Organically Grown Architectures:

Embryogenesis and Neurogenesis as New Paradigms for Decentralized Systems Design

René Doursat

Institut des Systèmes Complexes, CREA
CNRS & Ecole Polytechnique
1, rue Descartes, 75005 Paris

Organically Grown Architectures

1. Toward decentralized systems design
2. Embryogenetic systems
   A model of self-organizing 2-D and 3-D lattices
3. Neurogenetic systems
   A model of self-organizing random networks
4. “Planning the autonomy”
   The paradox of complex systems engineering

Organically Grown Architectures

1. **Toward decentralized systems design**
   a. The exploding growth in information systems
   b. Replacing "design" with "meta-design"
   c. Finding inspiration in natural complex systems
   d. Self-organized architectures

2. **Embryogenetic systems**
   A model of self-organizing 2-D and 3-D lattices

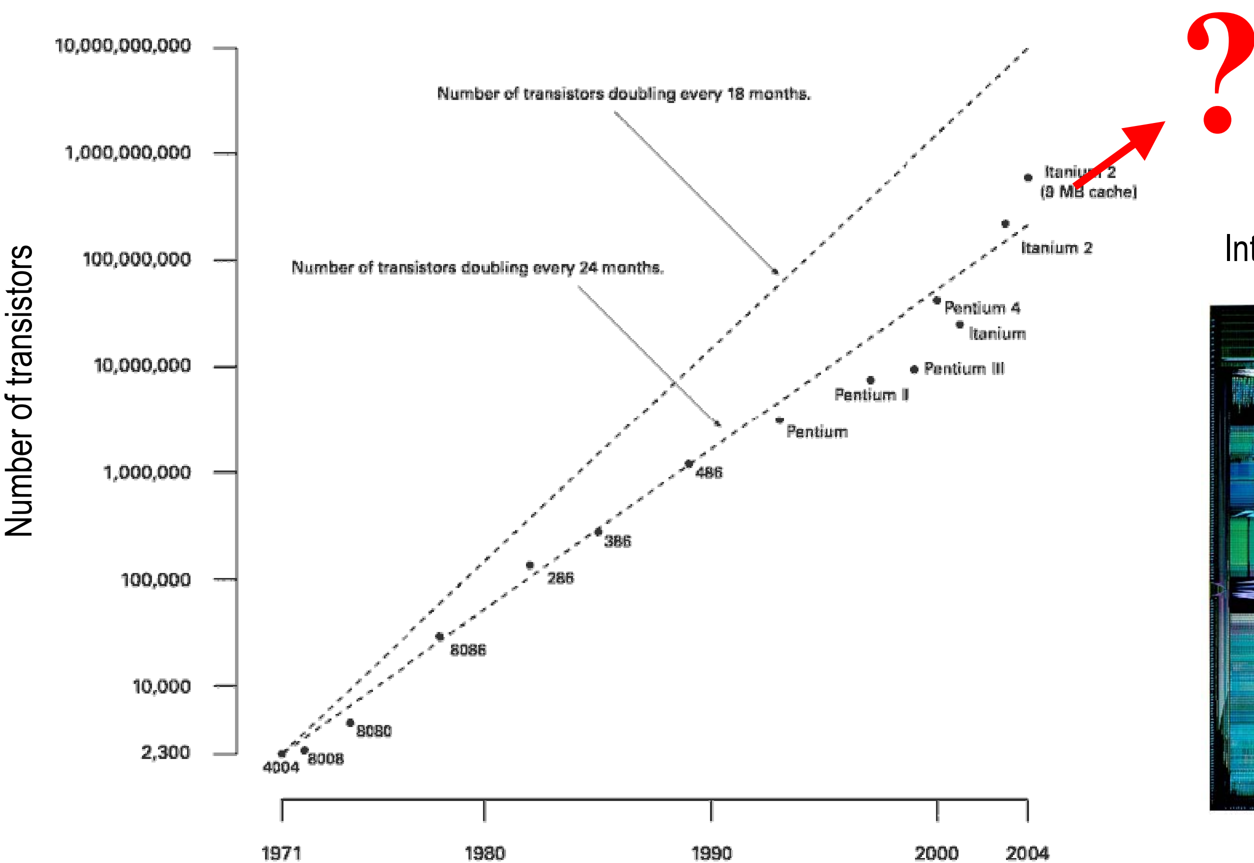
3. **Neurogenetic systems**
   A model of self-organizing random networks

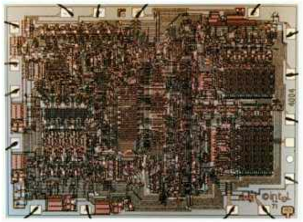
4. **"Planning the autonomy"**
   The paradox of complex systems engineering

1. Toward Decentralized Systems Design

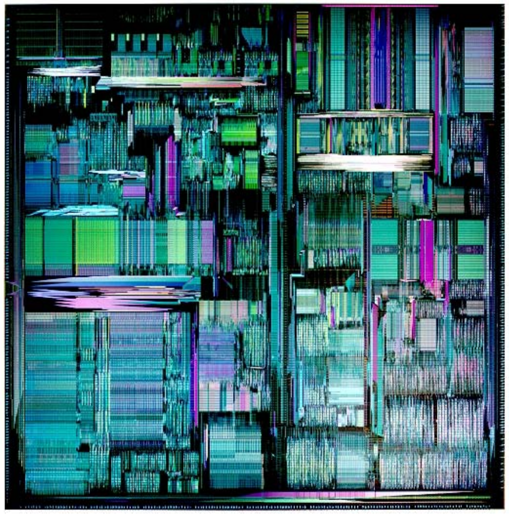
a. The exploding growth in information systems

- **Exploding growth in hardware**
  - ✓ number and interconnection of integrated components





Intel 4004 (1971): 2300 transistors



Intel Pentium 4 (2000): 42-55 million transistors

1. Toward Decentralized Systems Design
a. The exploding growth in information systems

- **Exploding growth in software**
  - ✓ number and interconnection of functions, modules and layers

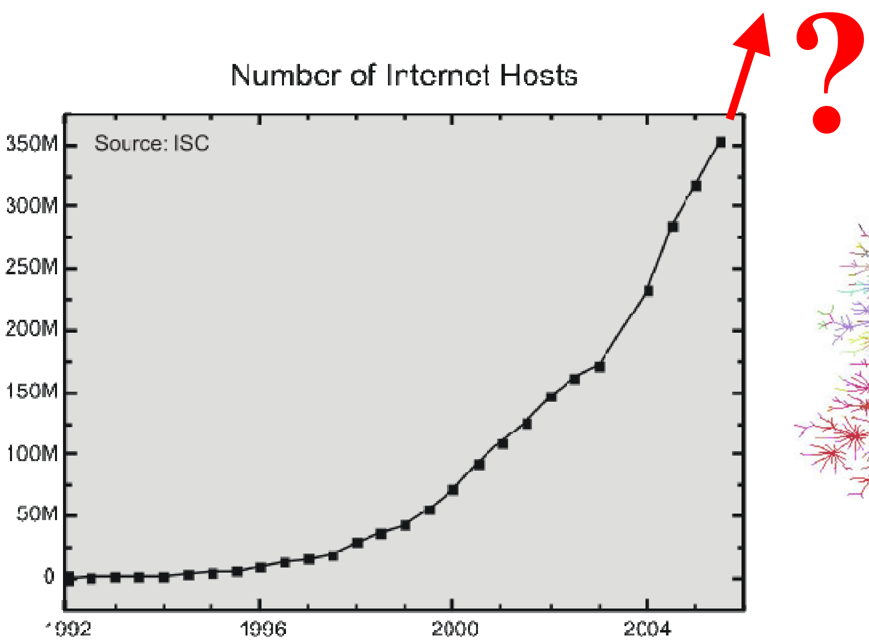
Year	Operating System	Code Size
1963	CTSS	32,000 words
1964	OS/360	1 million instructions
1975	Multics	20 million instructions
1990	Windows 3.1	3 million SLOC
2000	Windows NT 4.0	16 million SLOC
2002	Windows XP	40 million SLOC
2000	Red Hat Linux 6.2	17 million SLOC
2001	Red Hat Linux 7.1	30 million SLOC
2002	Debian 3.0	104 million SLOC
2005	Debian 3.1	213 million SLOC . . . → ?

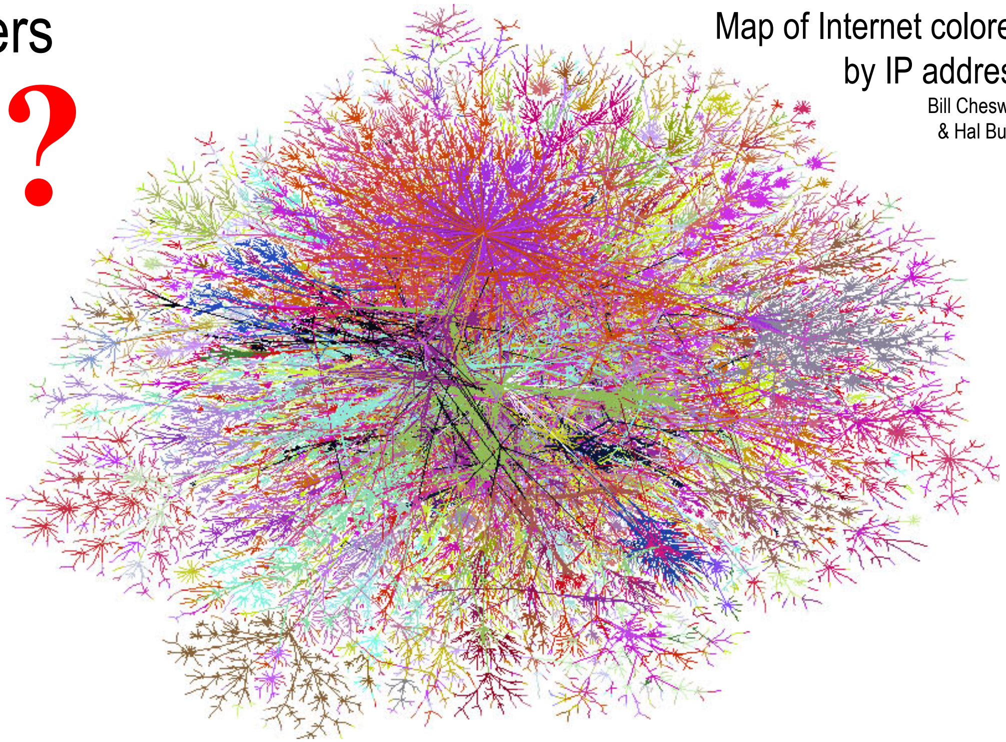
SLOC =
Source Lines Of Code

1. Toward Decentralized Systems Design

a. The exploding growth in information systems

- **Exploding growth in networks**
  - ✓ number and interconnection of distributed applications (client/server) and users





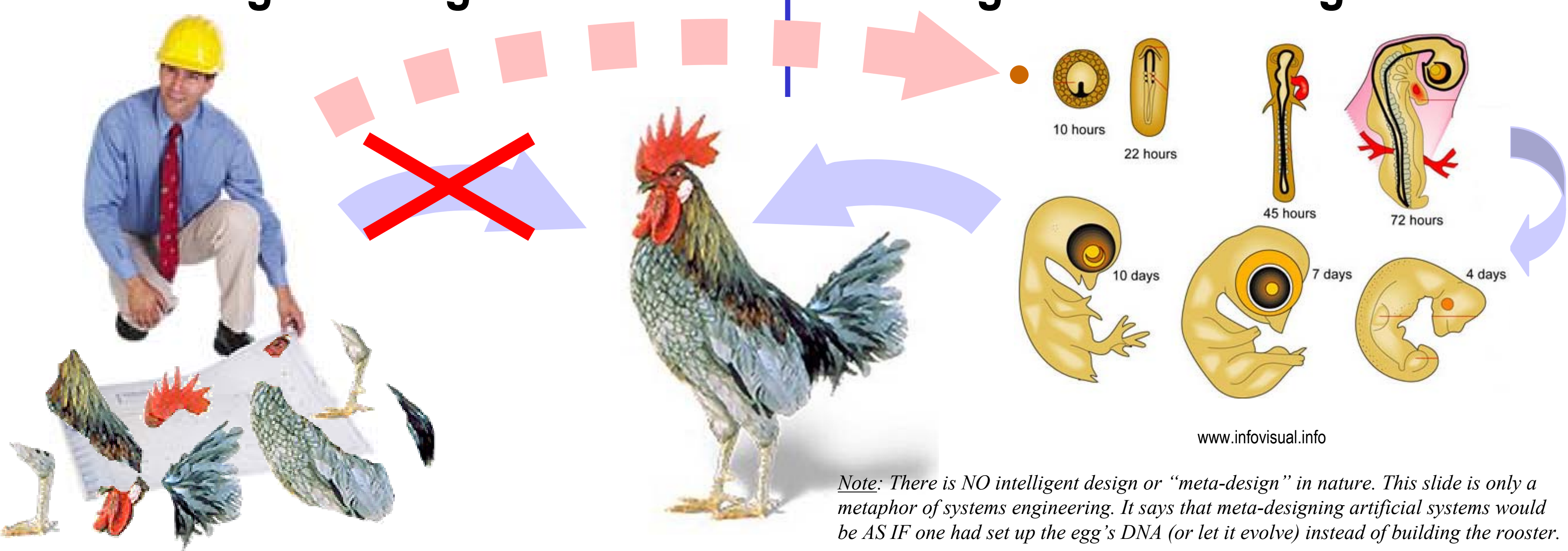
Map of Internet colored by IP address
Bill Cheswick & Hal Burch

→ *in sum: more users with greater mobility require better functionality from applications running on larger and faster architectures*

1. Toward Decentralized Systems Design
b. Replacing "design" with "meta-design"

- **This forces us to rethink the dogma of engineering**
  - ✓ instead of a centralized, heteronomous act of creation. . .
  - ✓ . . . "step back" and set *generic conditions* under which systems can be autonomous, i.e., self-assemble, self-regulate and evolve

intelligent design | **intelligent "meta-design"**



Note: There is NO intelligent design or "meta-design" in nature. This slide is only a metaphor of systems engineering. It says that meta-designing artificial systems would be AS IF one had set up the egg's DNA (or let it evolve) instead of building the rooster.

