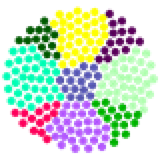


Spatial Self-Organization of Heterogeneous, Modular Architectures

Toward Morphogenetic Engineering

René Doursat

http://doursat.free.fr

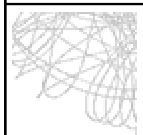
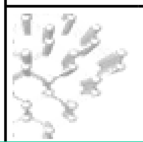
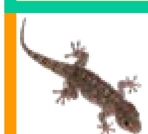
Toward Morphogenetic Engineering

1. Self-organized ***and*** structured systems
2. Toward “evo-devo” engineering
3. A model of programmable morphogenesis
4. Evolutionary meta-design
5. Preview: programmable complex networks

From flocks to shapes

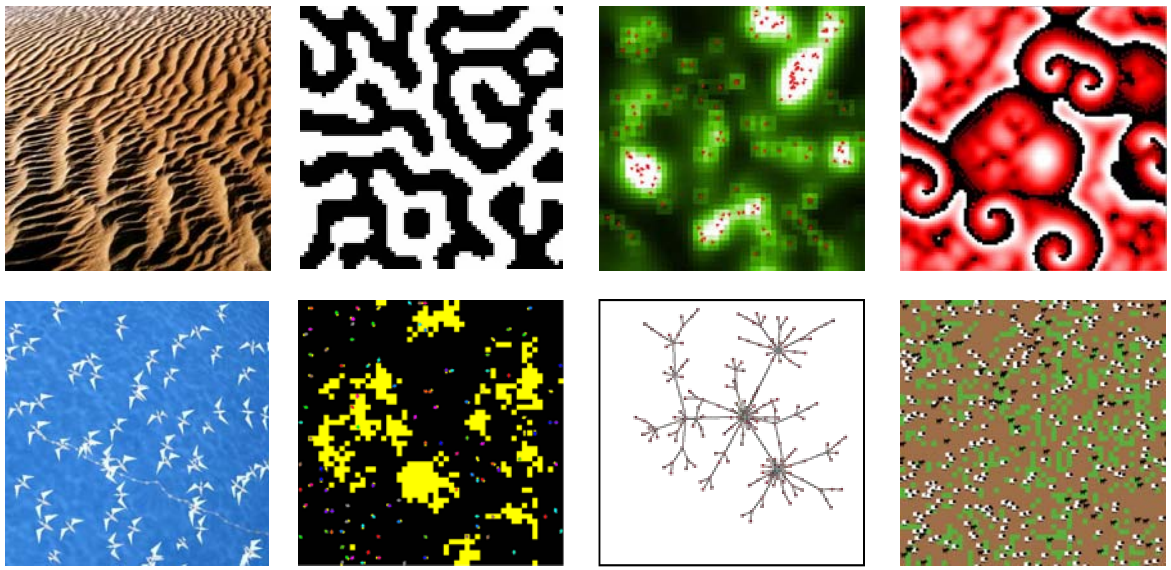
From “statistical” to “morphological” complex systems

➢ A brief taxonomy of systems

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

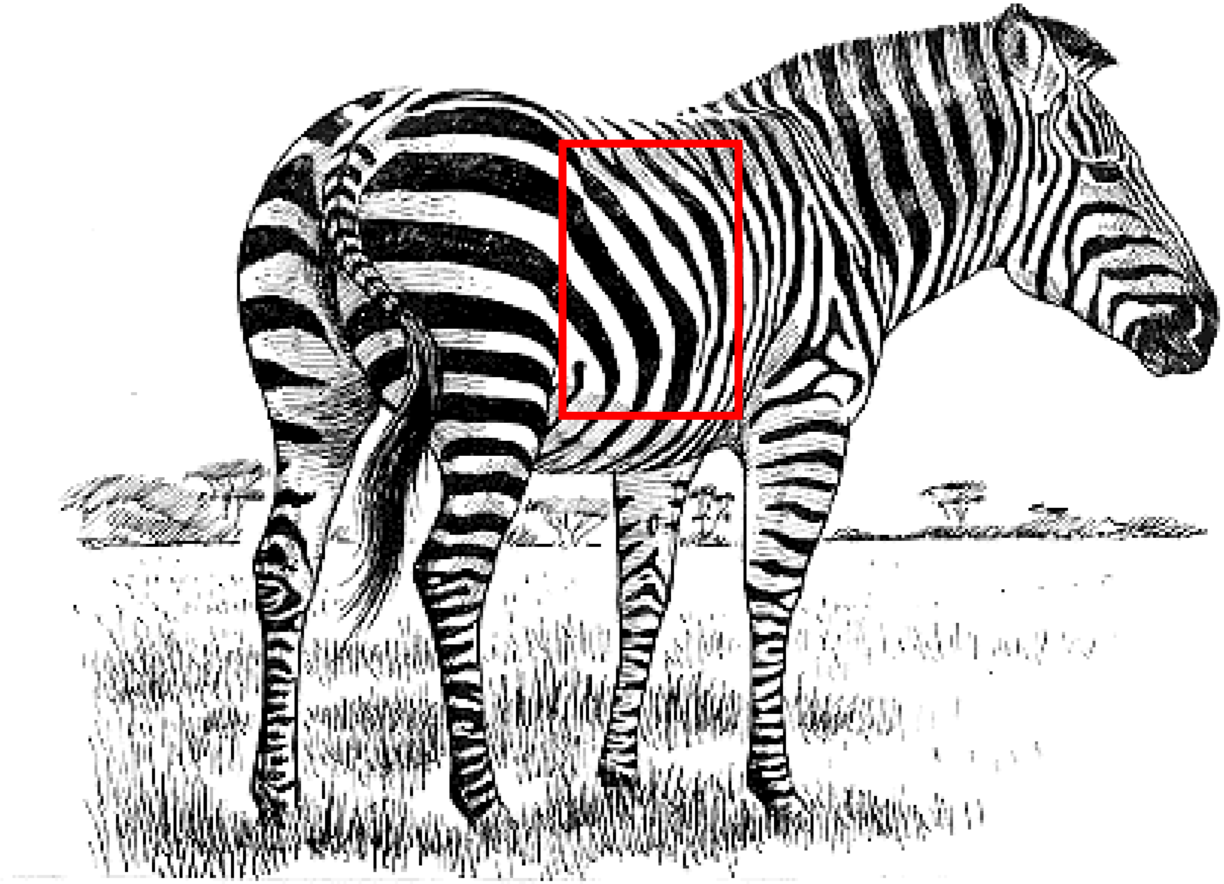
Statistical (self-similar) systems

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



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

Morphological (self-dissimilar) systems



"I have the stripes, but where is the zebra?"

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

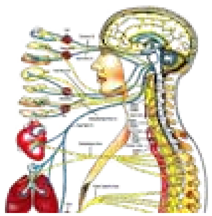
Morphological (self-dissimilar) systems

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

plants

vertebrates

arthropods



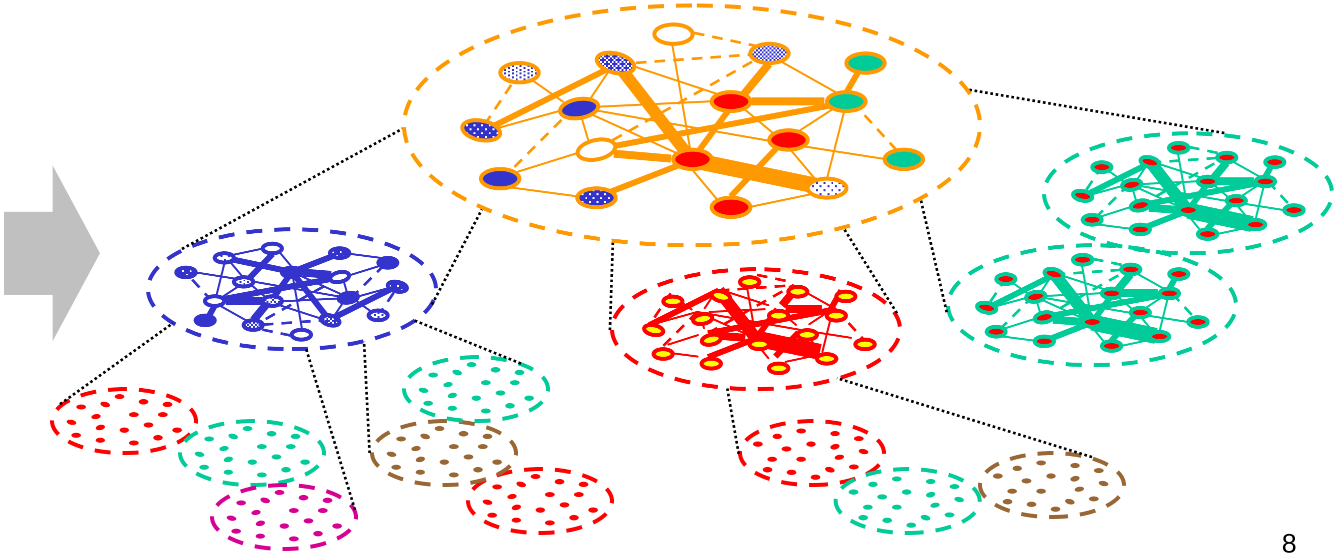
humans

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

- Biological organisms are self-organized ***and*** structured
  - ✓ because agent rules are more “sophisticated”: they can depend on the agent’s ***type*** and/or ***position*** in the system
  - ✓ the outcome (development) is truly complex but, paradoxically, can also be more ***controllable*** and ***programmable***

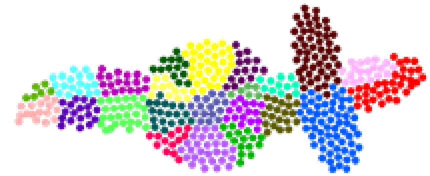
Beyond statistics: heterogeneity, modularity, reproducibility

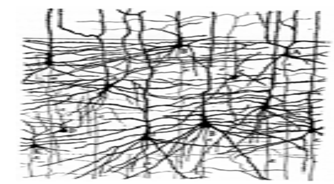
- Complex systems can be much more than a "soup"
  - ✓ "complex" doesn't necessarily imply "homogeneous"...
    → ***heterogeneous*** *agents and diverse patterns, via positions*
  - ✓ "complex" doesn't necessarily imply "flat" (or "scale-free")...
    → ***modular****, hierarchical, detailed architecture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



The need for morphogenetic abilities

- Model natural systems → transfer to artificial systems
  - ✓ need for morphogenetic abilities in biological modeling
    - organism development
    - brain development

