Organically Grown Architectures:
Embryogenesis and Neurogenesis as New Paradigms for Decentralized Systems Design

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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
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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

   ![Graph showing the exponential growth of transistors from Intel 4004 (1971) to Intel Pentium 4 (2000).]
1. Toward Decentralized Systems Design
   a. The exploding growth in information systems

   ✓ Exploding growth in software

   ✓ number and interconnection of functions, modules and layers

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

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

   ➞ 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

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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”

- 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
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

- 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)**

<table>
<thead>
<tr>
<th>Network</th>
<th>Nodes</th>
<th>Edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>BZ reaction</td>
<td>molecules</td>
<td>collisions</td>
</tr>
<tr>
<td>slime mold</td>
<td>amoebae</td>
<td>cAMP</td>
</tr>
<tr>
<td>embryo</td>
<td>cells</td>
<td>“morphogens”</td>
</tr>
<tr>
<td>insect colonies</td>
<td>ants, termites</td>
<td>pheromone</td>
</tr>
<tr>
<td>flocking, traffic</td>
<td>animals, cars</td>
<td>perception</td>
</tr>
<tr>
<td>swarm sync</td>
<td>fireflies</td>
<td>photons ± long-range</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>Network</th>
<th>Nodes</th>
<th>Edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internet</td>
<td>routers</td>
<td>wires</td>
</tr>
<tr>
<td>the brain</td>
<td>neurons</td>
<td>synapses</td>
</tr>
<tr>
<td>WWW</td>
<td>pages</td>
<td>hyperlinks</td>
</tr>
<tr>
<td>Hollywood</td>
<td>actors</td>
<td>movies</td>
</tr>
<tr>
<td>gene regulation</td>
<td>proteins</td>
<td>binding sites</td>
</tr>
<tr>
<td>ecosystems</td>
<td>species</td>
<td>competition</td>
</tr>
</tbody>
</table>

- 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
Organically Grown Architectures

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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”
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2. Embryogenetic systems
   a. Free vs. guided morphogenesis

➢ Self-organized forms of nature: physical, biological
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

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

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convection cells  
www.chabotspace.org

reaction-diffusion  
texturegarden.com/java/rd

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

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Purves et al., *Life: The Science of Biology*
2. Embryogenetic systems
   a. Free vs. guided morphogenesis

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

   How 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

![Diagram showing the interaction between genes and proteins]

- 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 spatial domains
  - thus combinations of switches can create patterns by union and intersection, for example: $I = (\neg A) \land B \land C$

![Diagram of developmental genes expressed in spatial domains](image)

*Drosophila* embryo

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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.

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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 “horizontal” + 3 “vertical” boundary nodes
2 “rectangular” domains 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
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   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

\[ \langle x_1(t) x_2(t) \rangle \gg \langle x_1(t) x_3(t) \rangle \]
\[ \langle x_4(t) x_5(t - \tau_{4.5}) x_6(t - \tau_{4.6}) \rangle \]

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 $P_0 \rightarrow P_1 \rightarrow P_2 \ldots$ linked by feedforward 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

\[
\begin{align*}
    n_0 &= 10 \\
    W &= 0.1 \\
    \theta &= 3 \\
    T &= 0.5 \\
    \alpha &= 0.1 \\
    s_0 &= 10
\end{align*}
\]
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

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

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*after Willshaw & von der Malsburg (1976)*

*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.

\[
W_{ij}(t) = W_{ij}(t - 1) + B_{ij}(t)
\]

\[
\begin{align*}
&x_i(t - \tau_{ij}) = 1, x_j(t) = 1 \Rightarrow B_{ij}(t) = +\alpha \\
&x_i(t - \tau_{ij}) = 1, x_j(t) = 0 \Rightarrow B_{ij}(t) = -\beta \\
&x_i(t - \tau_{ij}) = 0, x_j(t) = 1 \Rightarrow B_{ij}(t) = -\beta \\
&x_i(t - \tau_{ij}) = 0, x_j(t) = 0 \Rightarrow B_{ij}(t) = 0
\end{align*}
\]

- Successful spike transmission events $1 \rightarrow 1$ are rewarded, thus connectivity “builds up” in the wake of the propagation of activity.