1. Toward Decentralized Systems Design

b. Replacing "design" with "meta-design"

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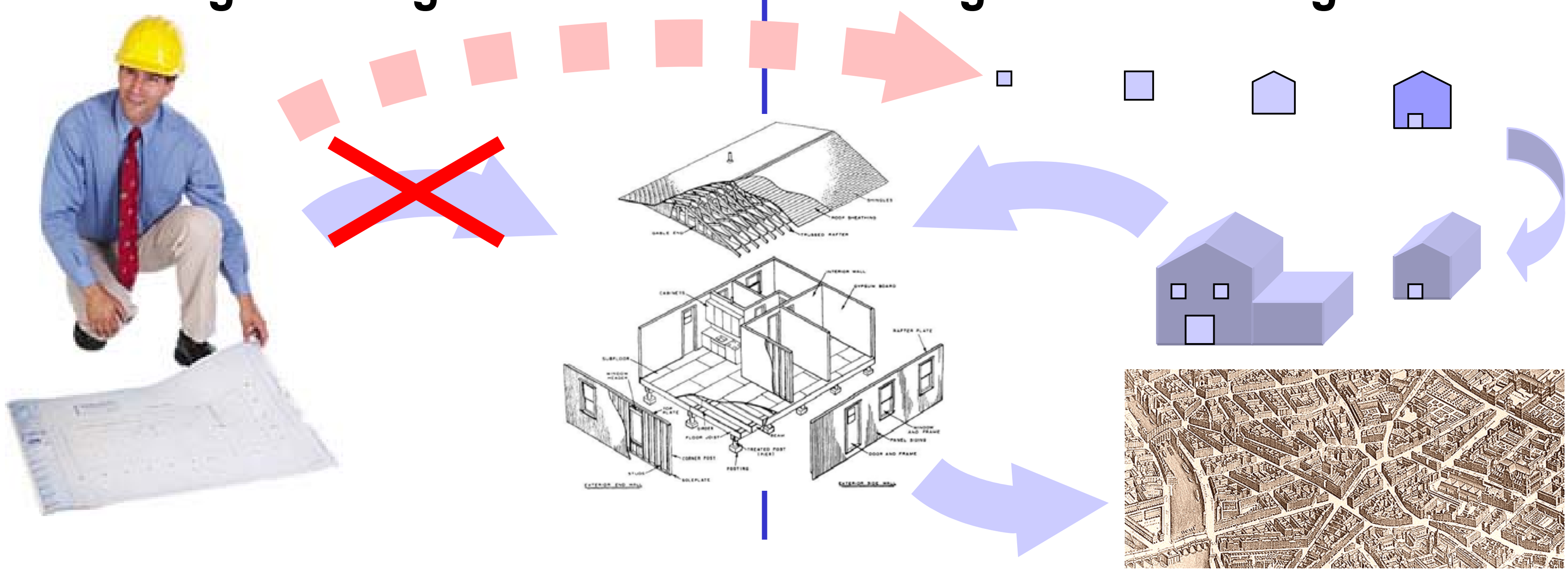
intelligent design | **intelligent "meta-design"**



1. Toward Decentralized Systems Design

b. Replacing "design" with "meta-design"

➢ Biological growth vs. human construction

✓ organisms **grow** endogenously; systems are **built** exogenously

→ *can we shift the paradigm, with inspiration from biology?*
can we "meta-design" a system to grow and evolve?

intelligent design

- centralized control
- the engineer as a micromanager
- manual, extensional design
- rigidly placing components
- tightly optimized
- sensitive to part failures
- needs to be redesigned
- *complicated* systems: planes, ~~computers,~~ buildings, etc.

intelligent "meta-design"

- decentralized control
- the engineer as a lawmaker
- automated, intentional design
- fuzzy self-placement
- hyperdistributed and redundant
- insensitive to part failures
- learns and evolves
- *complex* systems: cities, markets, Internet . . . computers?

1. Toward Decentralized Systems Design

c. Finding inspiration in natural complex systems

➢ **Complex systems are pervasive in the environment**

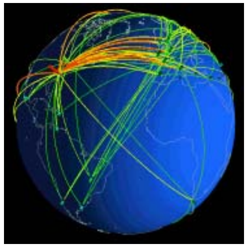
physical pattern formation

biological development

insect colonies

the brain

Internet



social networks

- ✓ large number of elements interacting locally
- ✓ simple individual behaviors create a complex emergent behavior
- ✓ decentralized dynamics: no master blueprint or external leader
- ✓ self-organization and evolution of innovative order

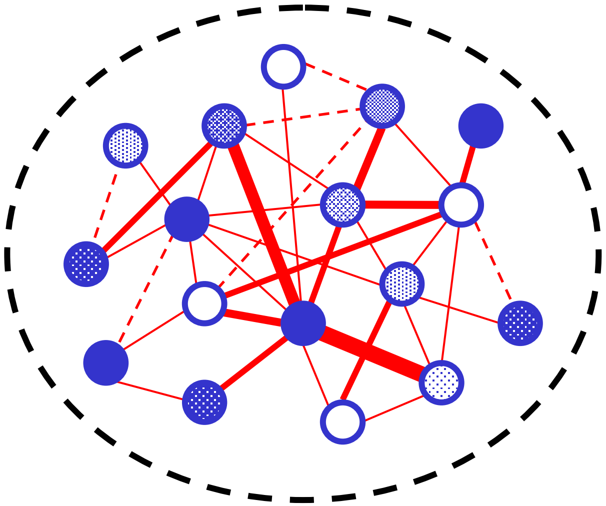
1. Toward Decentralized Systems Design
c. Finding inspiration in natural complex systems

- **Natural adaptive systems as a new paradigm for ICT**
  - ✓ decentralized, unplanned, complex systems might actually be the most economical & robust type of systems—the *simplest*!
    - combinatorial tinkering on redundant parts creates a "solution-rich space"
  - ✓ it is centralized, planned systems that are uniquely costly and fragile, as they require another intelligent system to be built
  - ✓ recent trends advocate and announce the convergence of nanoscience *(swarm of small components)*, biotechnology *(biological complexity)*, information technology *(systems design)* and cognitive science *(intelligent systems)*
    - programs: NBIC in the United States; FET and NEST in Europe
    - initiatives: "organic computing", "amorphous computing", "complex systems engineering", "pervasive computing", "ambient intelligence", etc.

1. Toward Decentralized Systems Design

d. Self-organized architectures

- **The backbone of complex systems is complex networks**
  - agents = nodes: different states of activity, varying on a fast time-scale
  - interactions = edges: different weight values, varying on a slow time-scale
  - system = network: evolving structure

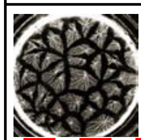
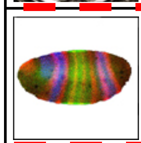
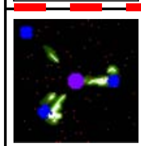


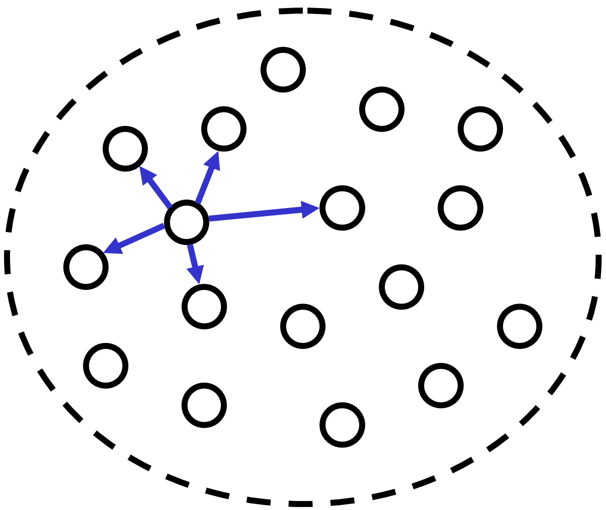
- ✓ complex behavior is difficult to describe or predict analytically
- ✓ complex networks are best explored **computationally**
- ✓ thus, discrete modeling and simulation are a crucial tool of investigation

1. Toward Decentralized Systems Design

d. Self-organized architectures

➢ Geometric, regular networks (2-D, 3-D)

Network	*Nodes*	*Edges*
 BZ reaction	*molecules*	*collisions*
 slime mold	*amoebae*	*cAMP*
 embryo	*cells*	*“morphogens”*
 insect colonies	*ants, termites*	*pheromone*
 flocking, traffic	*animals, cars*	*perception*
 swarm sync	*fireflies*	*photons* $\pm$ *long-range*

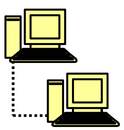
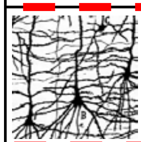
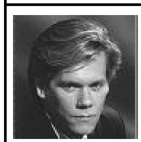
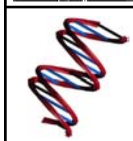
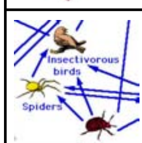


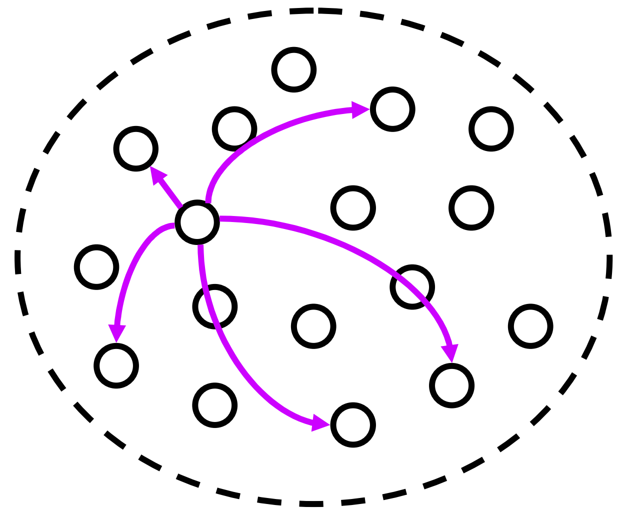
- ➢ interactions inside a local neighborhood in 2-D or 3-D geometric space
- ➢ limited “visibility” within Euclidean distance

1. Toward Decentralized Systems Design

d. Self-organized architectures

➢ **Semi-geometric, irregular networks**

Network	*Nodes*	*Edges*
 Internet	*routers*	*wires*
 the brain	*neurons*	*synapses*
 WWW	*pages*	*hyperlinks*
 Hollywood	*actors*	*movies*
 gene regulation	*proteins*	*binding sites*
 ecosystems	*species*	*competition*



- ➢ still local neighborhoods, but with "long-range" links:
  - either "element" nodes located in space
  - or "categorical" nodes not located in space
- ➢ still limited "visibility", but not according to distance

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   A model of self-organizing 2-D and 3-D lattices
   a. Free vs. guided morphogenesis
   b. Multiscale self-patterning: the growing canvas
   c. Cell division & migration: the deformable canvas
   d. Organic computing: the excitable canvas?

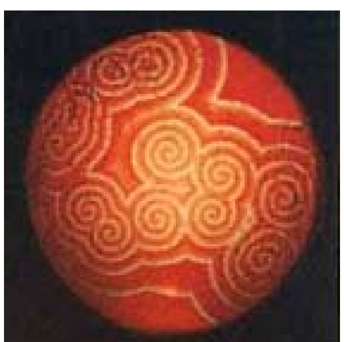
3. Neurogenetic systems
   A model of self-organizing random networks

4. “Planning the autonomy”
   The paradox of complex systems engineering

2. Embryogenetic systems
a. Free vs. guided morphogenesis

- **Self-organized forms of nature: physical, biological**

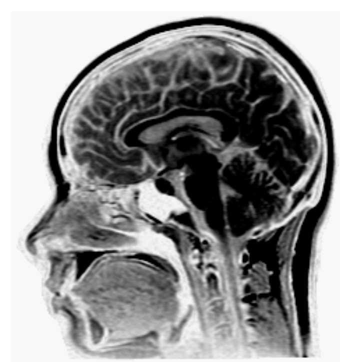
thermal convection
sand dunes, www.scottcamazine.com



chemical reaction
BZ, by A. Winfree, University of Arizona

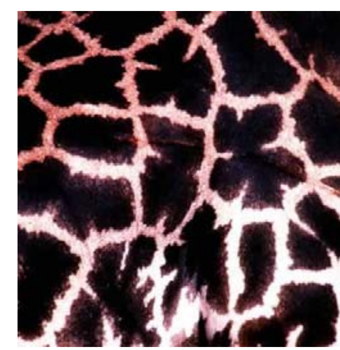
plant
pomegranate, by Köhler
www.plant-pictures.de

insect colony



the brain

animal
gecko, www.cepolina.com



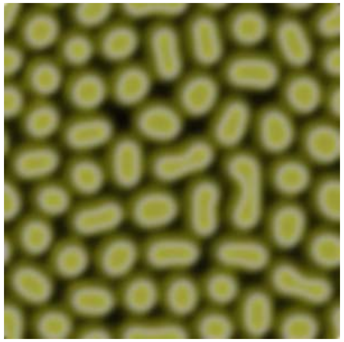
animal spots
www.scottcamazine.com

2. Embryogenetic systems
a. Free vs. guided morphogenesis

- **Different types and taxonomies of pattern formation**
  - ✓ natural forms can be inert / living, individual-level / collectivity-level, small-scale / large-scale, etc.
  - ✓ major distinction here: **free** forms / **guided** forms

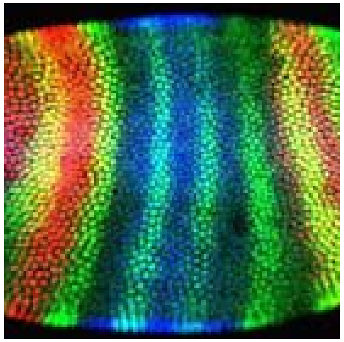
- **free**: Turing, reaction-diffusion
- randomly amplified fluctuations
- unpredictable: 4, 5 or 6 spots?
- statistically homogeneous

convection cells
www.chabotspace.org

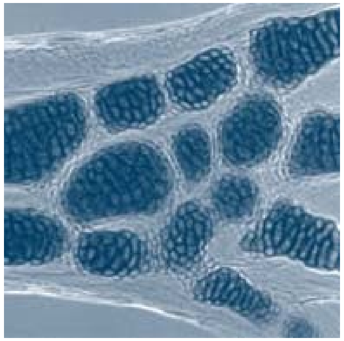


reaction-diffusion
texturegarden.com/java/rd

- **guided**: organism development
- deterministic genetic control
- reproducible: 4 limbs, 5 digits
- heterogeneous, rich in information



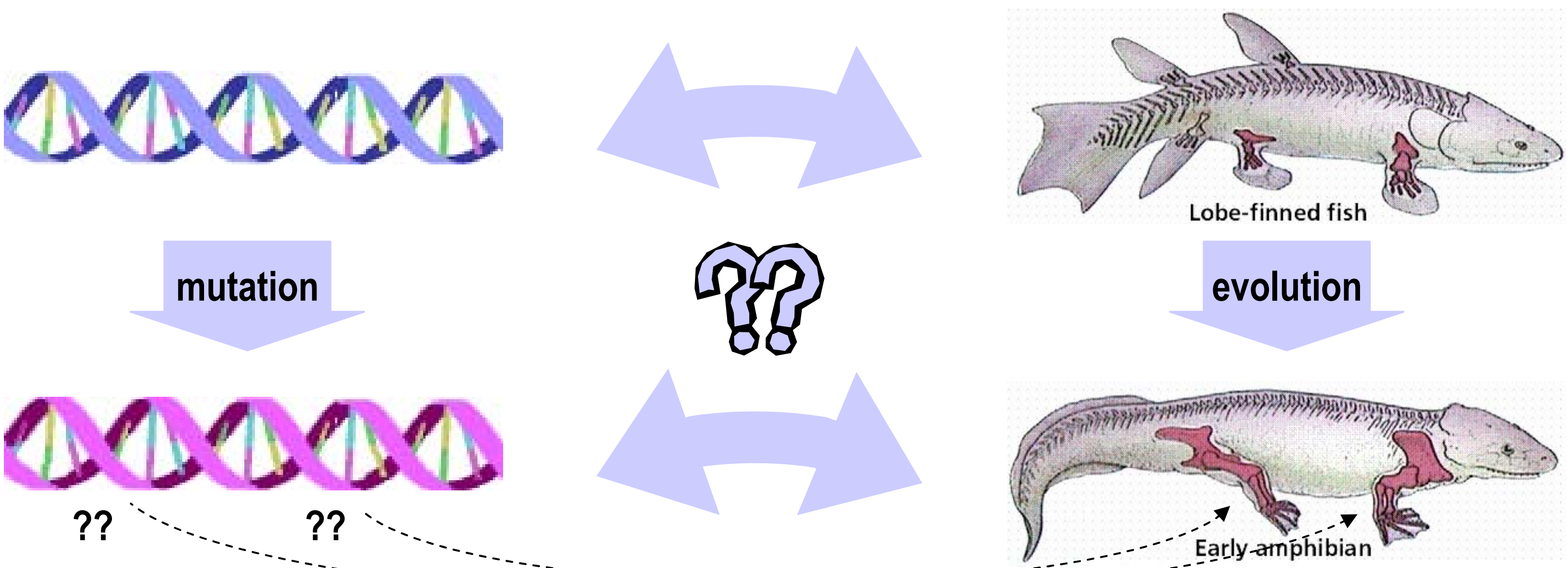
fruit fly embryo
Sean Caroll, U of Wisconsin



larval axolotl limb
Gerd B. Müller

2. Embryogenetic systems
a. Free vs. guided morphogenesis

- **Development: the missing link of the Modern Synthesis**
  - ✓ Darwin discovered the evolution of the **phenotype**
  - ✓ Mendel guessed, then Watson & Crick revealed the **genotype**
  - ✓ although the genotype-phenotype correlation is well established, the (epi)genetic mechanisms of development are still unclear



Purves et al., *Life: The Science of Biology*

2. Embryogenetic systems
a. Free vs. guided morphogenesis

<u>How</u> does a static, nonspatial genetic code dynamically unfold in time and 3-D space?