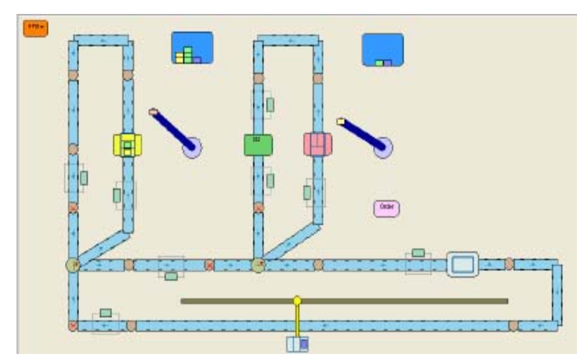




  - ✓ need for morphogenetic abilities in computer science & engineering
    - self-forming robot swarm
    - self-architecturing software
    - self-connecting micro-components

http://www.symbrion.eu

  - ✓ need for morphogenetic abilities in techno-social eNetworked systems
    - self-reconfiguring manufacturing plant
    - self-stabilizing energy grid
    - self-deploying emergency taskforce



MAST agents, Rockwell Automation Research Center
{pvrba, vmarik}@ra.rockwell.com

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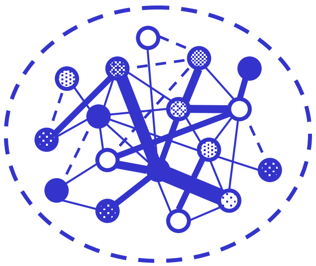
Complex (spatial) computing systems

➢ ABM meets MAS: two different perspectives

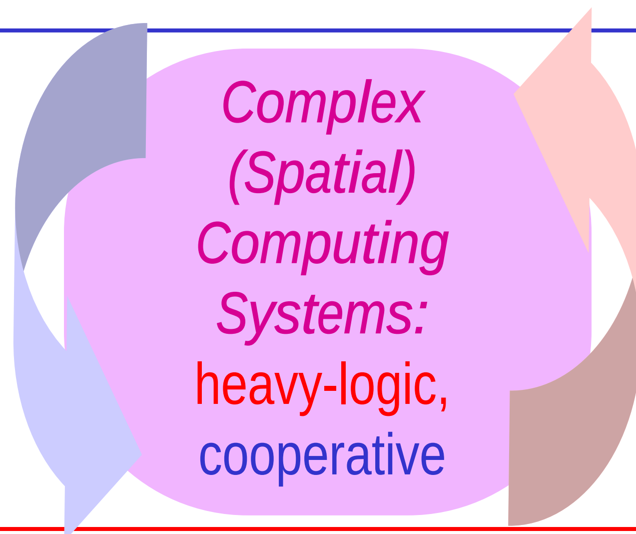


CS Science: understand "natural" CS

→ Agent-Based Modeling (ABM): light logic, cooperative

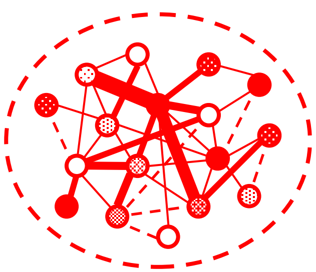
Export

- decentralization
- autonomy, homeostasis
- learning, evolution



Import

- observe, model
- control, harness
- design, use



CS Engineering: design new "artificial" CS

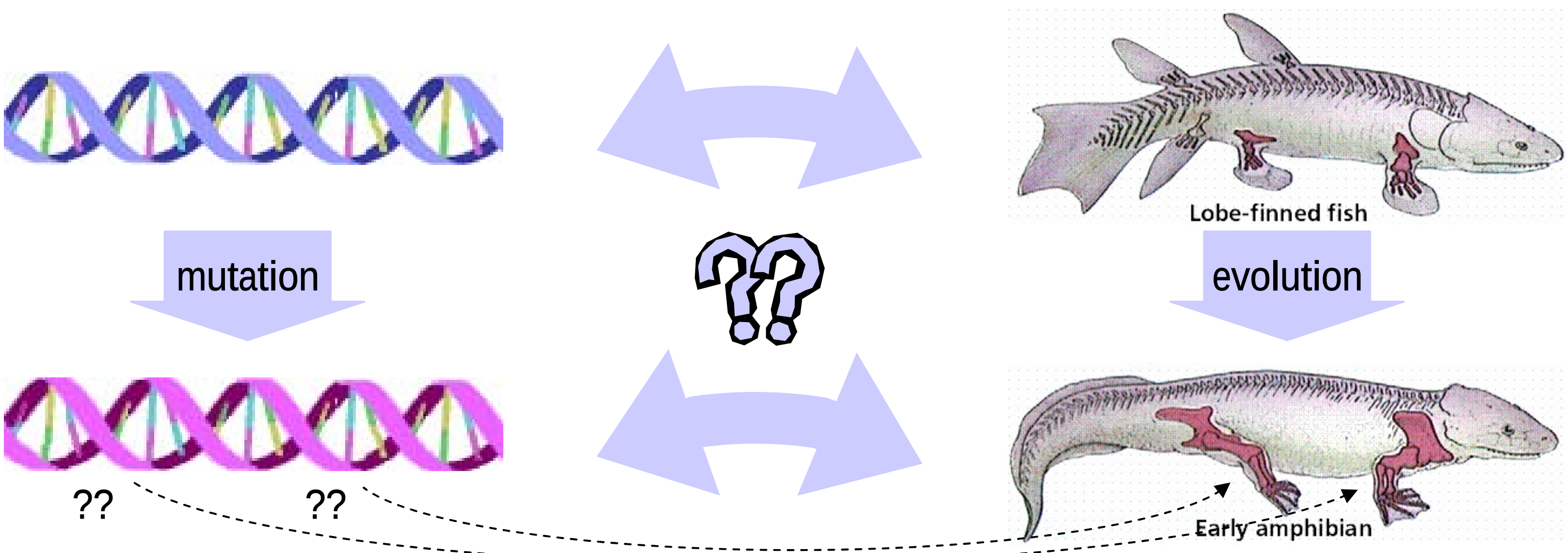
→ Multi-Agent Systems (MAS): heavy logic, selfish

2. Toward "evo-devo" engineering

➢ Development: the missing link of the Modern Synthesis...

"When Charles Darwin proposed his theory of evolution by variation and selection ... he could not explain variation. . . . To understand novelty in evolution, we need to understand organisms down to their individual building blocks ... for these are what undergo change."

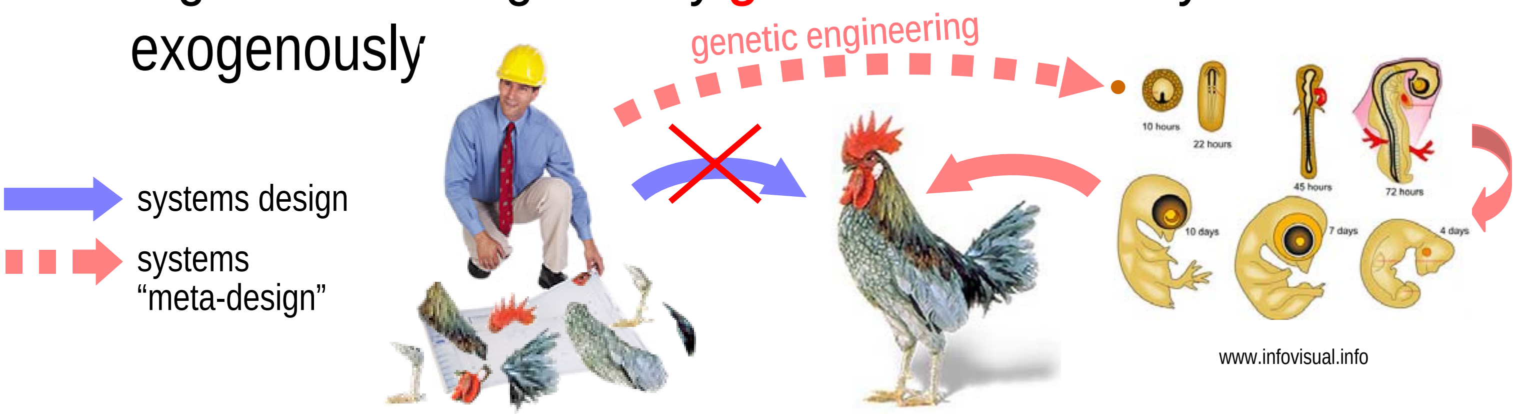
—Marc W. Kirschner and John C. Gerhart (2005)
***The Plausibility of Life*, p. ix**



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

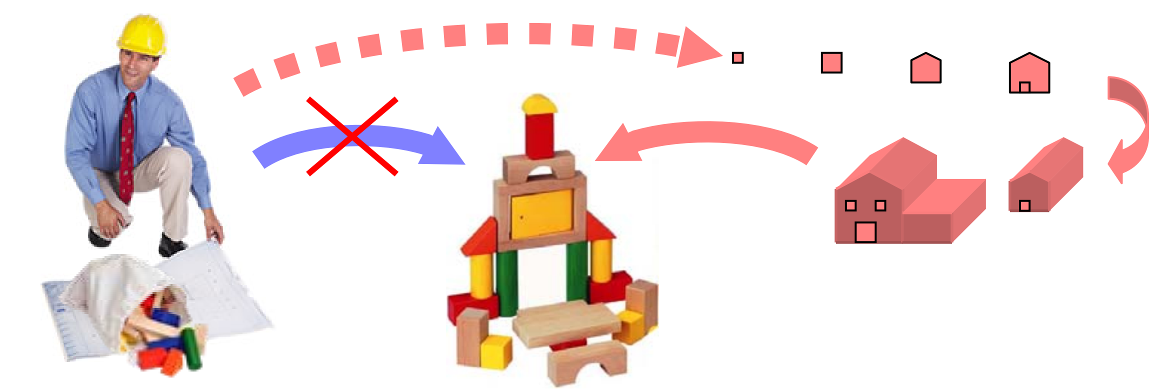
2. Toward "evo-devo" engineering

- ... and of evolutionary computing: Toward *"meta-design"*
  - ✓ organisms endogenously *grow* but artificial systems *are built* exogenously



  - ✓ future engineers should "step back" from their creation and only set *generic* conditions for systems to self-assemble and evolve

don't build the system (phenotype), <u>program the agents</u> (developmental genotype)—see, e.g., "artificial embryogeny"



