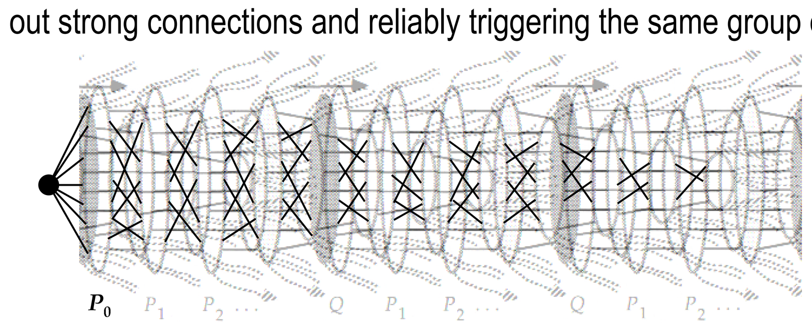
9. Development by Aggregation

- ✓ a special group of n_0 ***synchronous*** cells, P_0, is ***repeatedly*** (yet not necessarily periodically) activated and recruits neurons "downstream"



10. A Chain Grows like an Offshoot

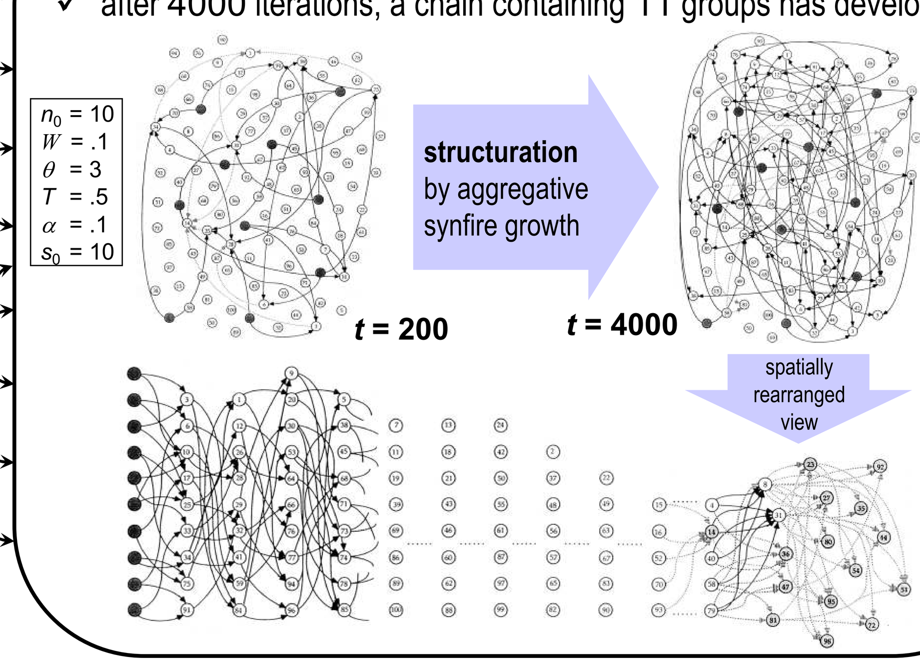
- ✓ P_0 becomes the root of a developing synfire chain P_0, P_1, P_2 ..., where P_0 itself might have been created by a ***seed neuron*** sending out strong connections and reliably triggering the same group of cells



- ✓ the accretion process is not strictly iterative: groups form over broadly overlapping periods of time: as soon as group P_k reaches a critical mass, its activity is high enough to recruit the next group P_{k+1}
- ✓ thus, the ***chain typically lengthens before it widens*** and presents a "beveled head" of immature groups at the end of a mature trunk