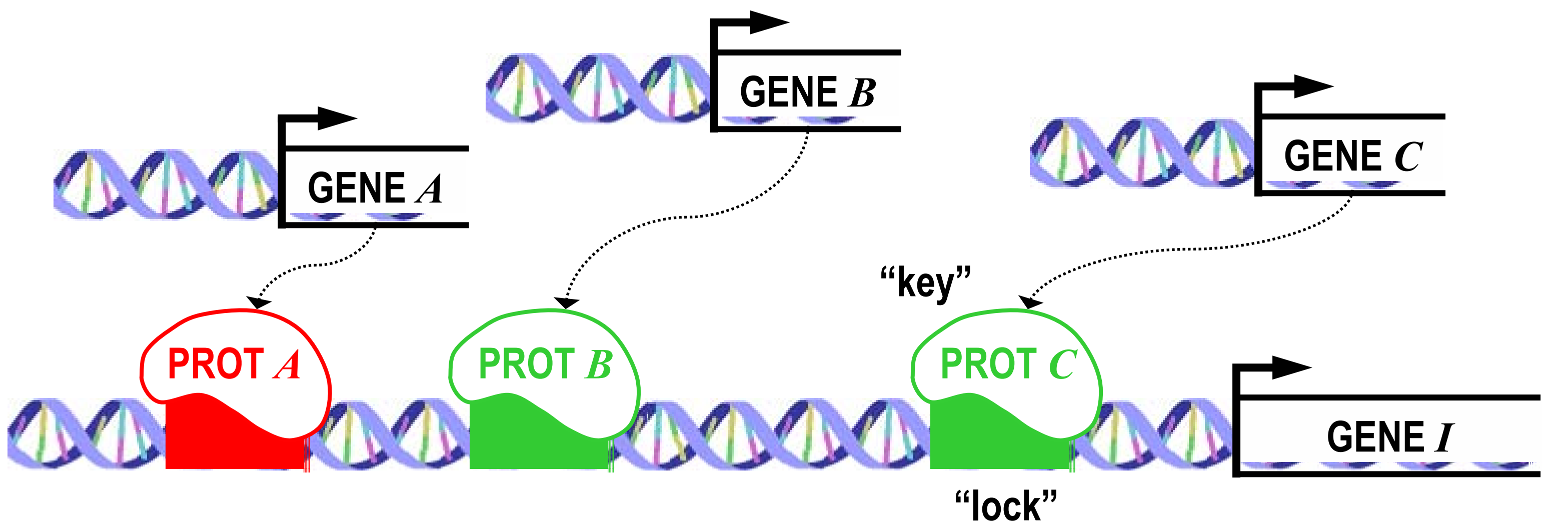
<u>How</u> are morphological changes correlated with genetic changes?

2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

- **Genetic switches are controlled by genetic expression**

✓ switch = regulatory site on DNA (“lock”) near a gene + protein that binds to this site (“key”), promoting or repressing the gene



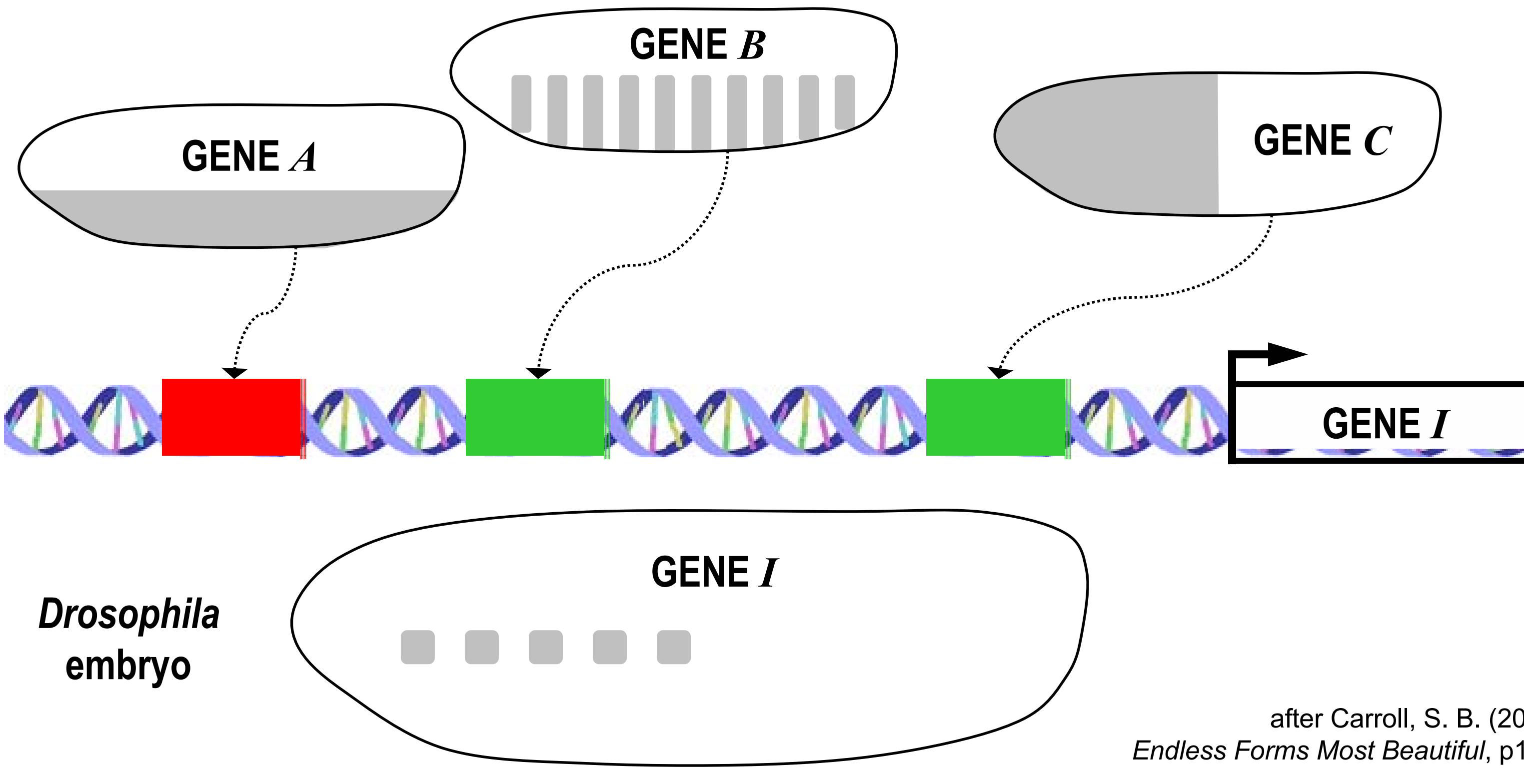
✓ switches can combine to form complex regulatory functions

→ *since switch proteins are themselves produced by genes, a cell can be modeled as a **gene-to-gene regulatory network** (GRN)*

2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

- **Developmental genes are expressed in <u>spatial</u> domains**
  - ✓ thus combinations of switches can create patterns by union and intersection, for example: $I = (\text{not } A) \text{ and } B \text{ and } C$



***Drosophila* embryo**

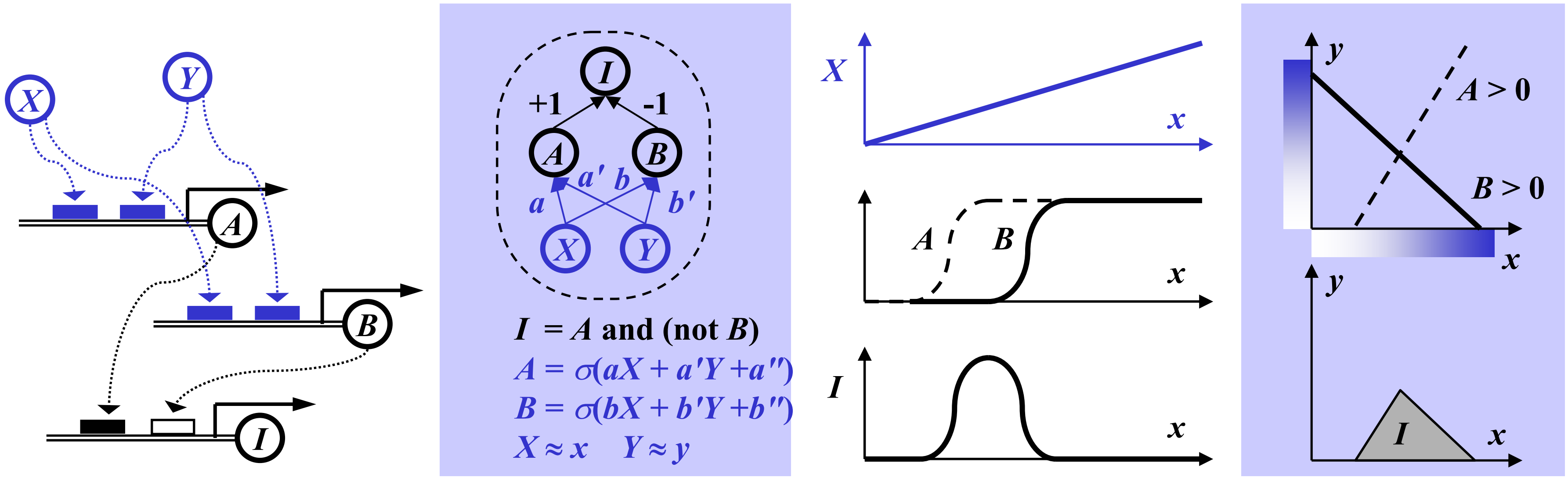
after Carroll, S. B. (2005)
Endless Forms Most Beautiful, p117

2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

➢ Three-tier GRN model: integrating positional gradients

✓ A and B are themselves triggered by proteins X and Y



✓ X and Y diffuse along two axes and form concentration gradients

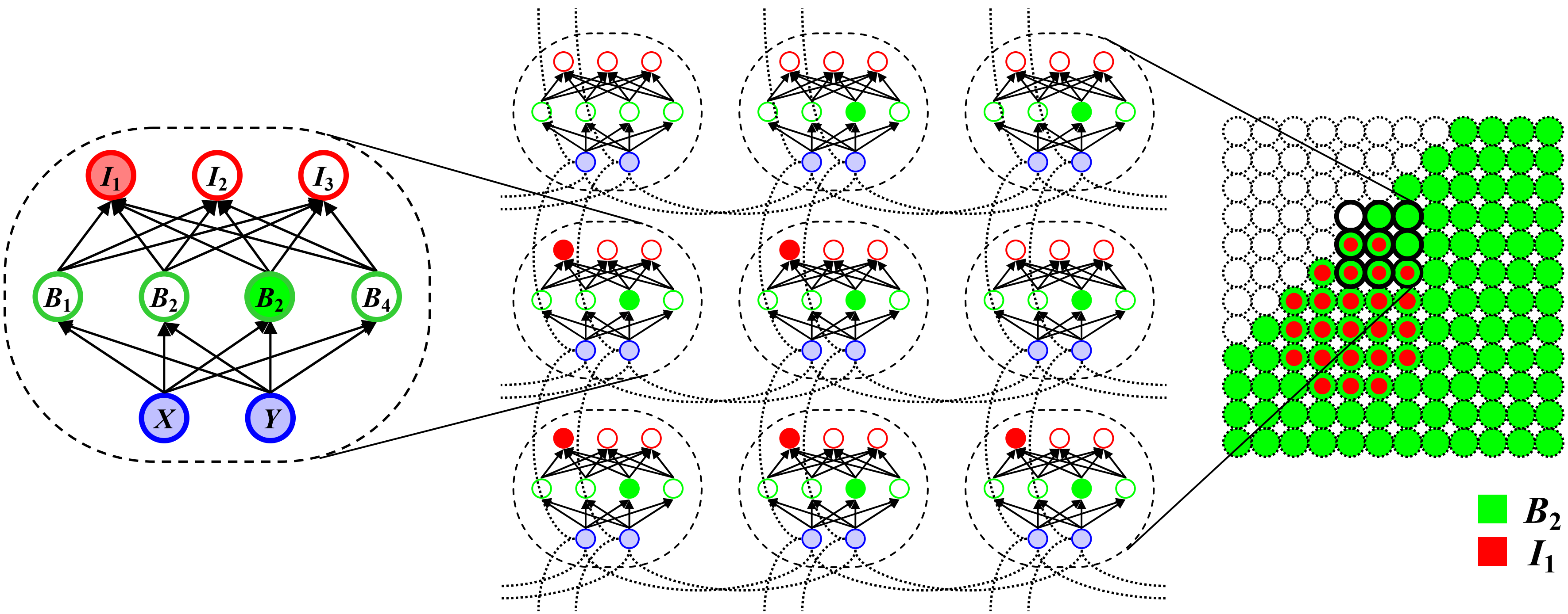
→ *different thresholds of lock-key sensitivity create different territories of gene expression in the geography of the embryo*