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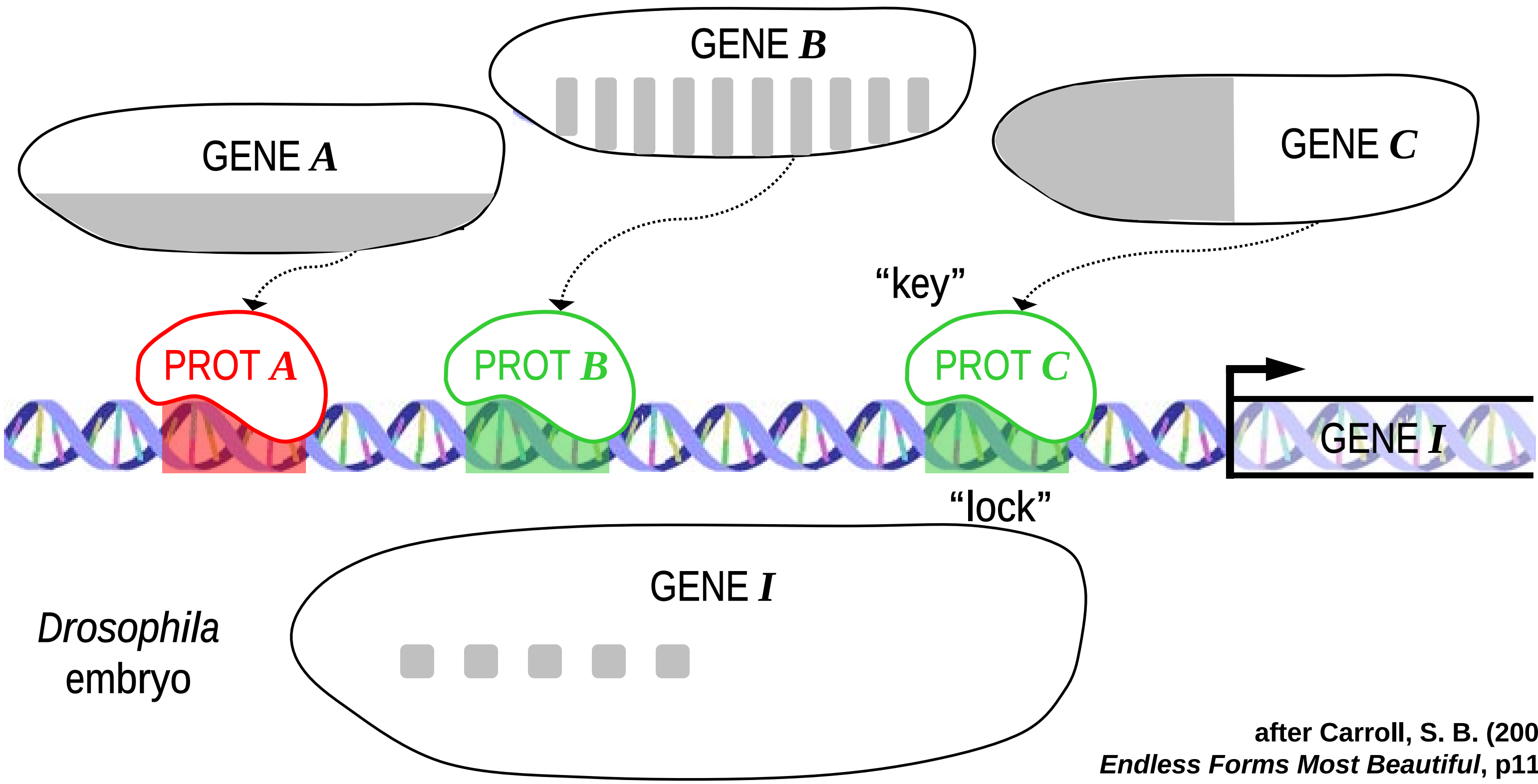
3. Programmable morphogenesis

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

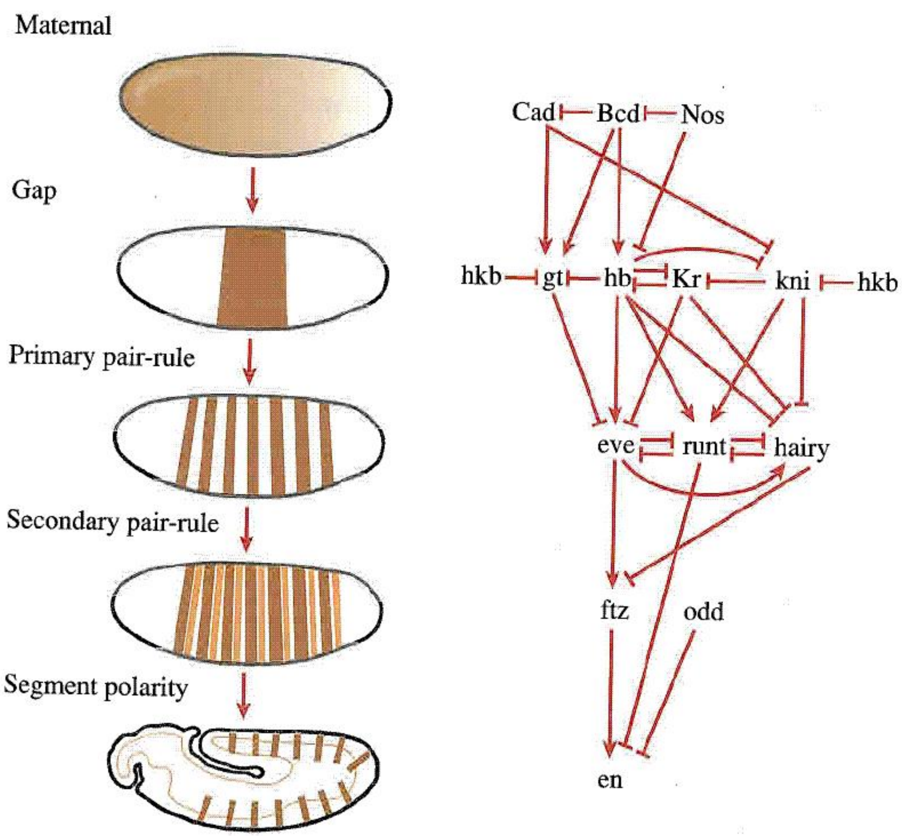


after Carroll, S. B. (2005)
***Endless Forms Most Beautiful*, p117**

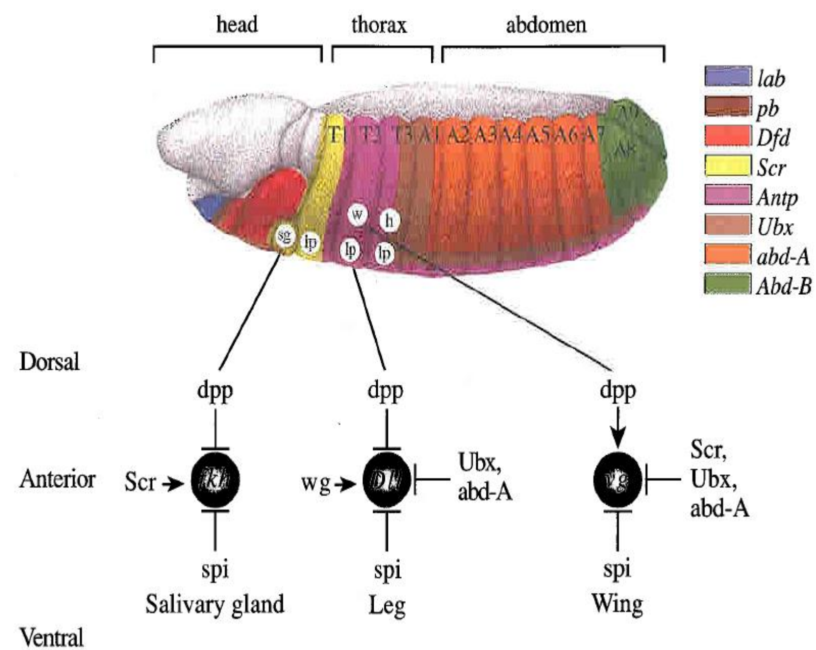
3. Programmable morphogenesis

➢ Segmentation & identity domains in *Drosophila*

- ✓ periodic A/P band patterns are controlled by a 5-tier gene regulatory hierarchy



- ✓ intersection with other axes creates organ primordia and imaginal discs (identity domains of future legs, wings, antennae, etc.)