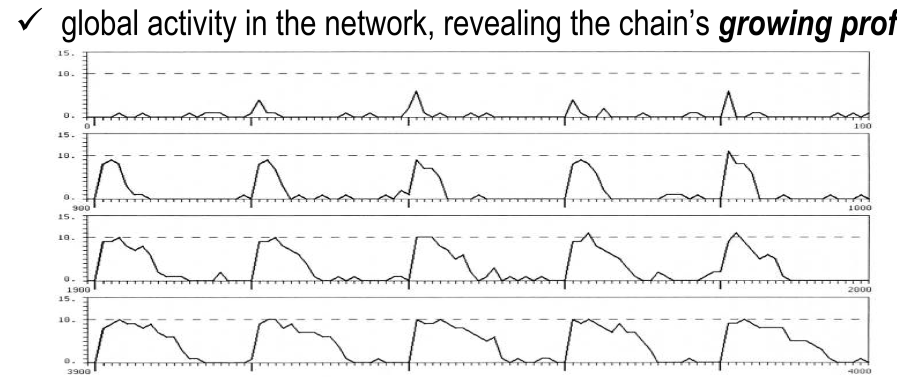
11. Numerical Simulation of a Chain

- ✓ after 4000 iterations, a chain containing 11 groups has developed



12. Evolution of Total Activity

- ✓ global activity in the network, revealing the chain's ***growing profile***



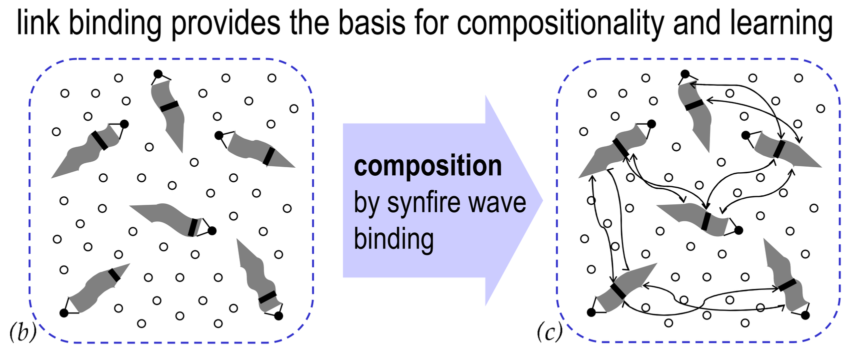
- ✓ ***other examples*** of chains (p: probability that connection $i \rightarrow j$ exists)

s_0	n_0	p	$n_0 \rightarrow n_1 \rightarrow n_2 \rightarrow n_3$ ...
7	5	1	(5) → 7 → 7 → 7 → 7 → 6 → 4 ...
7.	4	1	(4) → 7 → 8 → 7 → 7 ...
10	15	1	(15) → 14 → 13 → 12 → 11 → 10 → 9 → 8 → 6 → 7 → 7 → 5 → 4
7	15	1	(15) → 12 → 10 → 8 → 7 → 7 → 7 → 7 → 7 → 6 → 5 → 2 ...
8	12	1	(12) → 11 → 10 → 9 → 8 → 8 → 8 → 8 ...
8	10	.5	(10) → 14 → 13 → 13 → 13 → 11 → 5 ...
8	10	.8	(10) → 9 → 8 → 9 → 9 → 8 → 8 → 4 ...

FUTURE WORK

16. Synchronization and Coalescence

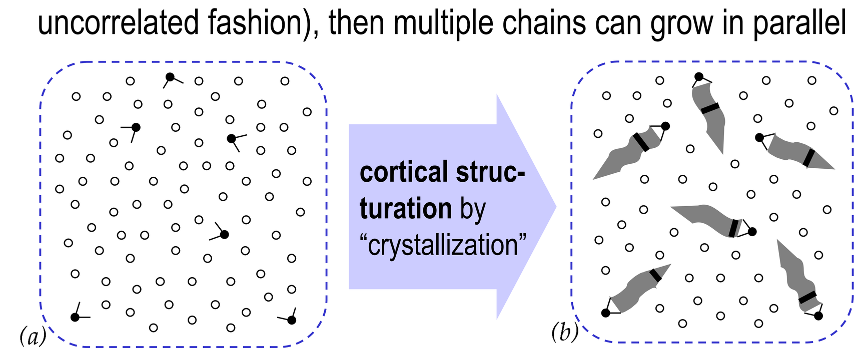
- ✓ on this substrate, the coalescence of synfire waves via dynamical link binding provides the basis for compositionality and learning