2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

➢ A lattice of Positional-Boundary-Identity (PBI) GRNs

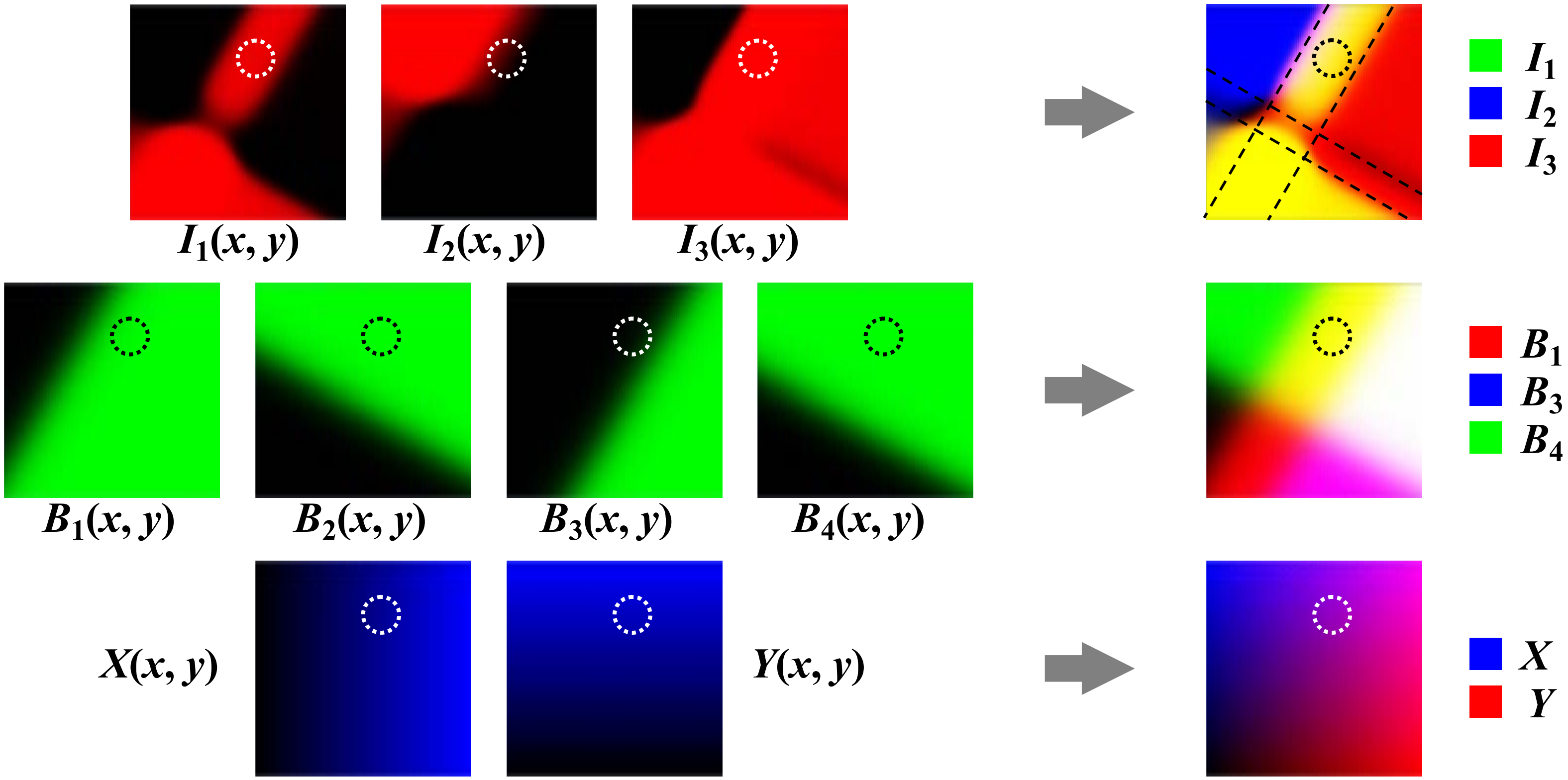
- ✓ network of networks: each GRN is contained in a cell, coupled to neighboring cells via the positional nodes (for diffusion)
- ✓ a pattern of gene expression is created on the lattice



2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

- **Example of numerical simulation with random weights**
  - ✓ the embryo's partitioning into territories is similar to the colorful compartments between lead cames in stained-glass works

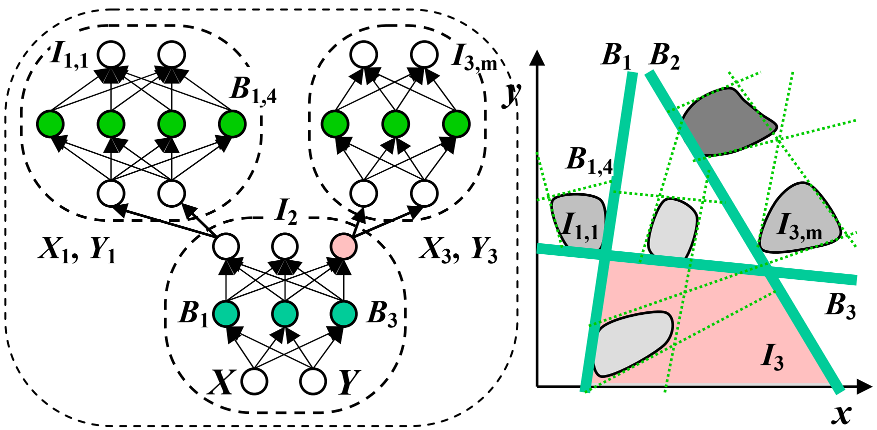


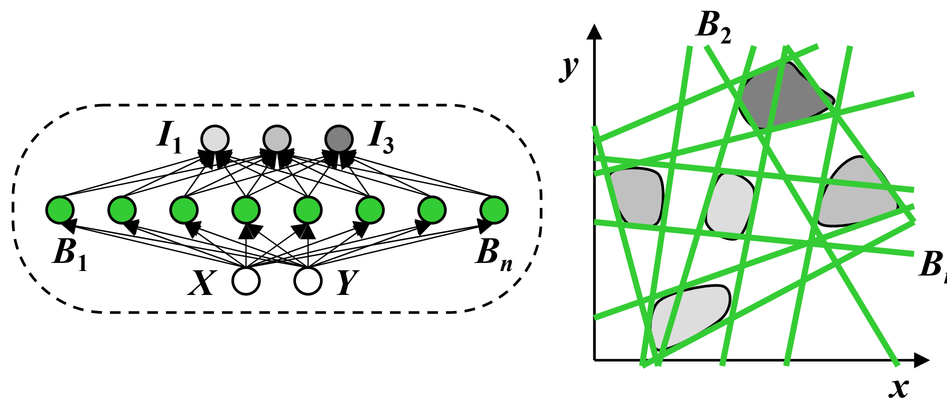
2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

➢ Multiscale refinement using a hierarchical GRN

- ✓ instead of one flat tier of B nodes, use a pyramid of PBI modules
- ✓ the activation of an I node controls the onset of a new P layer
- ✓ in the first stage, a base PBI network creates broad domains





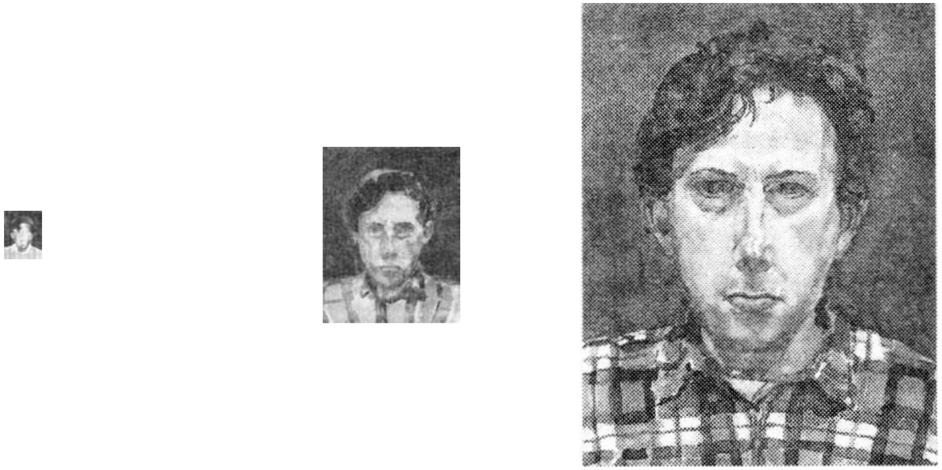
- ✓ in the next stage, another set of PBI networks subdivide these domains into compartments at a finer scale, etc.

2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

- **Morphological refinement by iterative growth**
  - ✓ details are not created in one shot, but gradually added. . .

  - ✓ . . . while, at the same time, the canvas grows



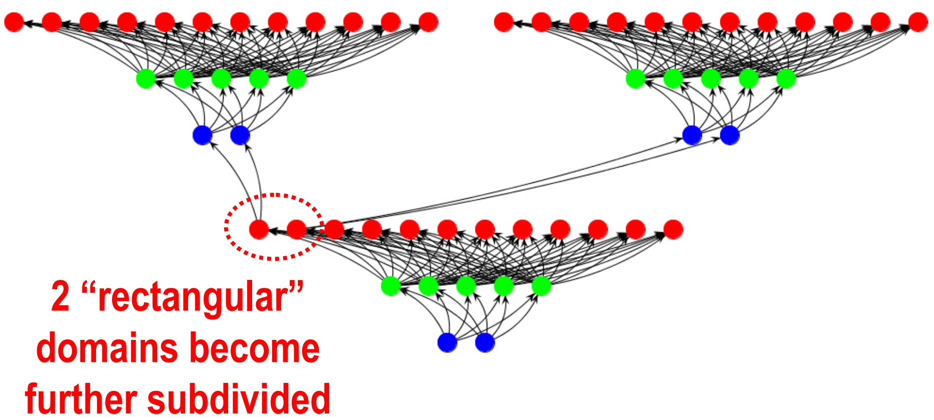
from Coen, E. (2000)
The Art of Genes, pp131-135

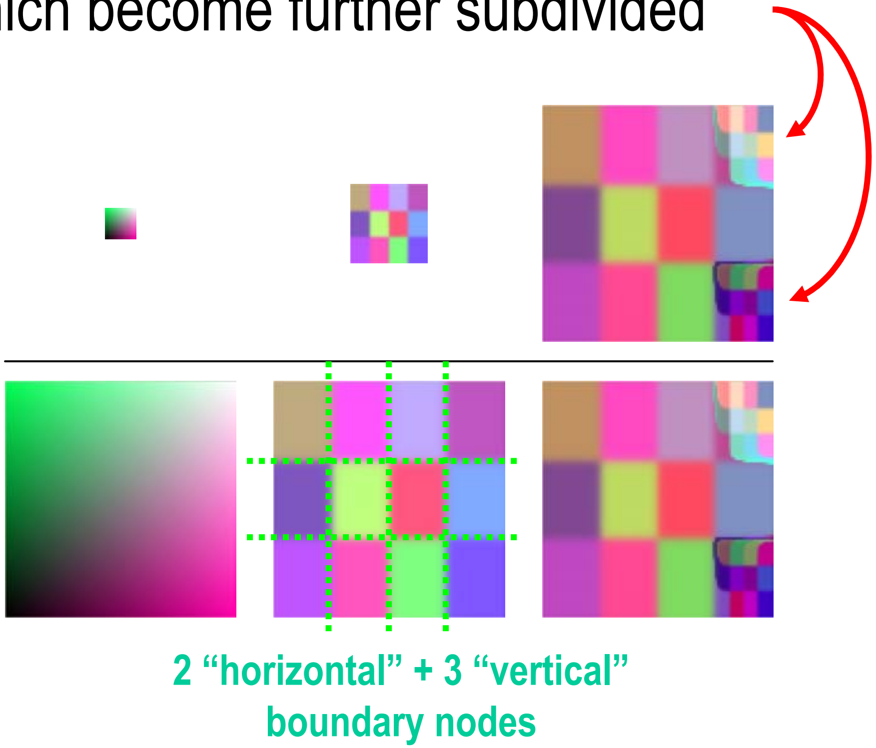
2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

➢ **Example of numerical simulation with preset weights**

- ✓ small stained glass embedded into bigger stained glass
- ✓ here, a 2-layer architecture of GRNs: 5 boundary nodes, 12 rectangular domains, 2 of which become further subdivided

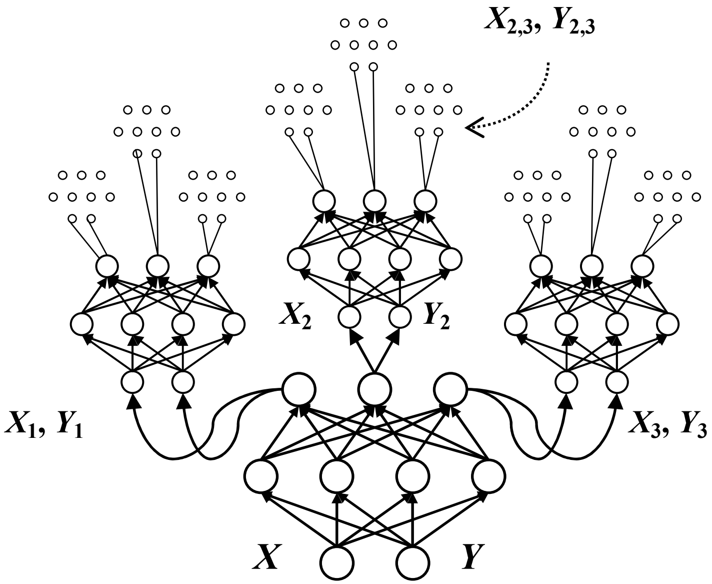




2. Embryogenetic systems

b. Multiscale self-patterning: the growing canvas

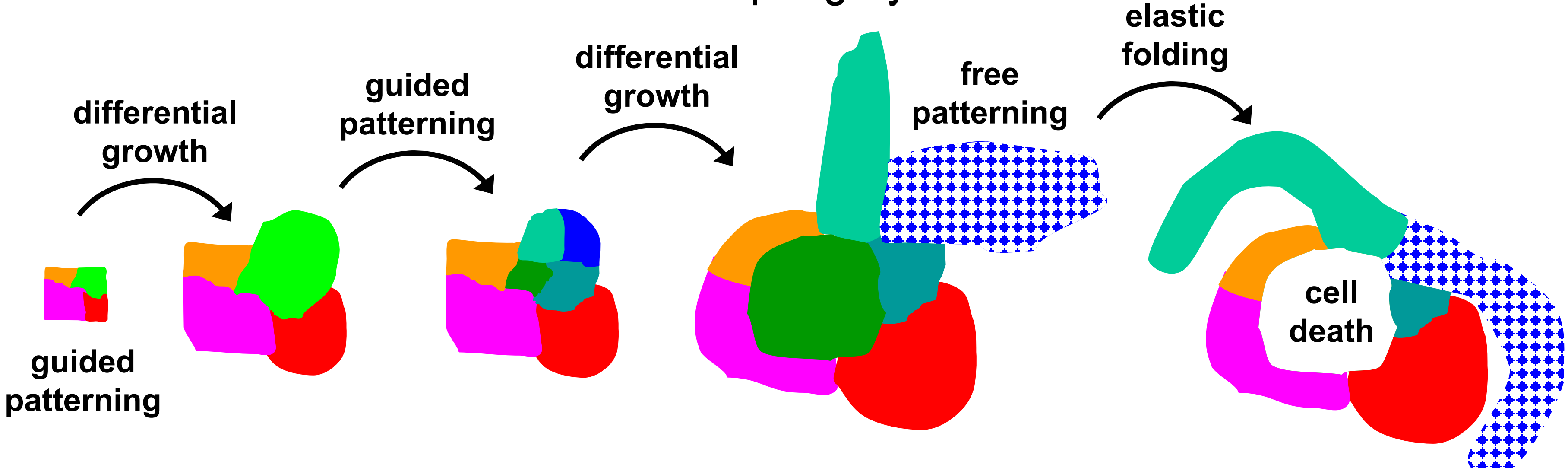
- **General idea of guided multiscale self-patterning**
  - ✓ possibility of image generation based on a generic hierarchical GRN
  - ✓ (here: illustration, not actual simulation)