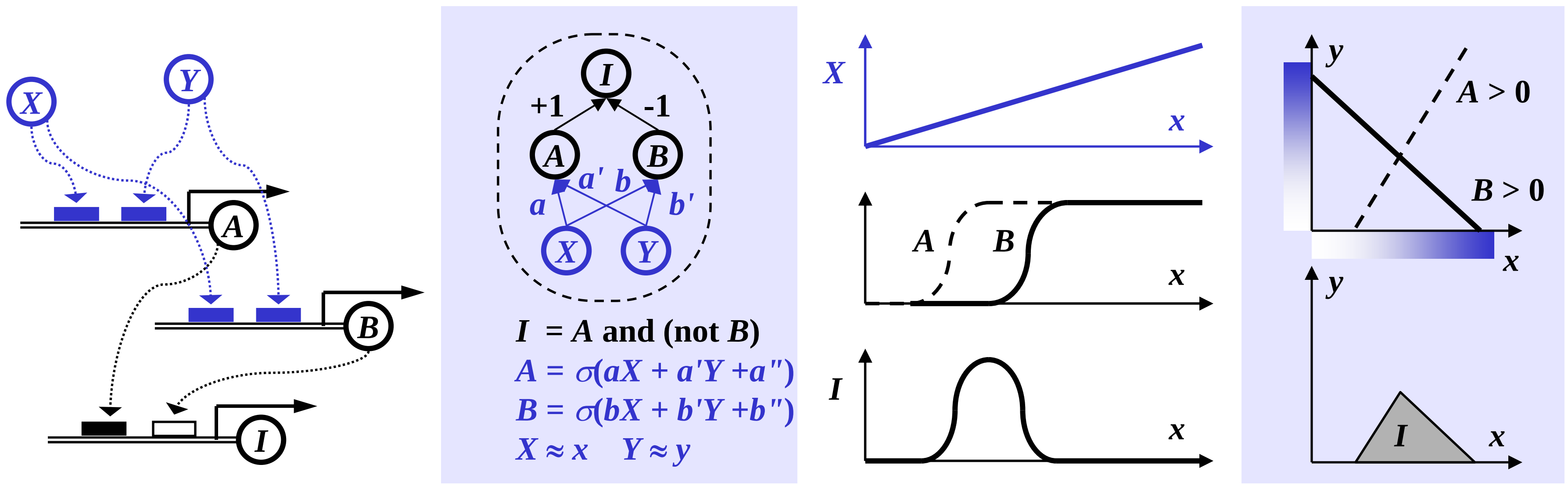


from Carroll, S. B., et al. (2001) *From DNA to Diversity*, p63

3. Programmable morphogenesis

➢ Three-tier GRN model: integrating positional gradients

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

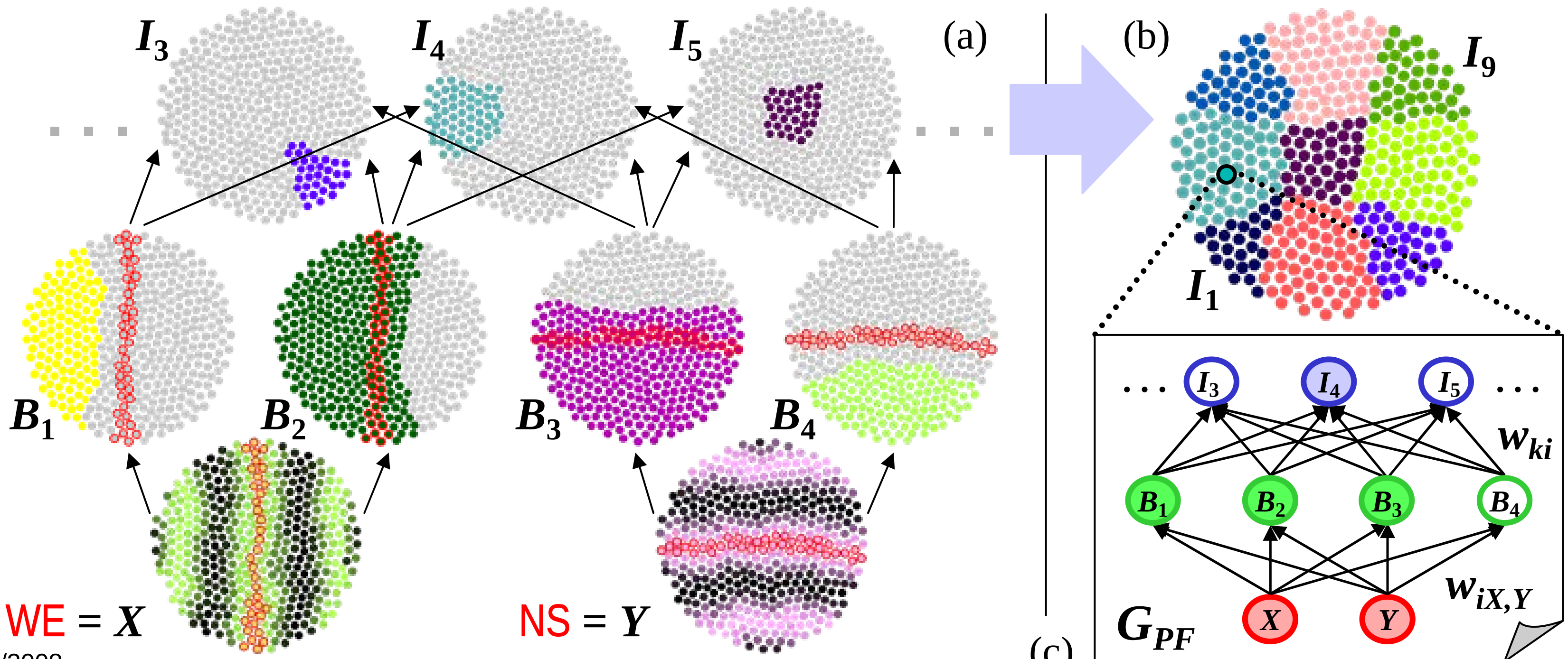


✓ X and Y diffuse along two axes and form concentration gradients

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

3. Programmable morphogenesis

- Programmed patterning (PF-II): the hidden embryo map
  - a) same swarm in different colormaps to visualize the agents' internal patterning variables X, Y, B_i and I_k (virtual *in situ hybridization)*
  - b) consolidated view of all identity regions I_k for $k = 1\ldots9$
  - c) gene regulatory network used by each agent to calculate its expression levels, here: $B_1 = \sigma(1/3 - X)$, $B_3 = \sigma(2/3 - Y)$, $I_4 = B_1B_3(1 - B_4)$, etc.



3. Programmable morphogenesis

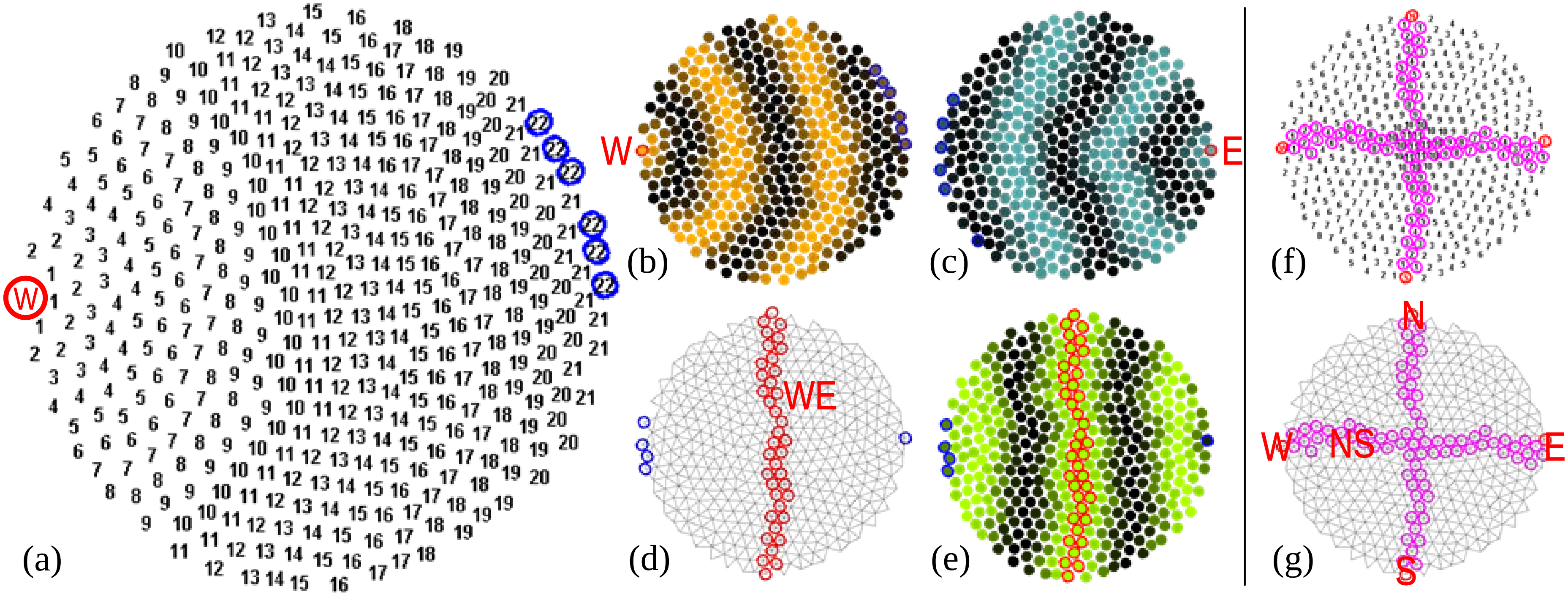
➢ Propagation of positional information (PF-I)

a) & b) circular gradient of counter values originating from source agent *W*

c) opposite gradient coming from antipode agent *E*

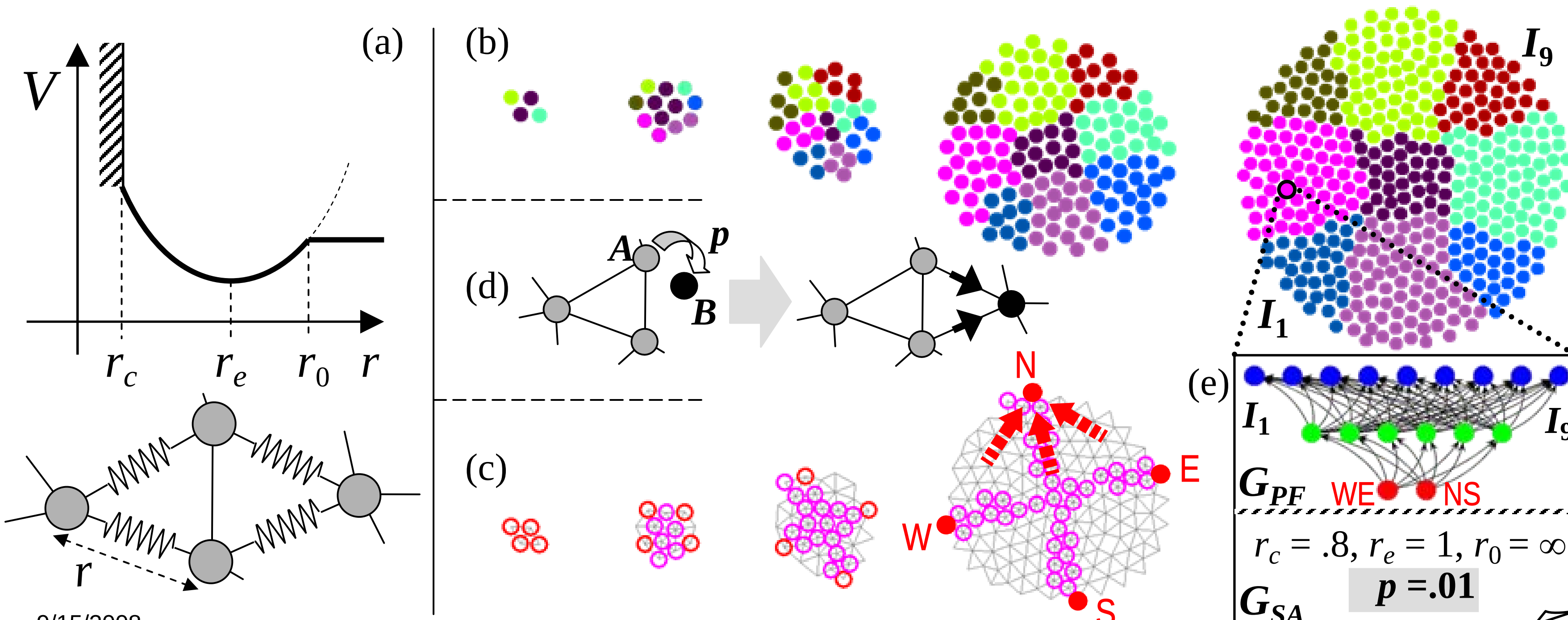
d) & e) planar gradient from *WE* agents (whose *W* and *E* counters equate ±1)

f) & g) complete coordinate compass, with *NS* midline.