\[
\begin{pmatrix}
  j_1 & j_2 & j_3 & j_4 \\
  i_1 & \ast & \ast & \ast \ast \\
  i_2 & \ast & \ast & \ast \ast \\
  i_3 & \ast & \ast & \ast \ast \\
\end{pmatrix}
\]

*$B_{ij}$ 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)

\[
W_{ij}(t) = W_{ij}(t-1) + B_{ij}(t) + C_{ij}(t)
\]

\[
\begin{aligned}
C_{ij}(t) &= -\left( \frac{\partial H}{\partial W_{ij}} \right) W_{ij}(t-1) + B(t) \\
H(W) &= \gamma \sum_i \left( \sum_j W_{ij} - s_0 \right)^2 + \gamma' \sum_j \left( \sum_i W_{ij} - s'_0 \right)^2
\end{aligned}
\]

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

![Diagram of synfire chain](image)
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 2nd time after $P_0$, $j$ has now 50% chance of doing so a 3rd time; else it stays at 12% while another cell, $j'$, reaches 12%

- 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 $P_0, P_1, P_2, \ldots$, 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 $i \rightarrow j$ exists)

<table>
<thead>
<tr>
<th>$s_0$</th>
<th>$n_0$</th>
<th>$p$</th>
<th>$n_0 \rightarrow n_1 \rightarrow n_2 \rightarrow n_3 \ldots$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>5</td>
<td>1</td>
<td>(5) $\rightarrow$ 7 $\rightarrow$ 7 $\rightarrow$ 7 $\rightarrow$ 6 $\rightarrow$ 4 $\ldots$</td>
</tr>
<tr>
<td>7.5</td>
<td>4</td>
<td>1</td>
<td>(4) $\rightarrow$ 7 $\rightarrow$ 8 $\rightarrow$ 7 $\ldots$</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>1</td>
<td>(15) $\rightarrow$ 14 $\rightarrow$ 13 $\rightarrow$ 12 $\rightarrow$ 11 $\rightarrow$ 10 $\rightarrow$ 9 $\rightarrow$ 8 $\rightarrow$ 6 $\rightarrow$ 7 $\rightarrow$ 7 $\rightarrow$ 5 $\rightarrow$ 4 $\ldots$</td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>1</td>
<td>(15) $\rightarrow$ 12 $\rightarrow$ 10 $\rightarrow$ 8 $\rightarrow$ 7 $\rightarrow$ 7 $\rightarrow$ 7 $\rightarrow$ 6 $\rightarrow$ 5 $\rightarrow$ 2 $\ldots$</td>
</tr>
<tr>
<td>8</td>
<td>12</td>
<td>1</td>
<td>(12) $\rightarrow$ 11 $\rightarrow$ 10 $\rightarrow$ 9 $\rightarrow$ 8 $\rightarrow$ 8 $\rightarrow$ 8 $\rightarrow$ 8 $\ldots$</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>.5</td>
<td>(10) $\rightarrow$ 14 $\rightarrow$ 13 $\rightarrow$ 13 $\rightarrow$ 13 $\rightarrow$ 11 $\rightarrow$ 5 $\ldots$</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>.8</td>
<td>(10) $\rightarrow$ 9 $\rightarrow$ 8 $\rightarrow$ 9 $\rightarrow$ 8 $\rightarrow$ 8 $\rightarrow$ 8 $\rightarrow$ 4 $\ldots$</td>
</tr>
</tbody>
</table>
3. Neurogenetic systems

b. Growing a synfire chain — \textbf{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 \textit{diversification} mechanism, by proposing multiple candidate-neurons that fire after $P_k$
  - in a second phase, competition \textbf{selects} among the large pool of candidates and rounds up a final set of winners $P_{k+1}$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{synfire_chains.png}
\caption{Snapshots of the landscape of $P_0 \rightarrow j$ weights and evolution of single $P_0 \rightarrow j$ weights.}
\end{figure}
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 \( \tau_{ij} \) and inhibitory neurons
3. Neurogenetic systems

c. Synfire chain composition — 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 & Ajanagadde (1993)
3. Neurogenetic systems

c. Synfire chain composition — Spatiotemporal 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)
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.

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   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:
  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
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