2. Embryogenetic systems

c. Cell division & migration: the deformable canvas

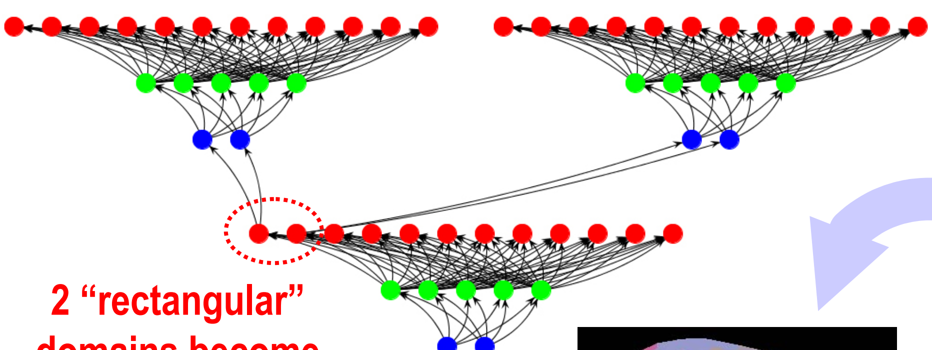
- **A few basic laws are sufficient to create great variation**
  - ✓ **guided patterning** — GRN-controlled expression maps
  - ✓ **differential growth** — domain-specific proliferation rates
  - ✓ **free patterning** — Turing-like epigenetic pattern formation
  - ✓ **elastic folding** — deformation from cellular mechanistic forces
  - ✓ **cell death** — detail-sculpting by removal



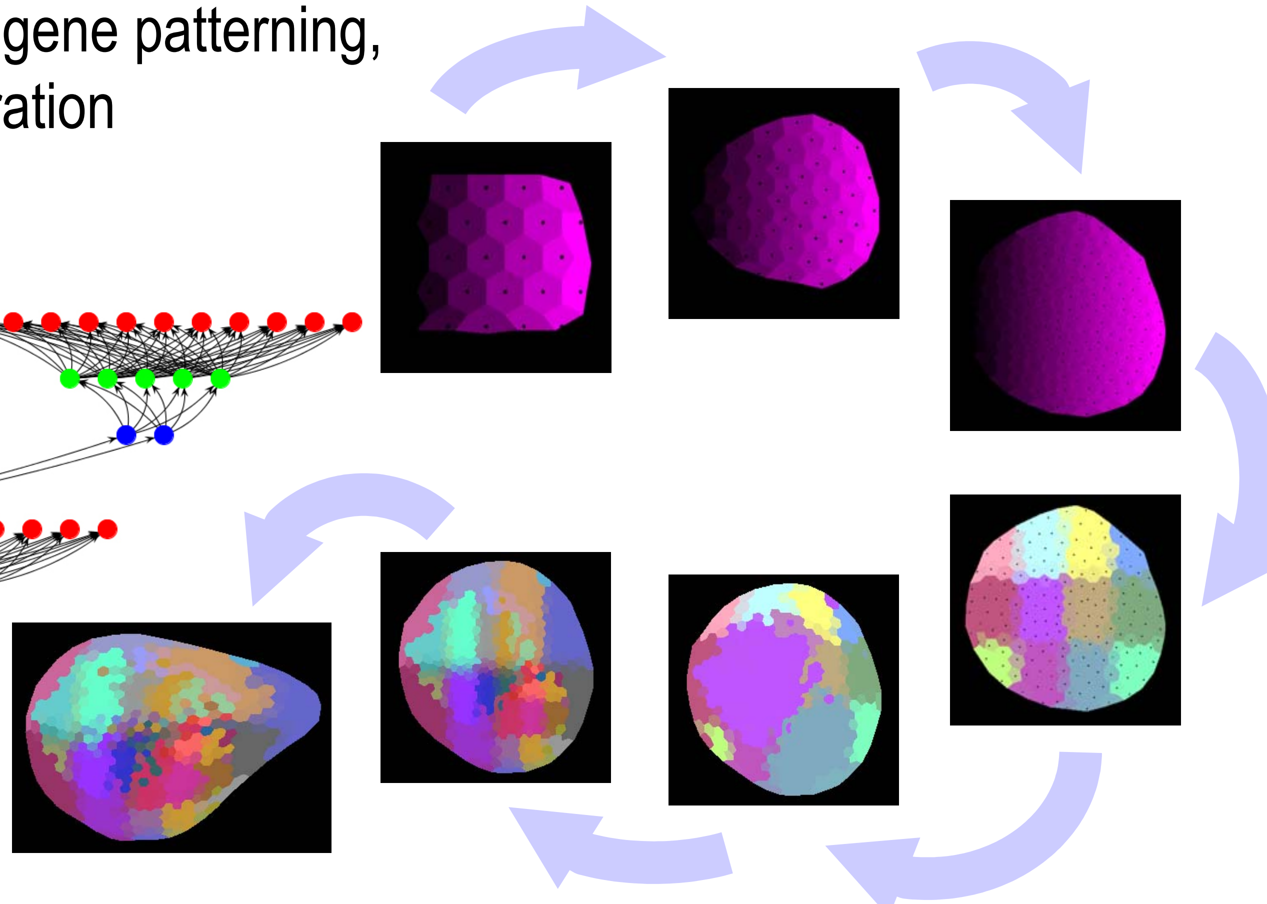
2. Embryogenetic systems

c. Cell division & migration: the deformable canvas

- **Example of simulation with cell division and migration**
  - ✓ starting from a 5x5 cell sheet, repeatedly applying a series of cell division, gene patterning, and cell migration processes



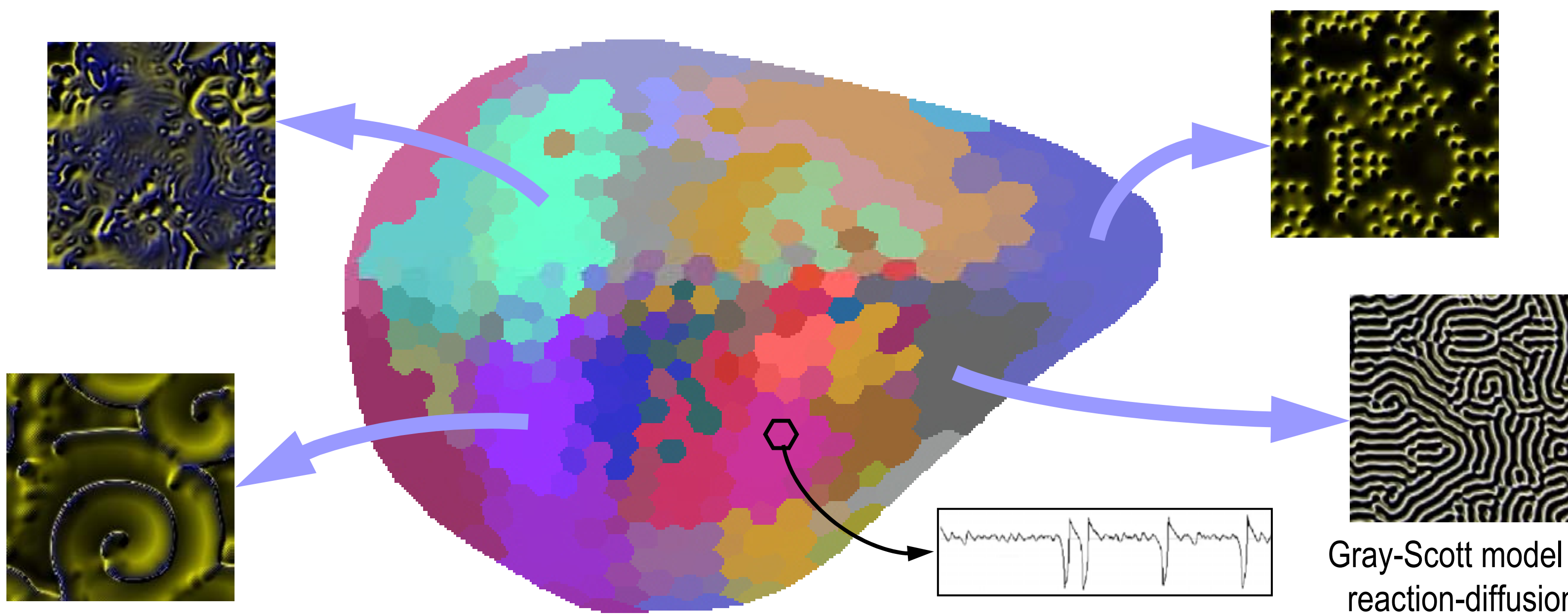
2 “rectangular” domains become further subdivided



2. Embryogenetic systems

d. Organic computing: the excitable canvas?

- **Possible computation performed by the organic system**
  - ✓ after self-patterning and self-assembling, the organism could become a dynamical system supporting computation
  - ✓ for example, cells could be the substrate of **excitable media** in various dynamic regimes, depending on their identity domain



Gray-Scott model of reaction-diffusion
texturegarden.com/java/rd

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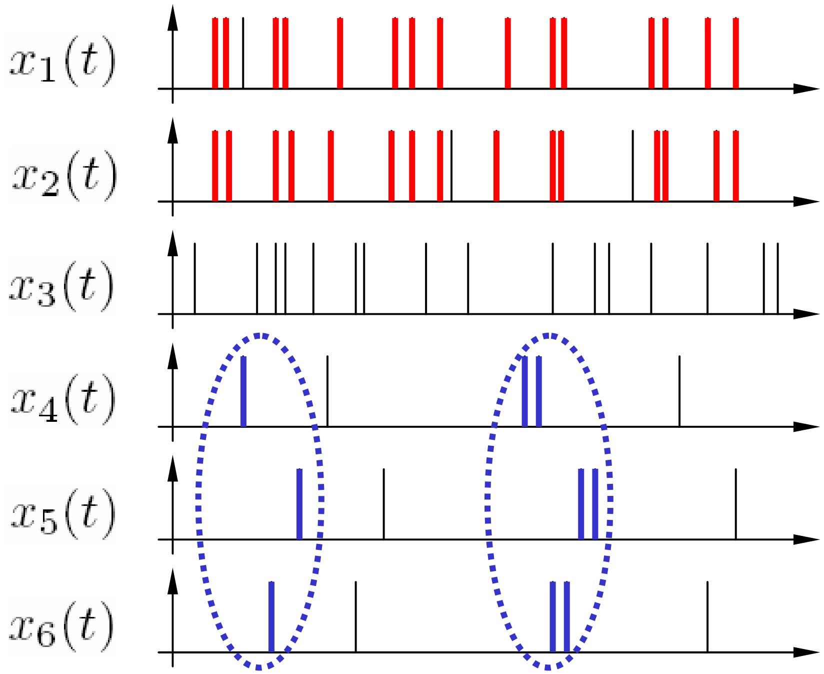
   A model of self-organizing random networks
   a. Overview: a tapestry of synfire chains
   b. Growing a synfire chain
   c. Synfire chain composition

4. "Planning the autonomy"
   The paradox of complex systems engineering

3. Neurogenetic systems

a. Overview — Rate vs. temporal coding



rate coding:
average spike frequency

$\langle\, x_1(t)\,\rangle = \bullet$

$\langle\, x_2(t)\,\rangle = \bullet$

$\langle\, x_3(t)\,\rangle = \bullet$

$\langle\, x_4(t)\,\rangle = \circ$

$\langle\, x_5(t)\,\rangle = \circ$

$\langle\, x_6(t)\,\rangle = \circ$

temporal coding:
spike correlations

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

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

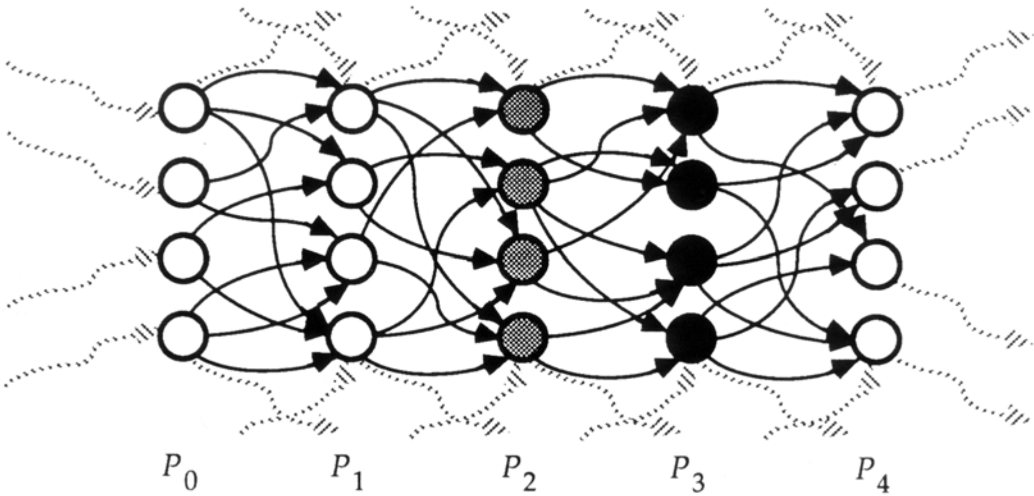
after von der Malsburg (1981) and Abeles (1982)

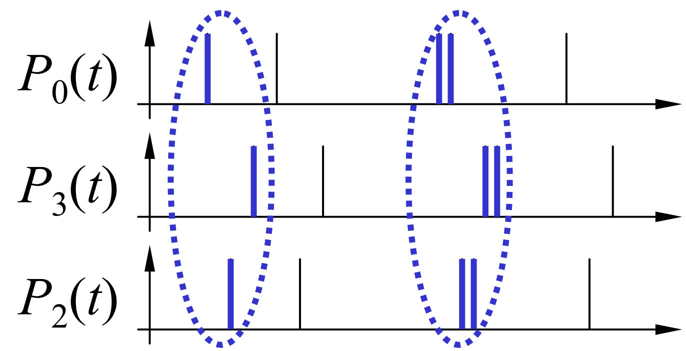
✓ there is more to neural signals than mean activity rates—***synchronization*** & ***delayed correlations*** among spikes (but not necessarily oscillatory)

3. Neurogenetic systems

a. Overview — 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)





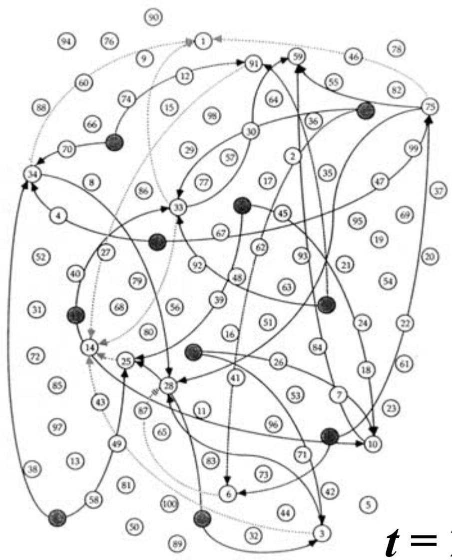
- ✓ synfire chains were hypothesized to explain neurophysiological recordings containing statistically significant delayed correlations
- ✓ the redundant divergent/convergent connectivity of synfire chains can preserve accurately synchronized action potentials, even under noise