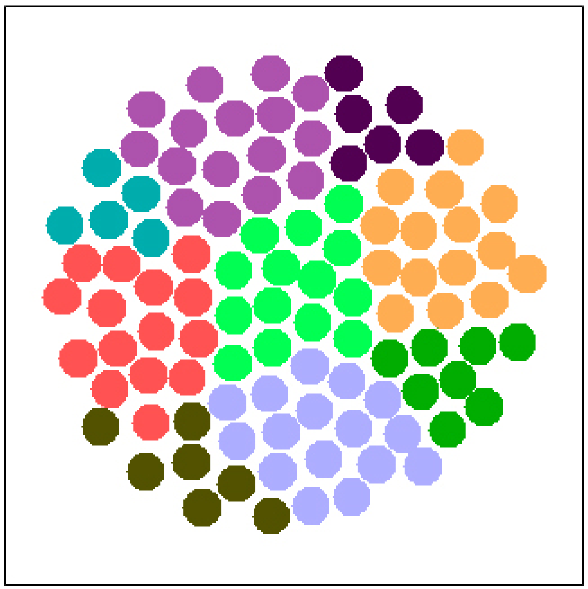
3. Programmable morphogenesis

- **Simultaneous growth *and* patterning (SA + PF)**
  - a) elastic adhesion forces; b) swarm growing from 4 to 400 agents by division
  - c) swarm mesh, gradient midlines; pattern is continually maintained by source migration, e.g., *N* moves away from *S* and toward *WE*
  - d) agent *B* created by *A*'s division quickly submits to SA forces and PF traffic
  - e) combined genetic programs inside each agent

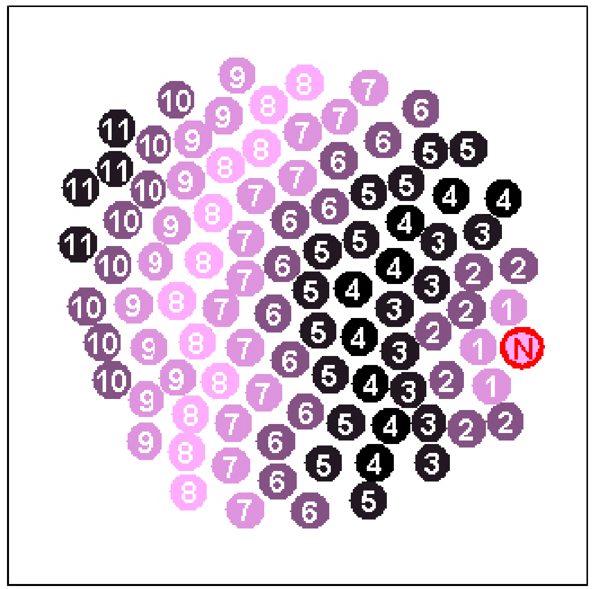


3. Programmable morphogenesis

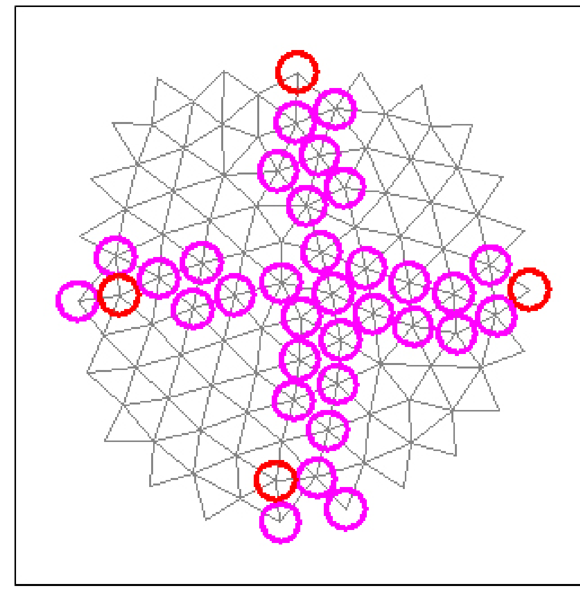
- Simultaneous growth *and* patterning (SA + PF)
  - ✓ example of simulation: 3 movies showing the same development highlighting 3 different planes (in different embryos)



highlighting
gene patterning (PF-II)



highlighting
gradient formation (PF-I)



highlighting
lattice (SA) with gradient lines

3. Programmable morphogenesis

➢ Morphological refinement by iterative growth

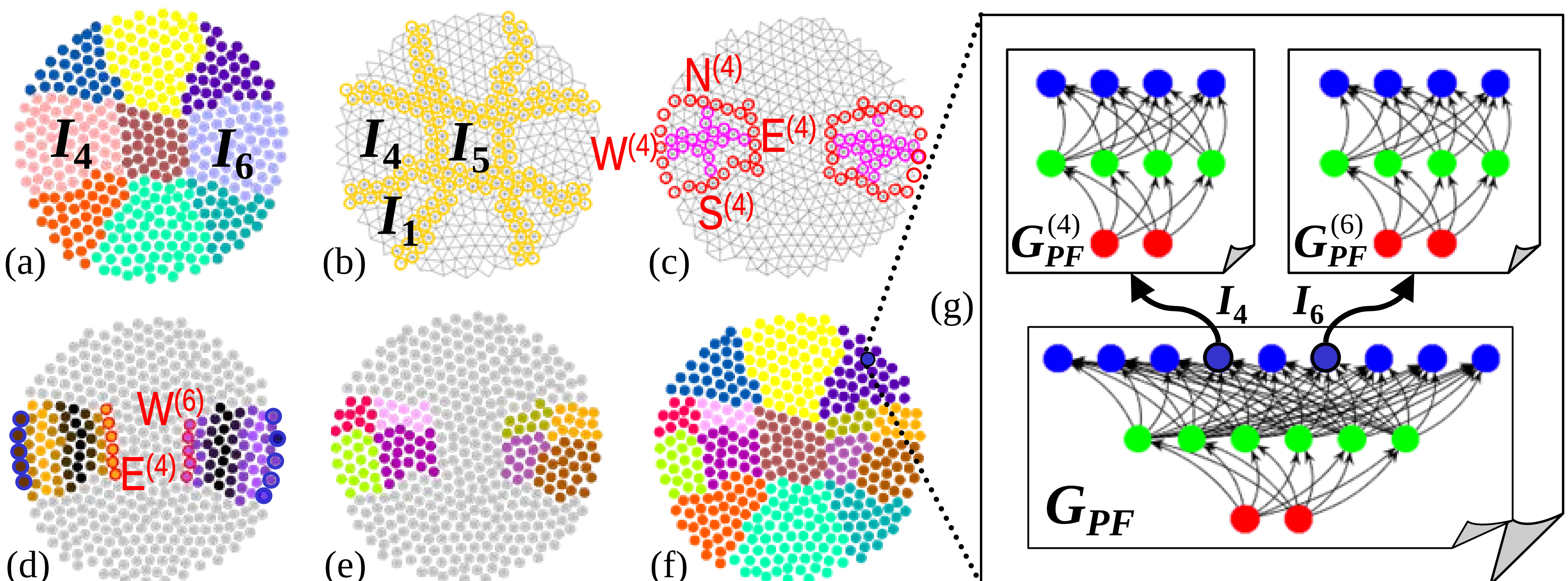
- ✓ details are not created in one shot, but gradually added. . .

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

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

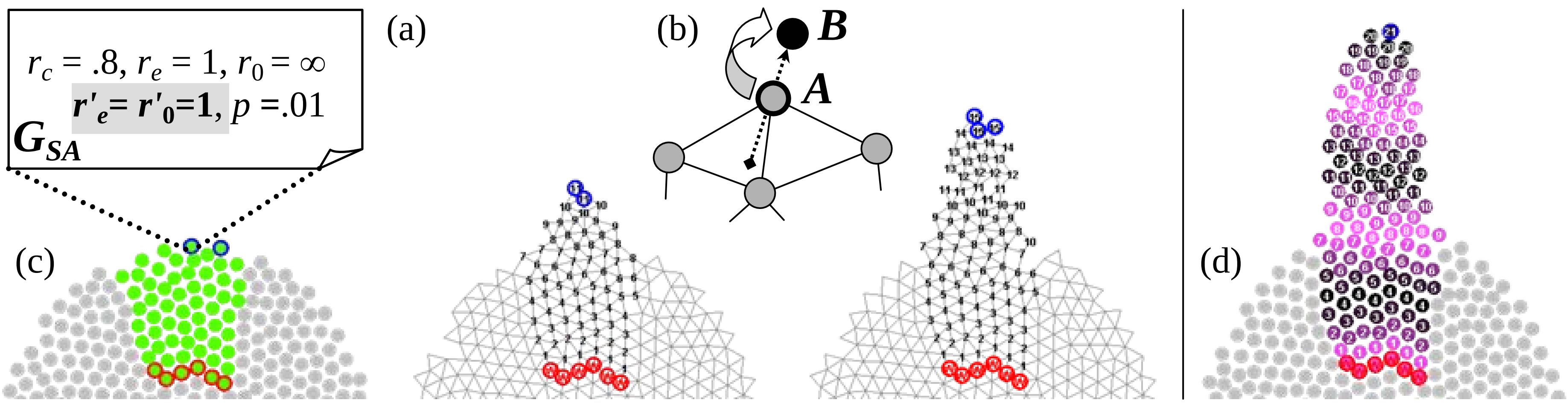
3. Programmable morphogenesis

- Modular, recursive patterning (PF[k])...
  - b) border agents highlighted in yellow
  - c) border agents become new gradient sources inside certain identity regions
  - d) missing border sources arise from the ends (blue circles) of other gradients
  - e) & f) subpatterning of the swarm in I_4 and I_6
  - g) corresponding hierarchical gene regulation network