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

15. The Self-Made Tapestry

- ✓ the recursive growth of a chain from endogenous neural activity is akin to the accretive ***growth of a crystal from an inhomogeneity***
- ✓ if multiple "seed neurons" coexist in the network (and fire in an uncorrelated fashion), then multiple chains can grow in parallel

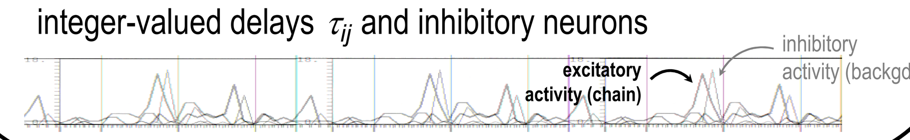


- ✓ concurrent chain development defines a ***mesoscopic scale of neural organization***, at a finer granularity than macroscopic AI symbols but higher complexity than microscopic neural potentials

14. Synfire Braids

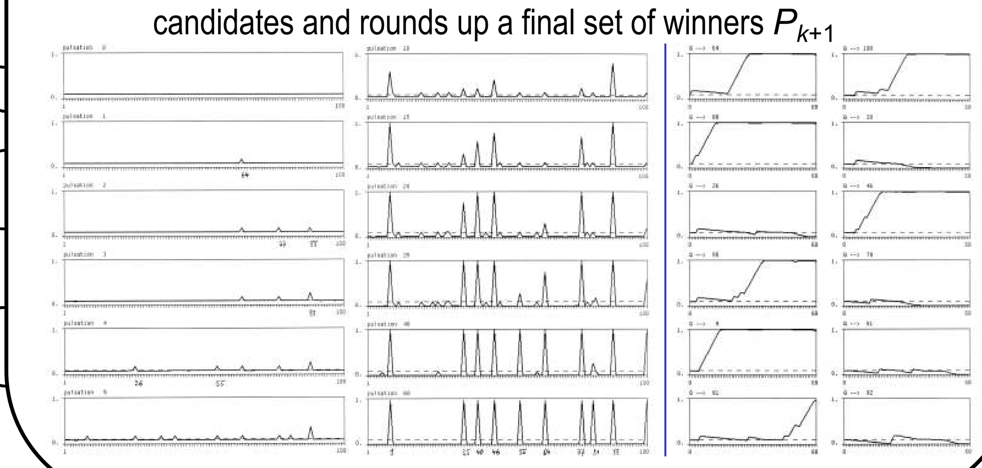
- ✓ synfire braids are more general structures with longer delays among nonconsecutive neurons, but no identifiable synchronous groups—they were rediscovered as "polychronous groups" (Izhikevich, 2006)

- ✓ in a synfire braid, ***delay transitivity*** $\tau_{AB} + \tau_{BC} = \tau_{AD} + \tau_{DC}$ favors strong spike coincidences, hence a stable propagation of activity
- ✓ our model also shows the growth of synfire braids with nonuniform integer-valued delays τ_{ij} and inhibitory neurons



13. Evolution of Connections

- ✓ the aggregation of P_{k+1} by P_k is a form of "Darwinian" evolution
  - in a first phase, noise acts as a ***diversification*** mechanism, by proposing multiple candidate-neurons that fire after P_k
  - in a second phase, competition ***selects*** among the large pool of candidates and rounds up a final set of winners P_{k+1}



snapshots of the landscape of $P_0 \rightarrow j$ weights — evolution of single $P_0 \rightarrow j$ weights