3. Neurogenetic systems

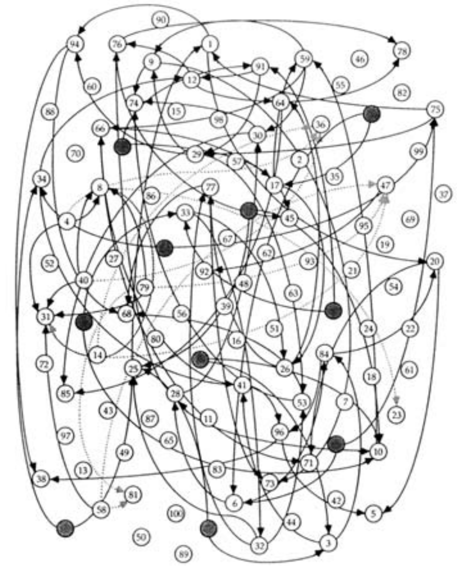
a. Overview — The growth of a synfire chain

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

$n_0 = 10$
$W = .1$
$\theta = 3$
$T = .5$
$\alpha = .1$
$s_0 = 10$

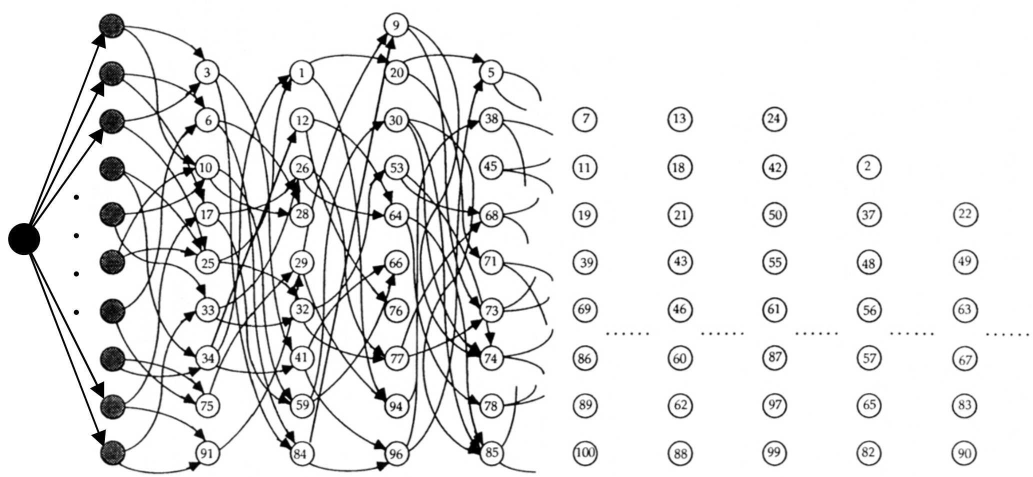


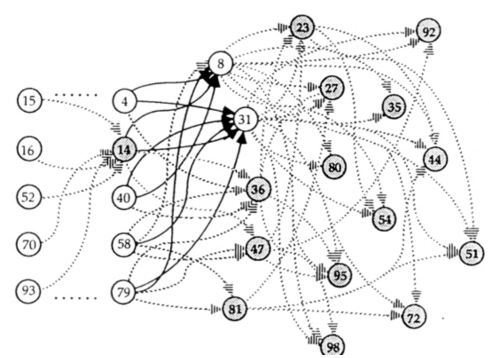
structuration
by aggregative
synfire growth



$t = 200$ $t = 4000$

spatially
rearranged
view

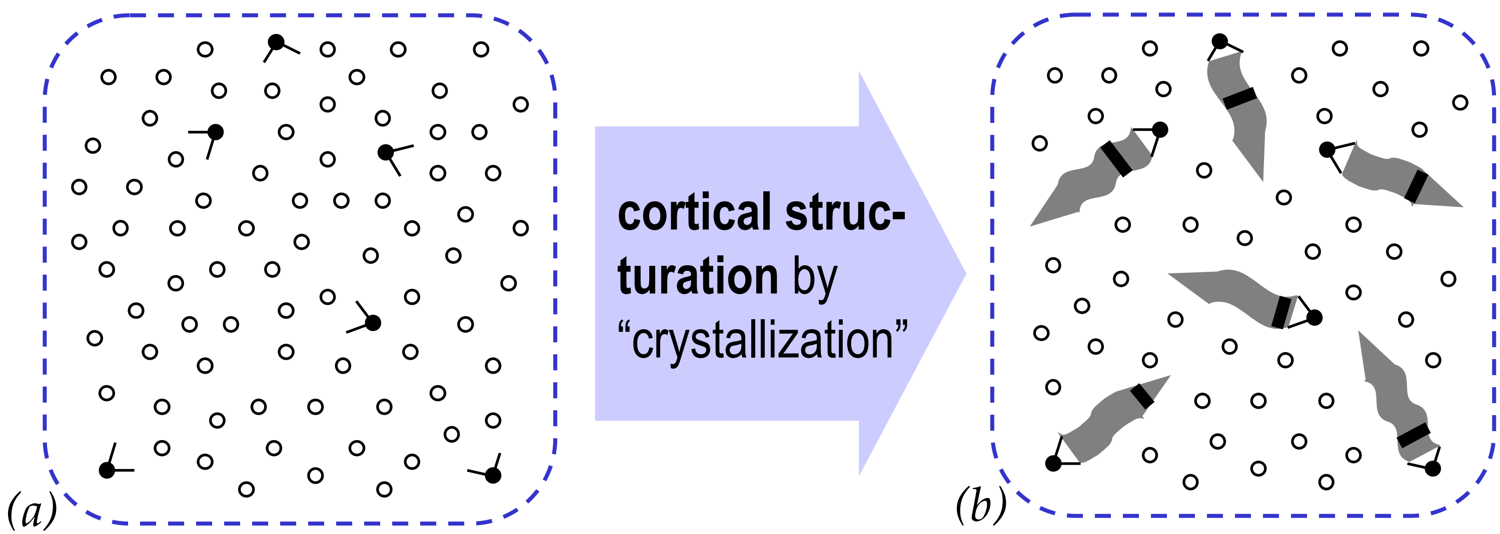




3. Neurogenetic systems

a. Overview — 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

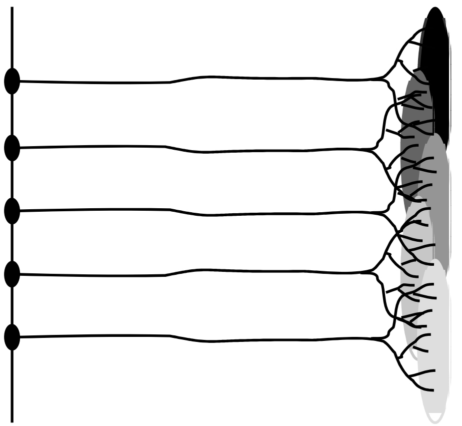


- ✓ concurrent chain development defines a ***mesoscopic scale of neural organization***, at a finer granularity than macroscopic AI symbols but higher complexity than microscopic neural potentials

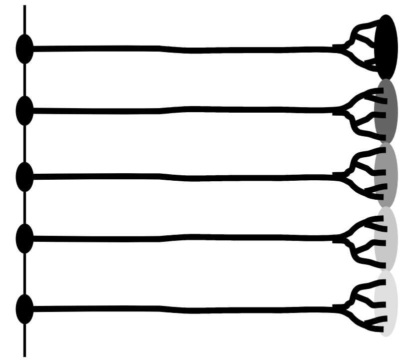
3. Neurogenetic systems

b. Growing a synfire chain — Neocortical development by focusing

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

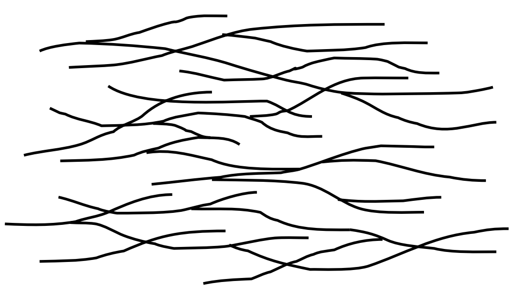


focusing of innervation in the retinotopic projection

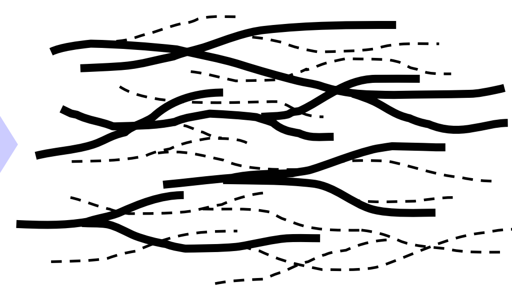


after Willshaw & von der Malsburg (1976)

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



"selective stabilization" by activity/connectivity feedback

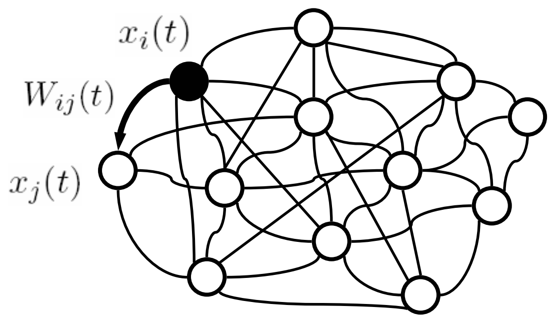


after Changeux & Danchin (1976)

3. Neurogenetic systems

b. Growing a synfire chain — Rule A: neuronal activation

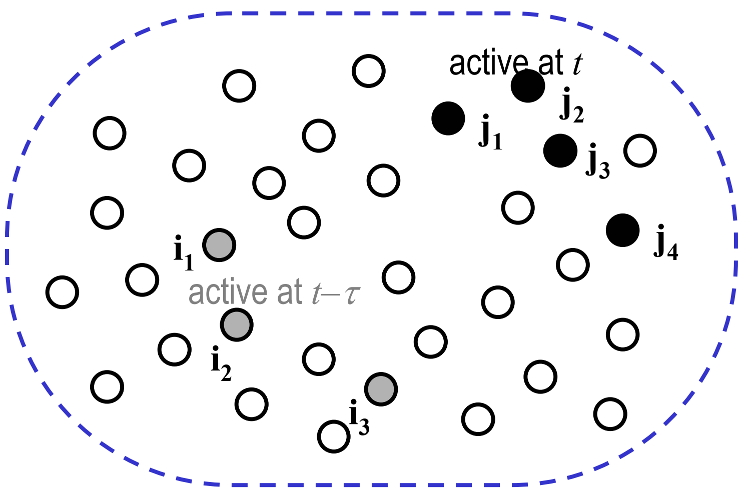
- ✓ we consider a network of simple binary units obeying a ***LNP spiking dynamics*** on the 1ms time scale (similar to "fast McCulloch & Pitts")

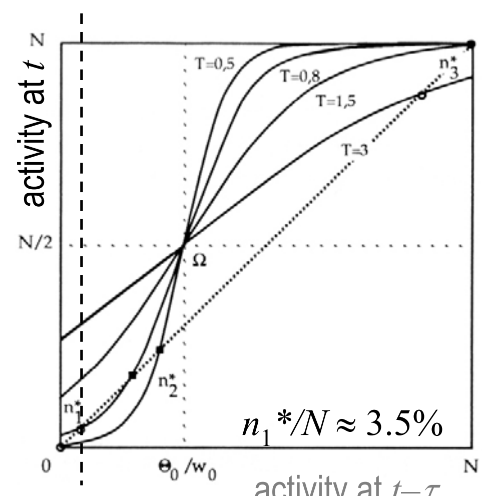


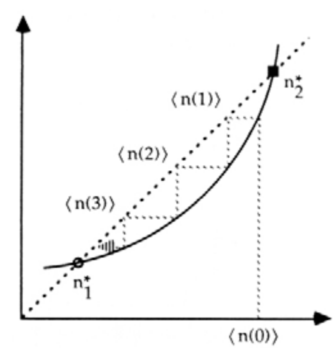
$$P[x_j(t)=1] = \frac{1}{1+e^{-(V_j(t)-\theta_j)/T}}$$

$$V_j(t) = \sum_i W_{ij}(t)\, x_i(t-\tau_{ij})$$

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







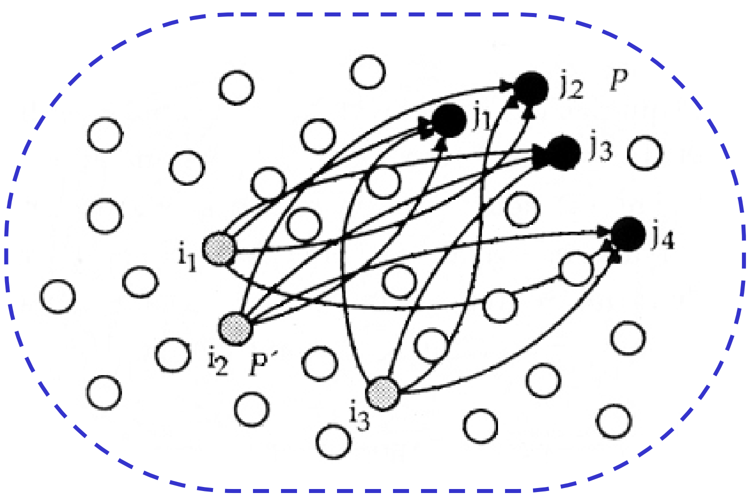
3. Neurogenetic systems

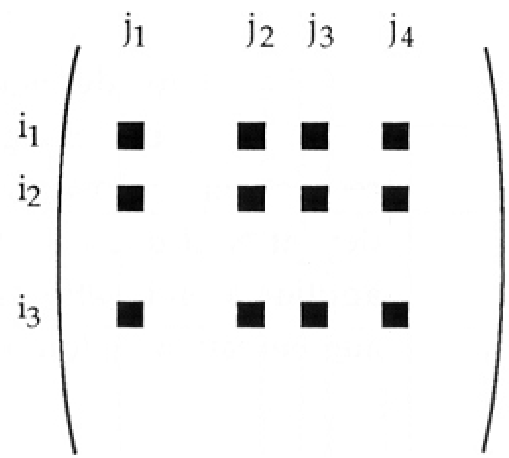
b. Growing a synfire chain — Rule B: synaptic cooperation