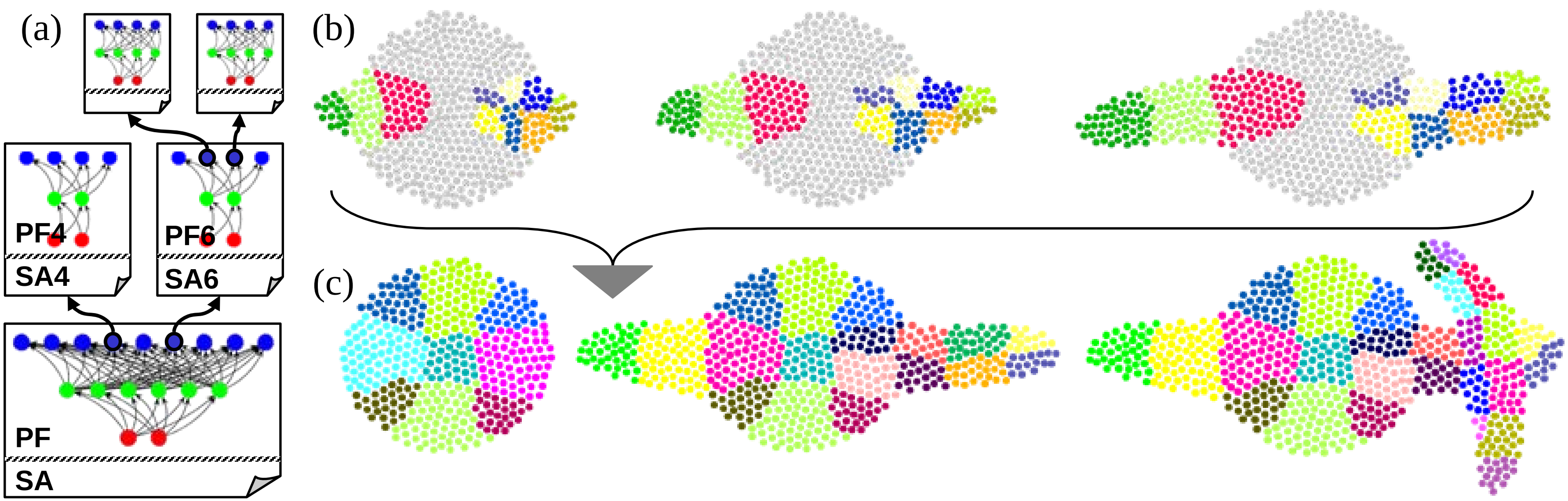
3. Programmable morphogenesis

- ... in parallel with modular, anisotropic growth (SA[k])
  - a) genetic SA parameters are augmented with repelling V values r'_e and r'_0 used between the growing region (green) and the rest of the swarm (gray)
  - b) daughter agents are positioned away from the neighbors' center of mass
  - c) offshoot growth proceeds from an "apical meristem" made of gradient ends (blue circles)
  - d) the gradient underlying this growth



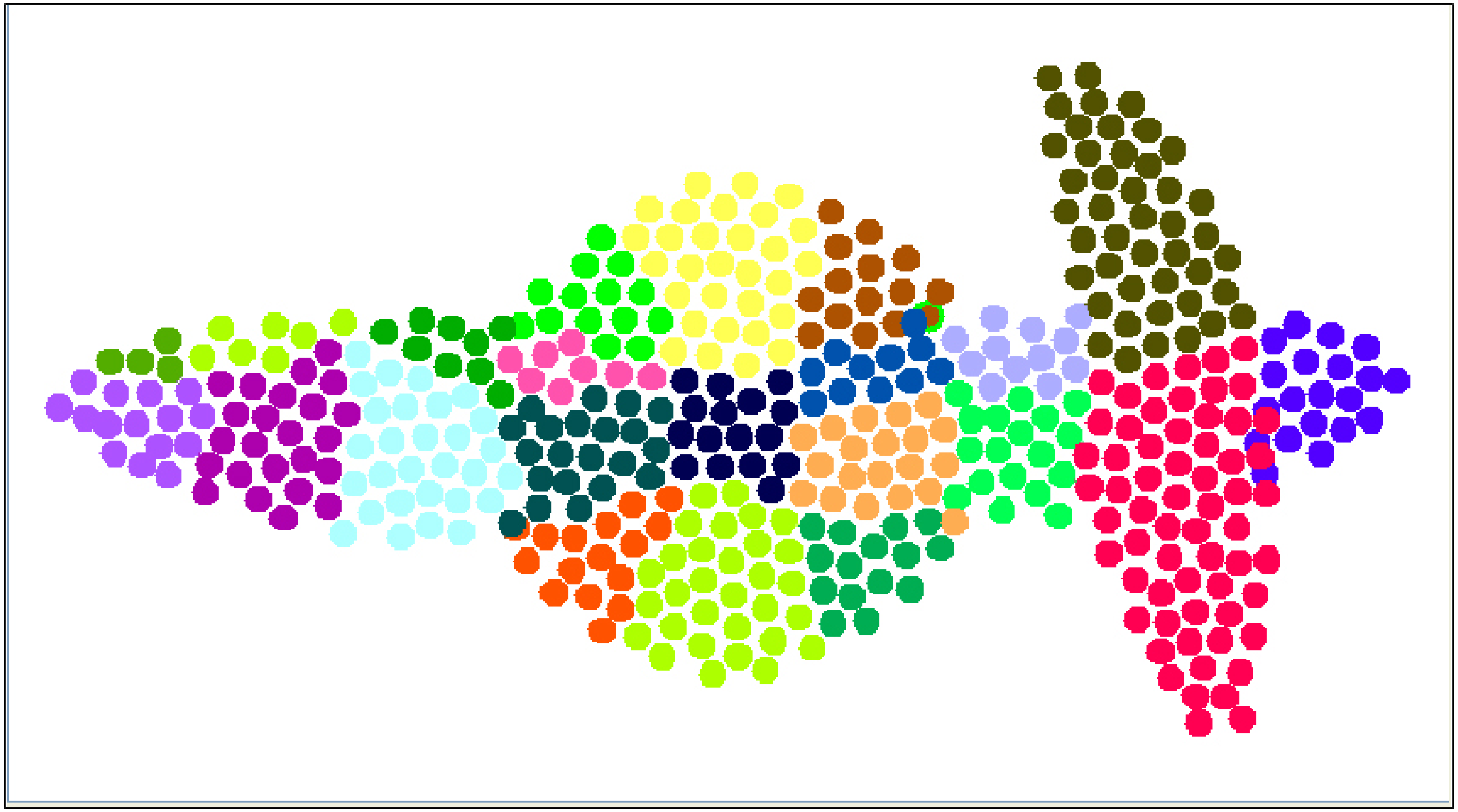
3. Programmable morphogenesis

- Modular growth *and* patterning (SA[k] + PF[k]): 3 levels
  - a) example of a three-level modular genotype giving rise to the artificial organism on the right
  - b) three iterations detailing the simultaneous limb-like growth process and patterning of these limbs during execution of level 2 (modules 4 and 6)
  - c) main stages of the complex morphogenesis, showing full patterns after execution of levels 1, 2 and 3.



3. Programmable morphogenesis

- Modular growth *and* patterning (SA[k] + PF[k]): 3 levels



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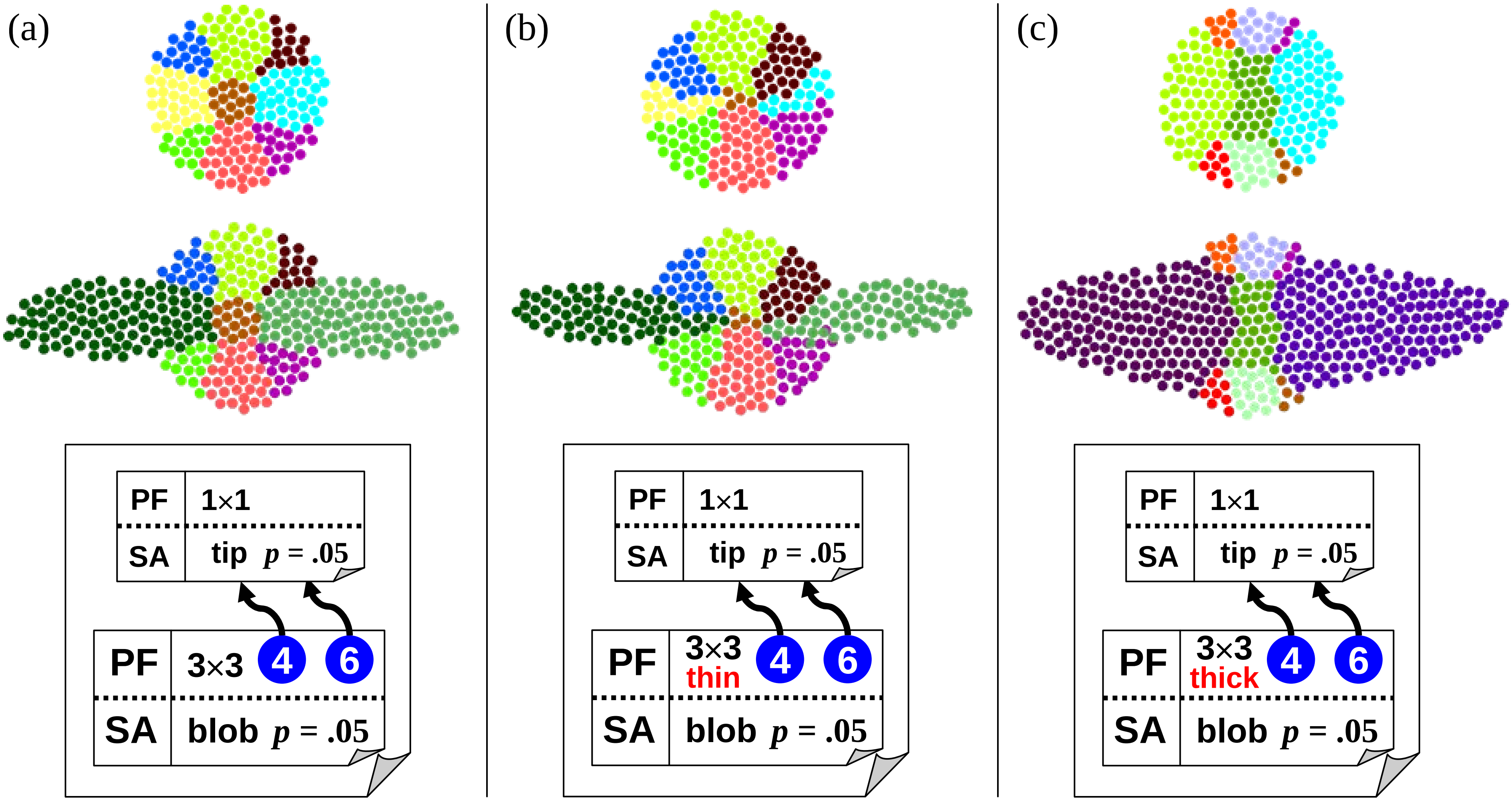
4. Evolutionary meta-design