- ✓ 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 $\beta = 0$

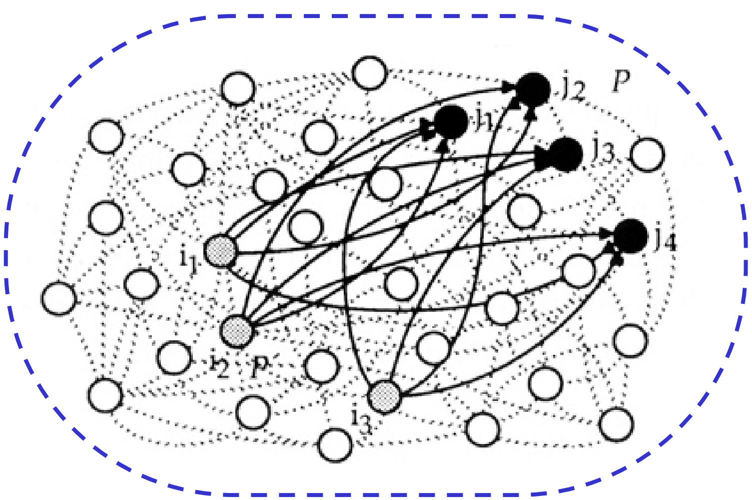
3. Neurogenetic systems

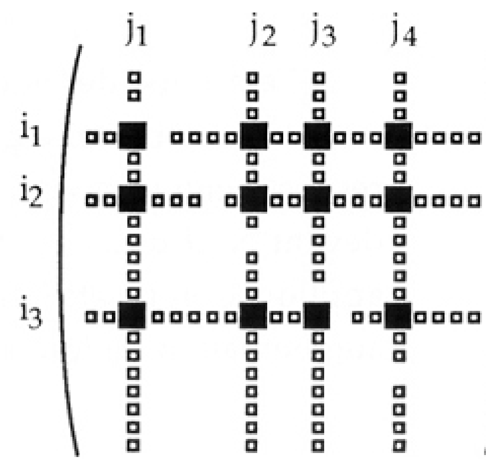
b. Growing a synfire chain — Rule C: synaptic competition

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

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

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





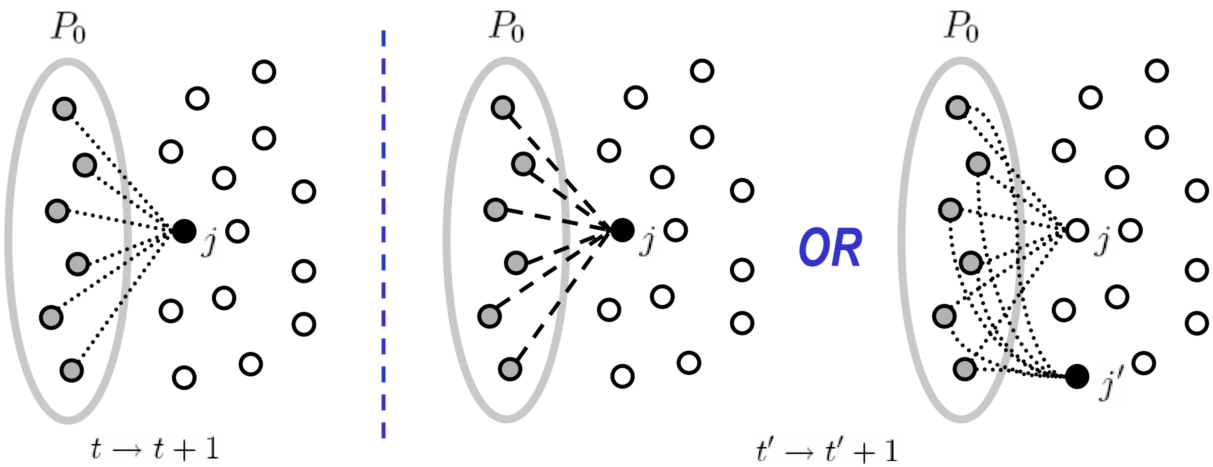
$B_{ij} + C_{ij}$ matrix

3. Neurogenetic systems

b. Growing a synfire chain — Development by aggregation

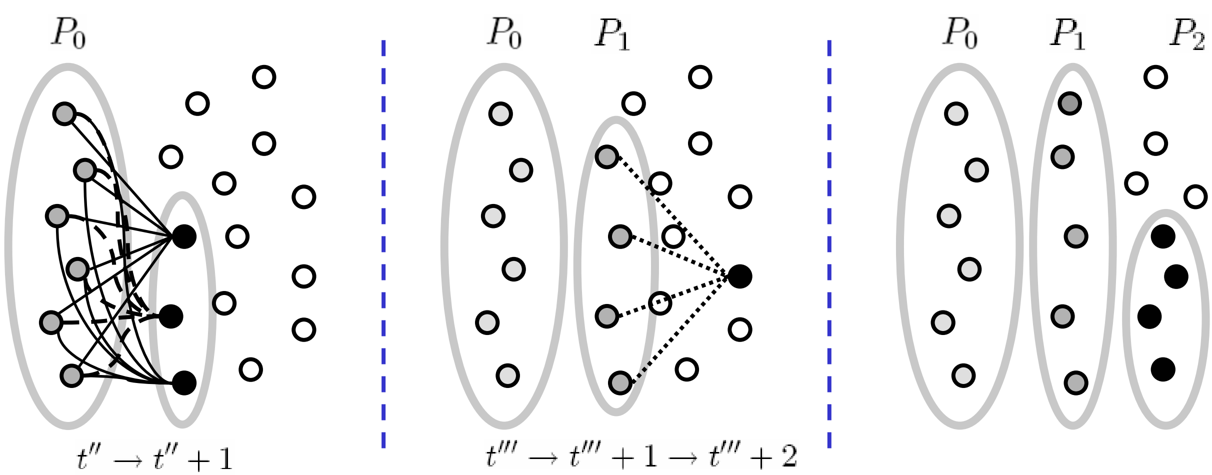
✓ a special group of n_0 ***synchronous*** cells, P_0, is ***repeatedly*** (yet not necessarily periodically) activated and recruits neurons "downstream"

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



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

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

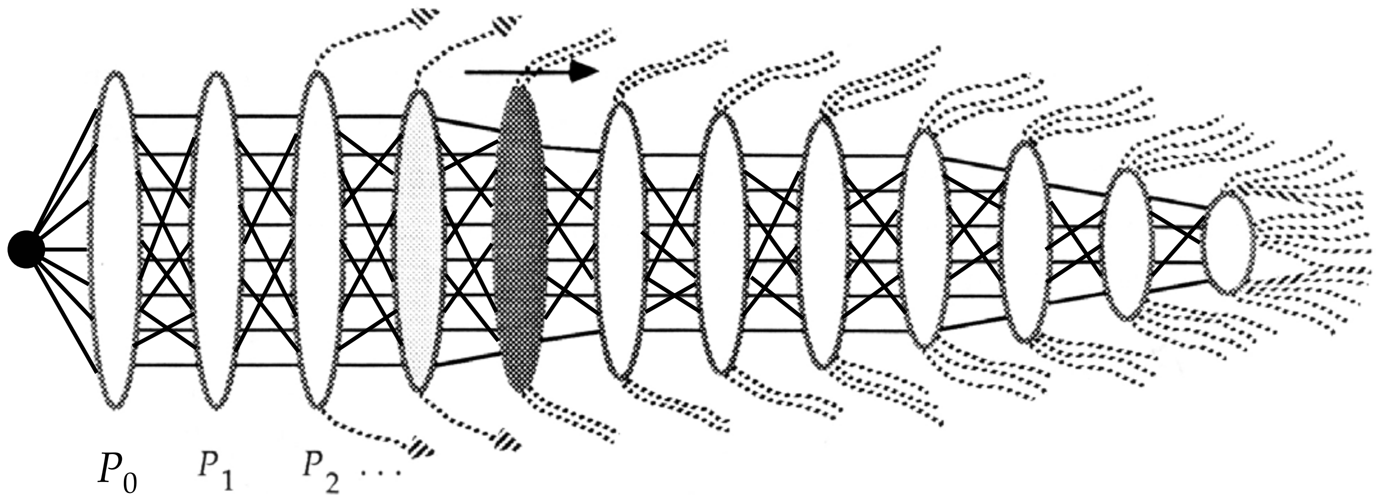


once it reaches a critical mass, P_1 also starts recruiting and forming a new group P_2, etc.

3. Neurogenetic systems

b. Growing a synfire chain — Extending 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

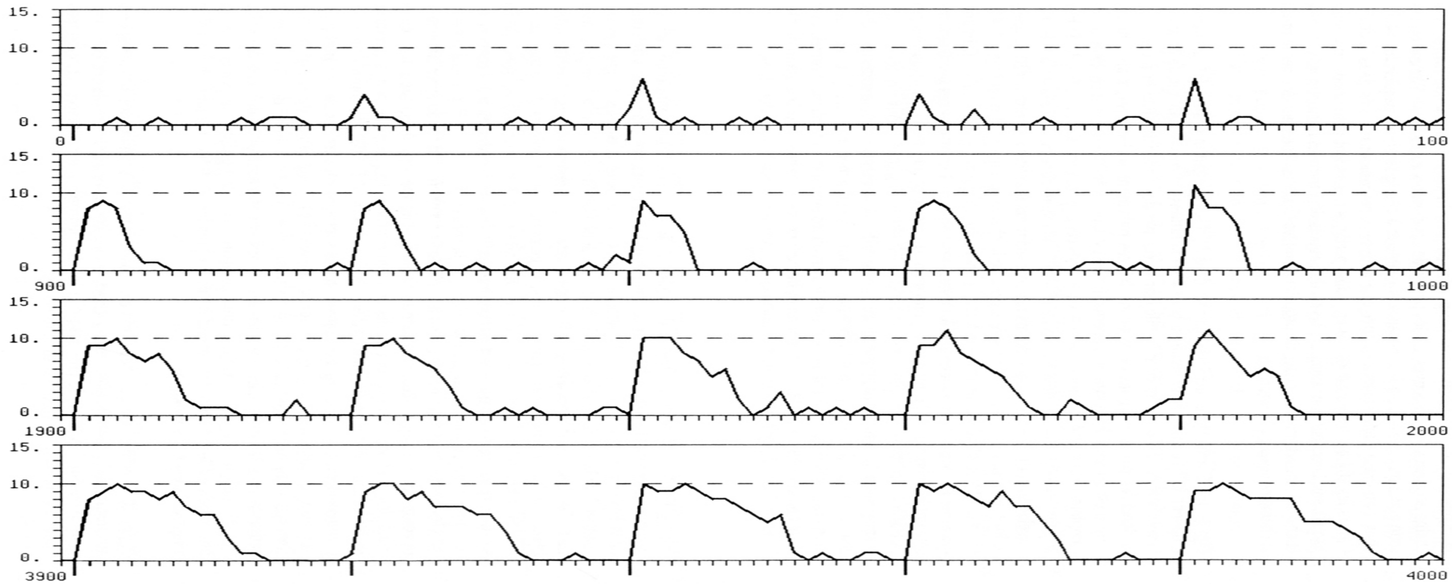


- ✓ the accretion process is not strictly iterative: groups form over broadly overlapping periods of time: as soon as group P_k reaches a critical mass, its activity is high enough to recruit the next group P_{k+1}
- ✓ thus, the ***chain typically lengthens before it widens*** and presents a "beveled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

3. Neurogenetic systems

b. Growing a synfire chain — Evolution of total activity

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



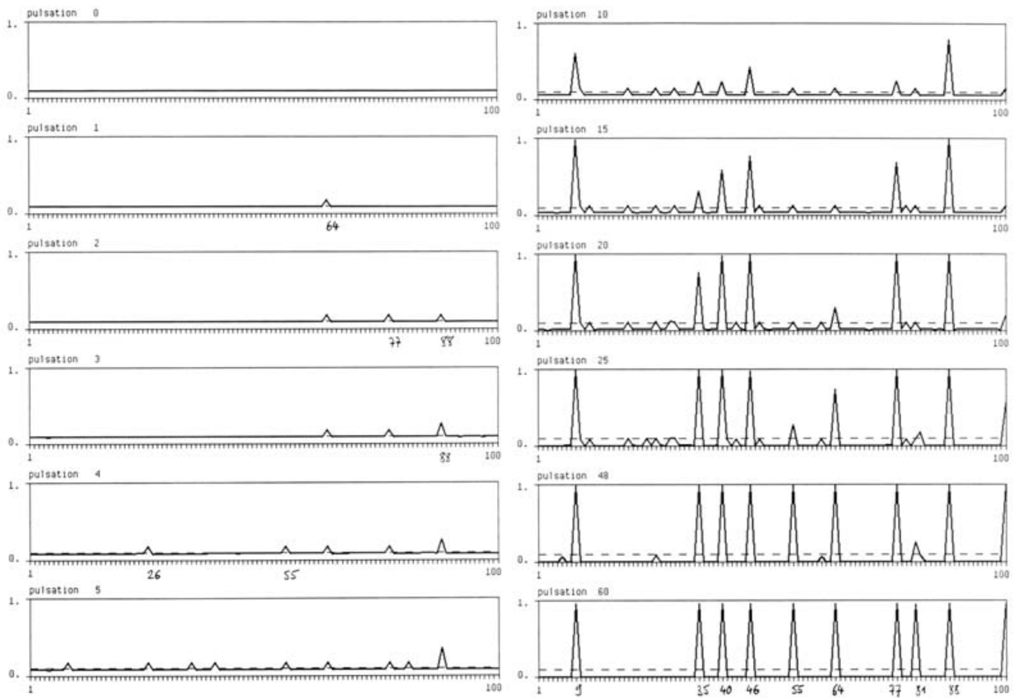
✓ ***other examples*** of chains (p: probability that connection $i \to j$ exists)

s_0	n_0	p	$n_0 \to n_1 \to n_2 \to n_3$ ...
7	5	1	(5) → 7 → 7 → 7 → 7 → 6 → 4 ...
7.5	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 ...

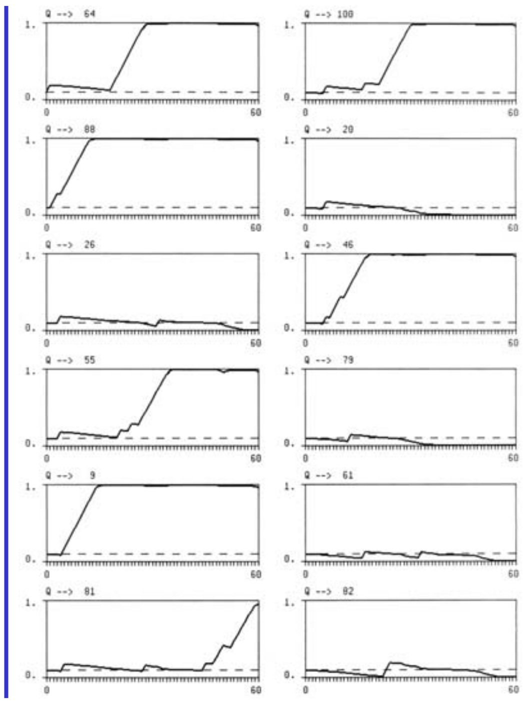
3. Neurogenetic systems

b. Growing a synfire chain — 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

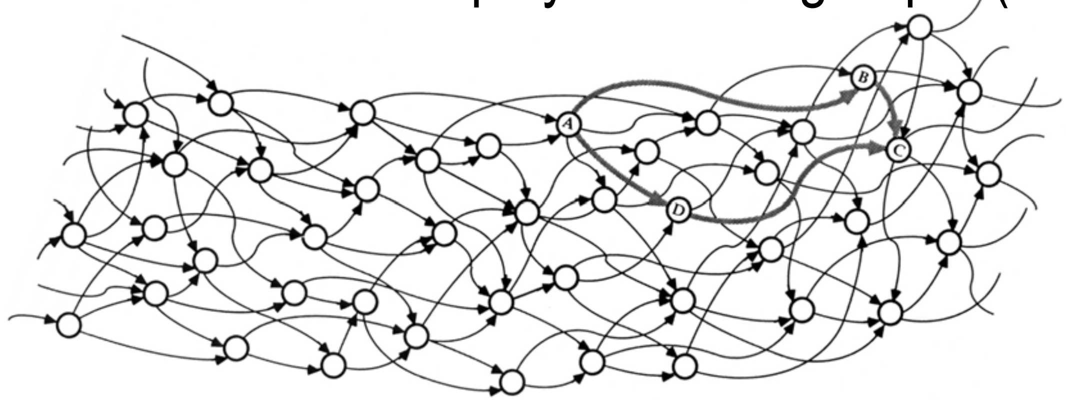


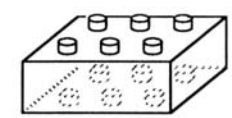
evolution of single $P_0 \rightarrow j$ weights

3. Neurogenetic systems

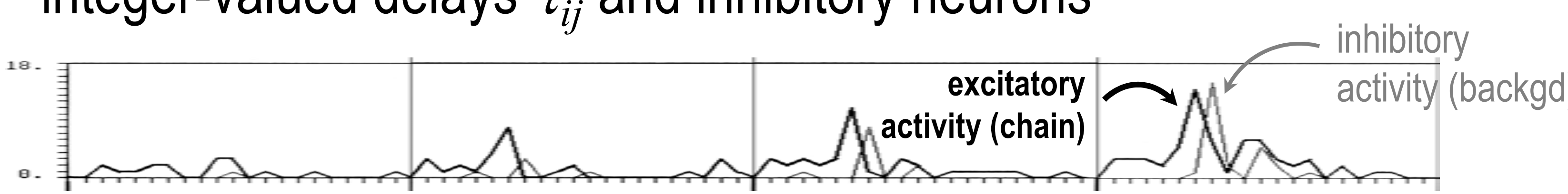
b. Growing a synfire chain — Synfire braids

- ✓ 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)



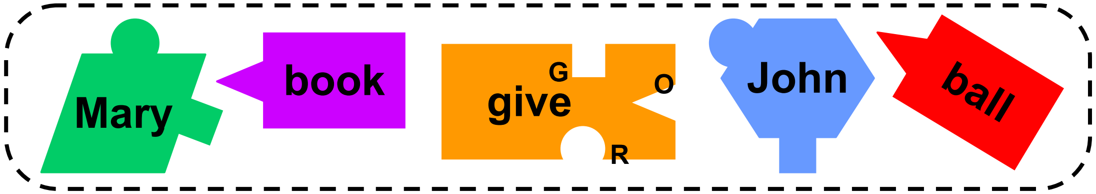


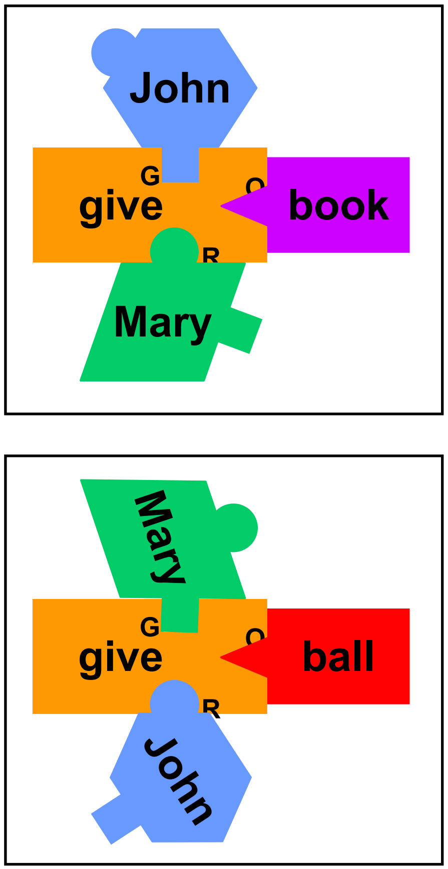
- ✓ in a synfire braid, ***delay transitivity*** $\tau_{AB} + \tau_{BC} = \tau_{AD} + \tau_{DC}$ favors strong spike coincidences, hence a stable propagation of activity
- ✓ our model also shows the growth of synfire braids with nonuniform integer-valued delays τ_{ij} and inhibitory neurons

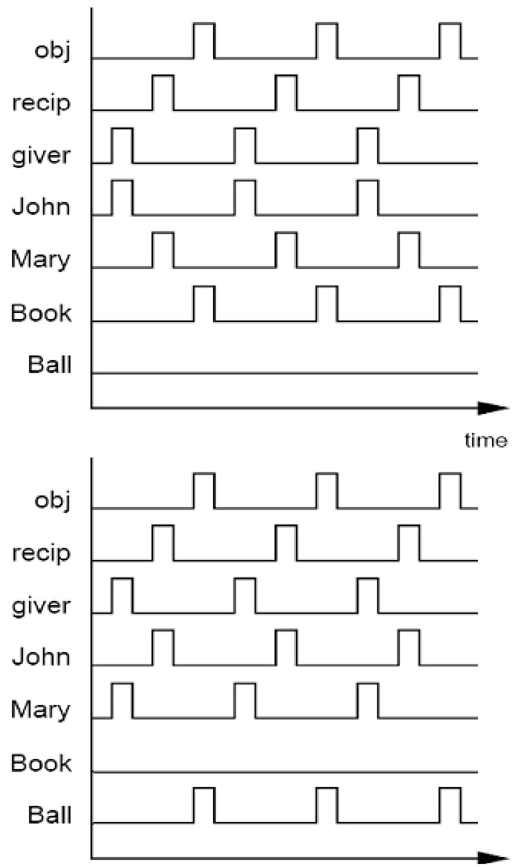


3. Neurogenetic systems

c. Synfire chain composition — The compositionality of cognition







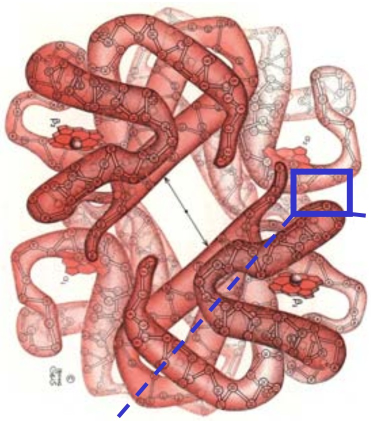
after Bienenstock (1995)

graphs after Shastri & Ajjanagadde (1993)

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

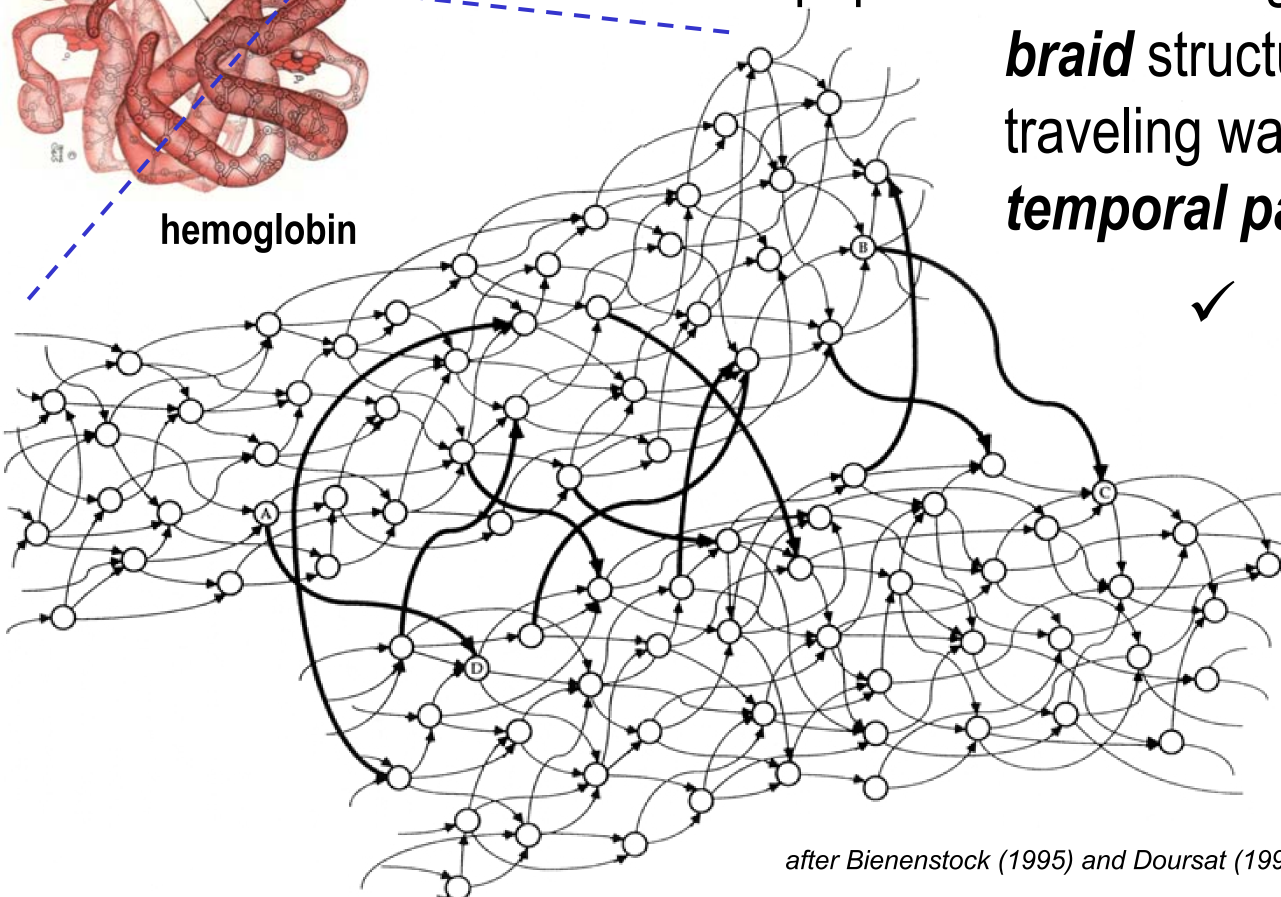
3. Neurogenetic systems

c. Synfire chain composition — Spatiotemporal binding

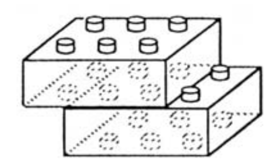


hemoglobin

- ✓ 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 ***spatio-temporal pattern*** (STP)
  - ✓ two STPs can synchronize via ***coupling links***



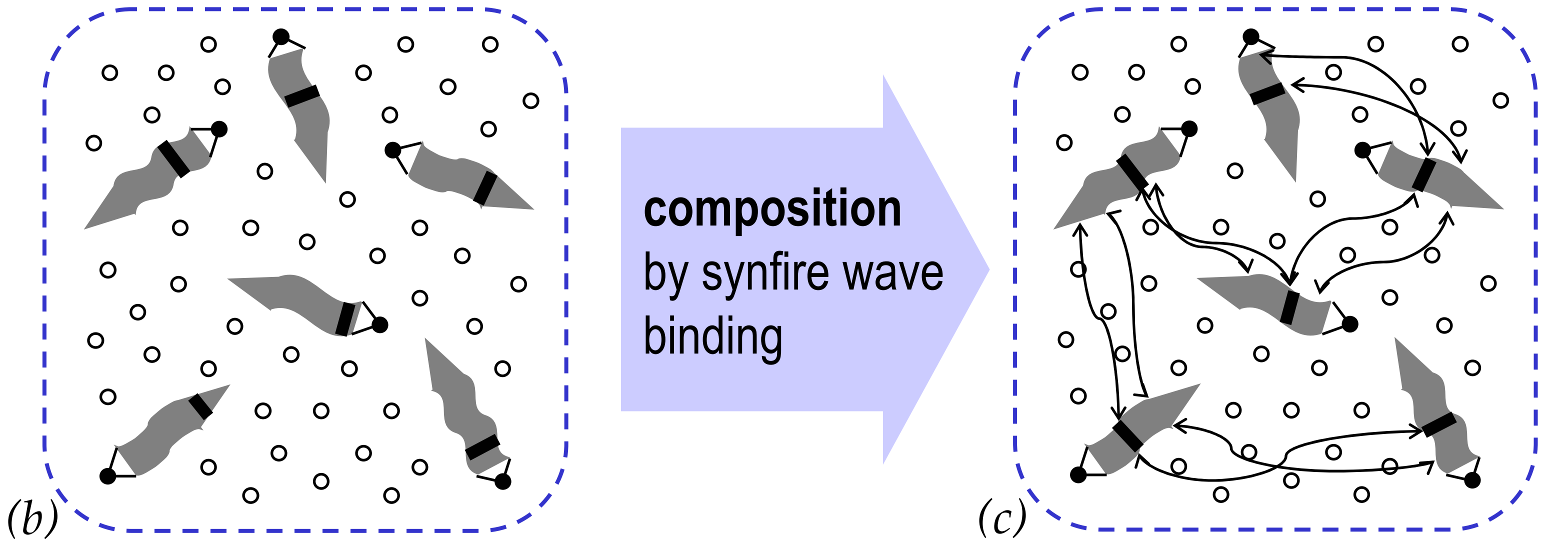
after Bienenstock (1995) and Doursat (1991)



3. Neurogenetic systems

c. Synfire chain composition — 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)

Organically Grown Architectures

1. Toward decentralized systems design
2. Embryogenetic systems
   A model of self-organizing 2-D and 3-D lattices
3. Neurogenetic systems
   A model of self-organizing random networks
4. “Planning the autonomy”
   The paradox of complex systems engineering

4. “Planning the Autonomy”

The paradox of complex systems engineering

- **Growth, function, selection**
  - ✓ the three challenges of complex systems engineering:

parameters = “genetic code”

1. how does the system **grow**?
   - development follows a few basic mechanisms at the microlevel:
   - cells change state (genetic expression, neural activity)
   - cells communicate (positional signals, synaptic transmission)
   - cells move (migration) and create other cells (division)
2. how does the system **compute**?
   - after development, what is its macroscopic *function*? how does it interact with its environment?
   - computing (input/output), moving & acting (robotics), etc.
3. how does the system **evolve** and how is it **selected**?

4. “Planning the Autonomy”

The paradox of complex systems engineering

How can we control complexity?

How can we both “let go” and still have requirements at the same time?

How can we “optimize” the parameters (genetic code) of a self-organized process?

4. "Planning the Autonomy"

The paradox of complex systems engineering

- **3. Selecting without expectations**
  - ✓ different degrees of fitness constraints
  - a) selecting for a specific **organism** (shape, pattern)
    - reverse problem: given the phenotype, what should be the genotype?
    - **direct** recipe; ex: Nagpal's macro-to-microprogram Origami compilation
    - otherwise: **learn** or **evolve** under strict fitness → difficult to achieve!
  - b) selecting for a specific **function**, leaving freedom of architecture
    - given a task, optimize performance (computing, locomotion, etc.)
    - be surprised by pattern creativity; ex: Avida, GOLEM, Framsticks
  - c) selecting the **unexpected**
    - create a "solution-rich" space by diversifying the requirements
    - "harvest" interesting organisms from a free-range menagerie

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