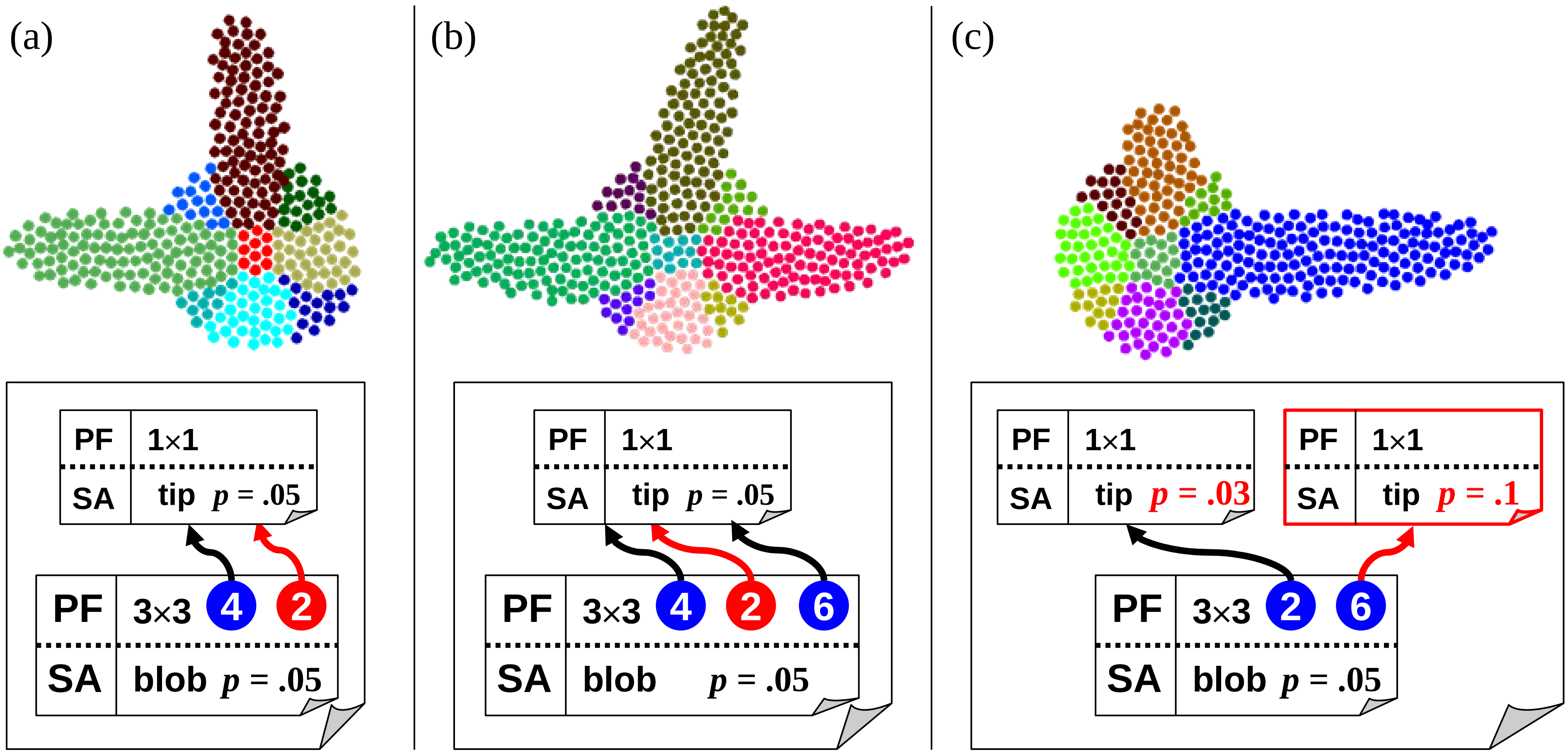
- Modular growth and patterning (SA[k] + PF[k]): 2 levels
  - a) wild type; b) "thin" mutation of the base body plan; c) "thick" mutation



4. Evolutionary meta-design

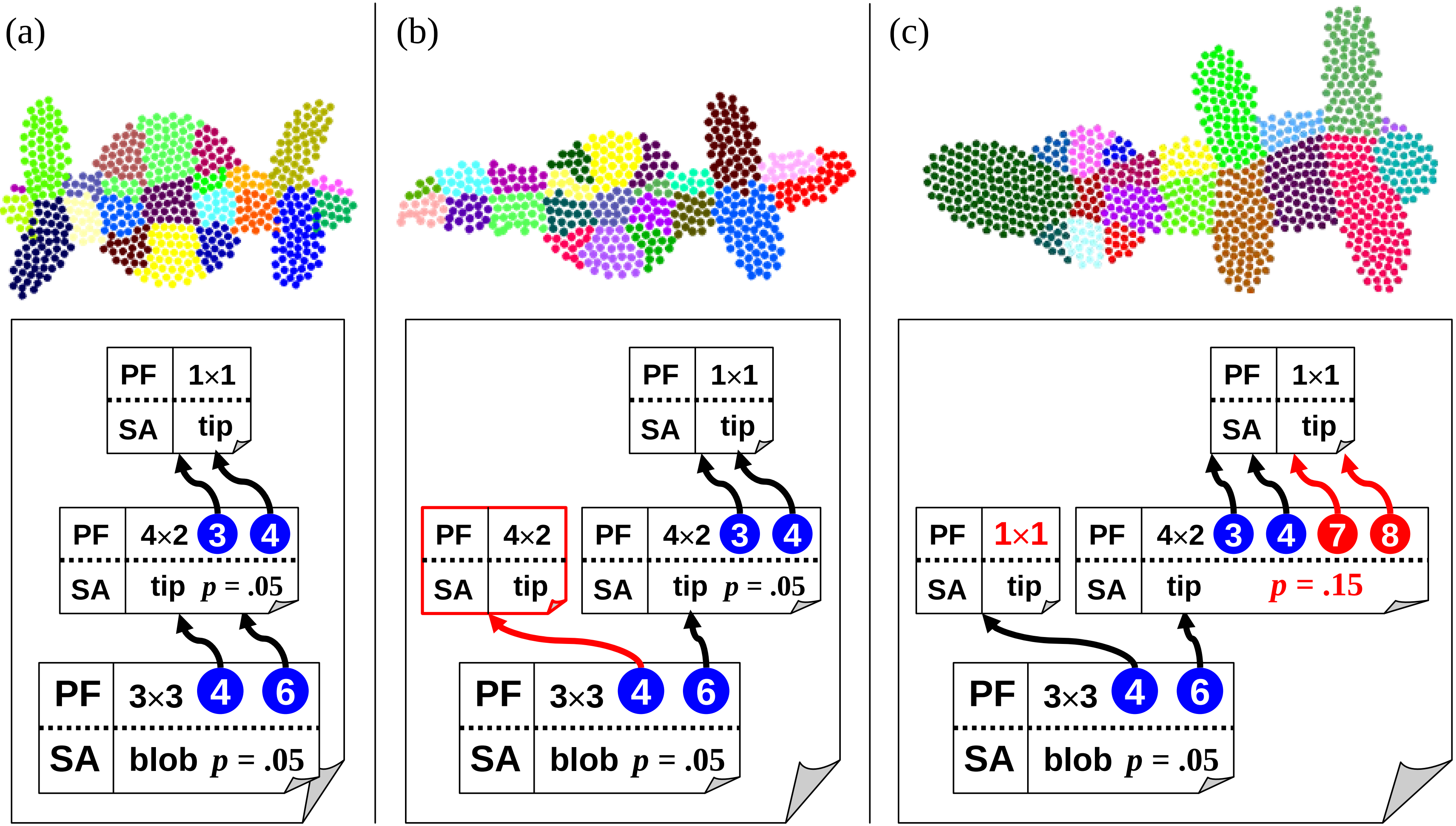
- Modular growth and patterning (SA[k] + PF[k]): 2 levels

  a) antennapedia; b) homology by *duplication*; c) *divergence* of the homology



4. Evolutionary meta-design

➢ Modular growth and patterning (SA[k] + PF[k]): 3 levels



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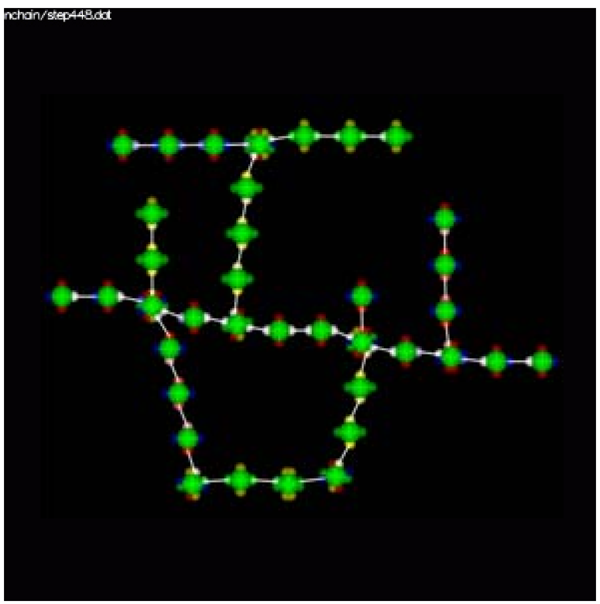
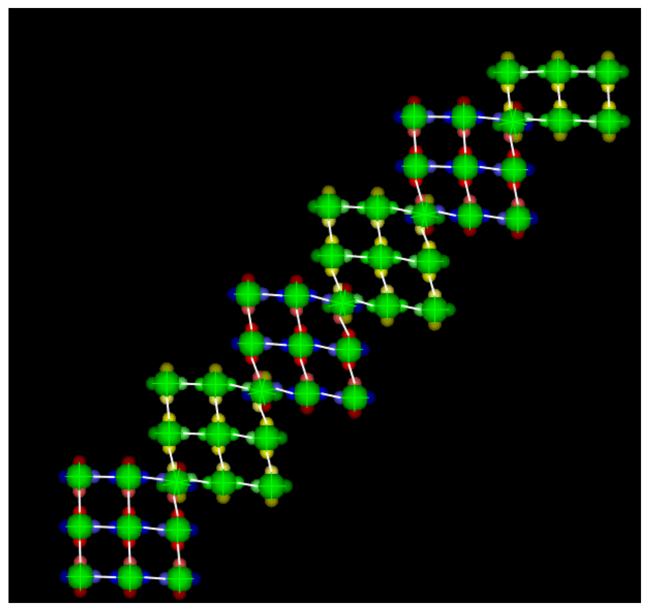
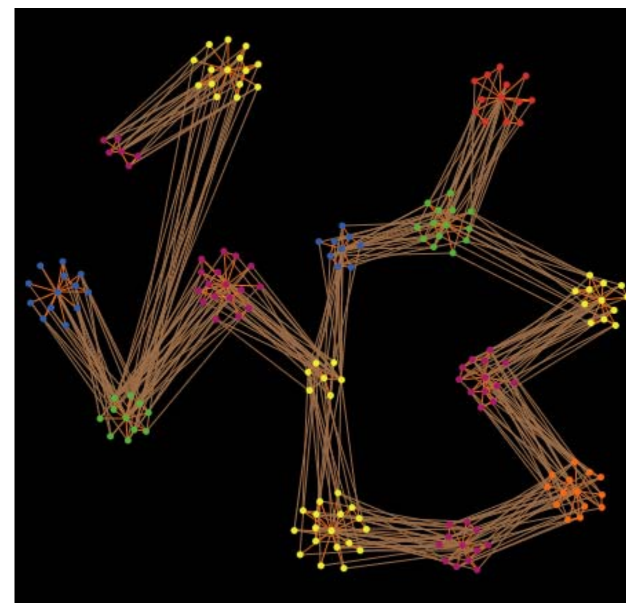
From scale-free to structured networks



single-node
composite branching



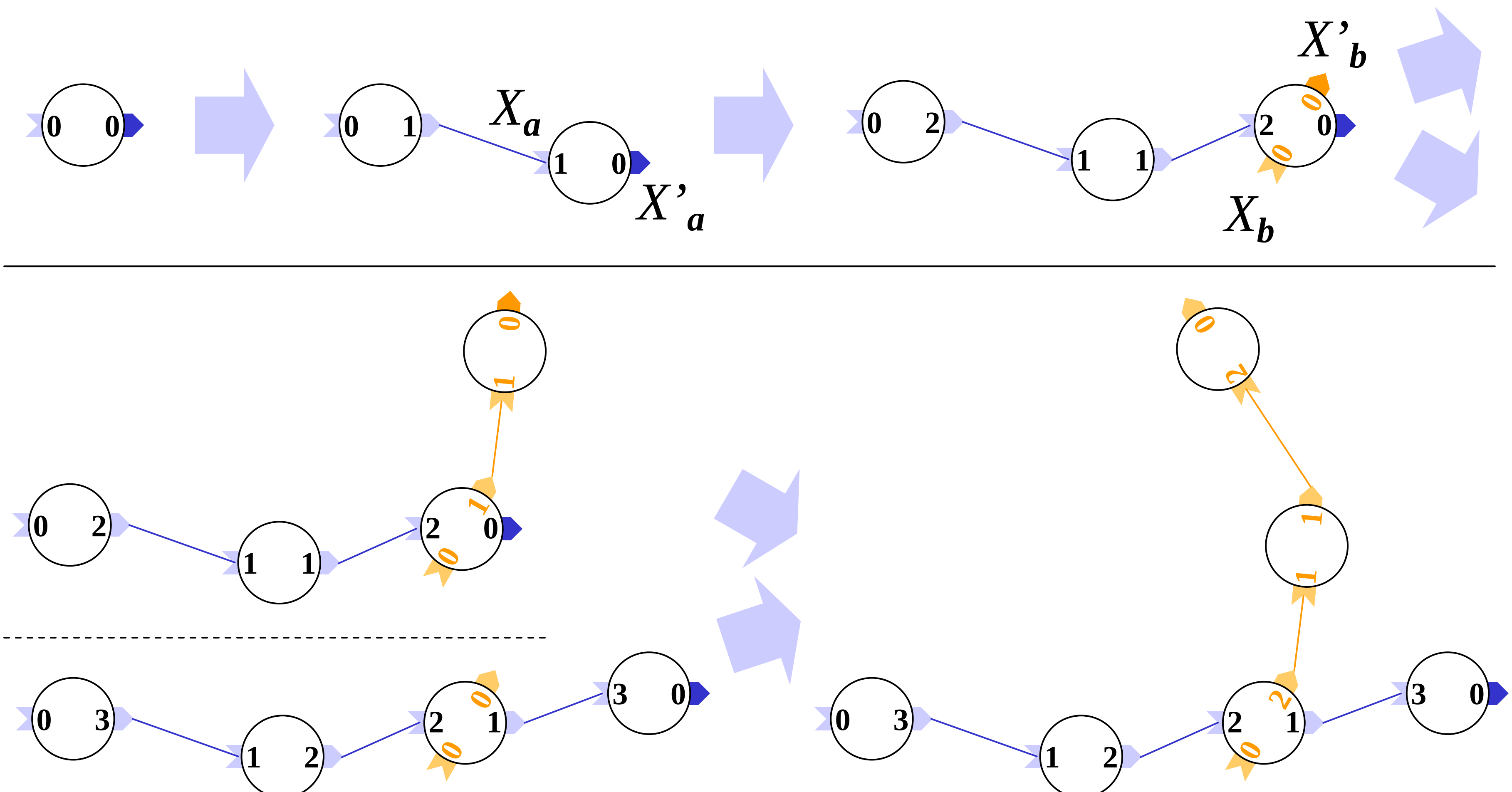
iterative lattice pile-up



clustered
composite branching

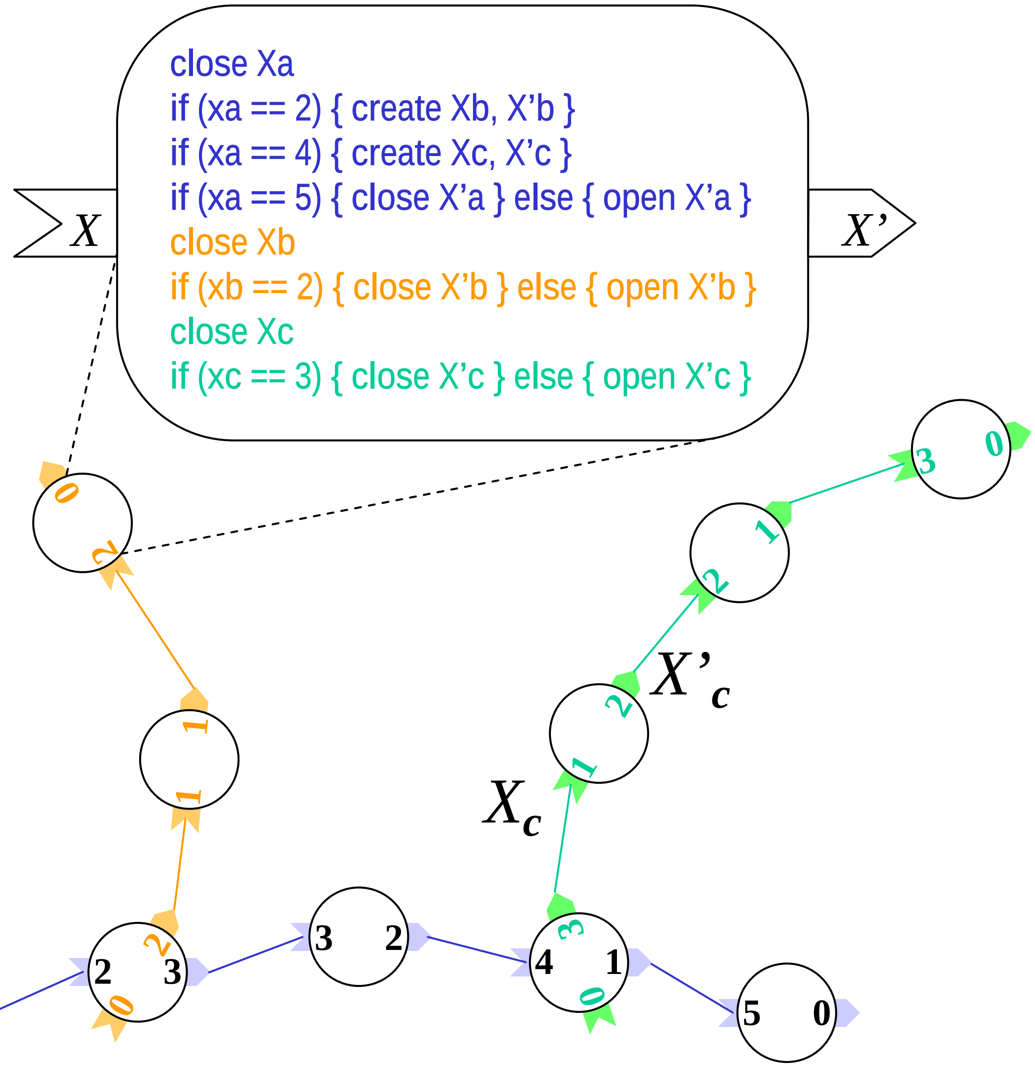
5. Programmable complex networks

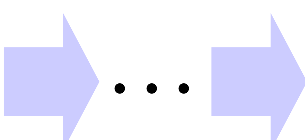
- From preferential to programmed attachment
  - ✓ modular structures by local counters and port logic



5. Programmable complex networks

- From preferential to programmed attachment
  - ✓ the node routines are the *“genotype”* of the network





www.ITRevolutions.org, Venice, December 2008

http://www.iscpif.fr/ITR2008

ICST

IT REVOLUTIONS 2008

17th -19th December, 2008, Venice, Italy

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CALL FOR PARTICIPATION

"Approaching Complexity" Theme

SCOPE

Conference Theme: Mitigating Paradox at the eSociety Tipping Point

The Institute for Computer Sciences, Social-Informatics and Telecommunications (ICST) IT Revolutions 2008 conference invites scholars, researchers, government officials, and industry leaders to participate by submitting position papers expressing their vision. Papers should address strategic directions in approaching complexity by outlining the major issues and identifying the gaps between the traditional and new ways, thus ensuring a smooth transition toward an information and communications technology (ICT)-driven future.

Today's technology is getting ahead of society: the old ways, although still dominant, are becoming more and more dysfunctional. We are experiencing an "Age of Paradox" as the new ways disrupt how we used to do things and the traditional ways we used to view the world. Just as the major inventions that shaped past Century were made by 1920, it is expected that the major innovations that will shape the 21st Century are going to be made by 2020.

Morphogenetic Engineering Workshop, Paris 2009

http://www.iscpif.fr/MEW2009

Exporing various engineering approaches to the artificial design and implementation of autonomous systems capable of developing complex, heterogeneous morphologies

Thank you