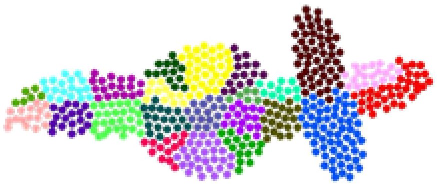
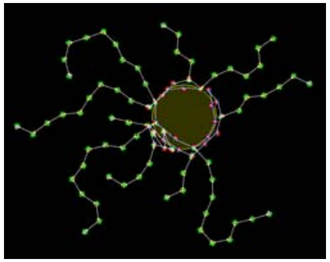


Embryomorphic engineering:



How elaborate, modular architectures can be self-organized, too

René Doursat

http://www.iscpif.fr/~doursat

ISC PARIS ÎLE DE FRANCE INSTITUT DES SYSTEMES COMPLEXES

Systems that are self-organized and architectured

free self-organization

the scientific challenge of complex systems: how can they integrate a true ***architecture?***

Peugeot Picasso

(evolutionary) design

the engineering challenge of complicated systems: how can they integrate ***self-organization?***

make components evolve

Peugeot Picasso

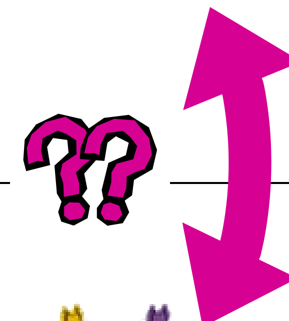
decompose the system

self-organized architecture / architectured self-organization

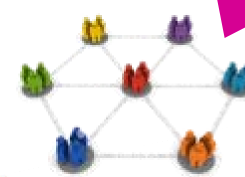
Toward programmable self-organization

➢ Self-organized (complex) systems

- ✓ a myriad of self-positioning, self-assembling agents
- ✓ collective order is not imposed from outside (only influenced)
- ✓ comes from purely *local* information & interaction around each agent
- ✓ no agent possesses the global map or goal of the system
- ✓ but every agent may contain all the *rules* that contribute to it



➢ Structured systems



- ✓ true *architecture*: non-trivial, complicated morphology
  - *hierarchical*, multi-scale: regions, parts, details, agents
  - *modular*: reuse, quasi-repetition
  - *heterogeneous*: differentiation & divergence in the repetition

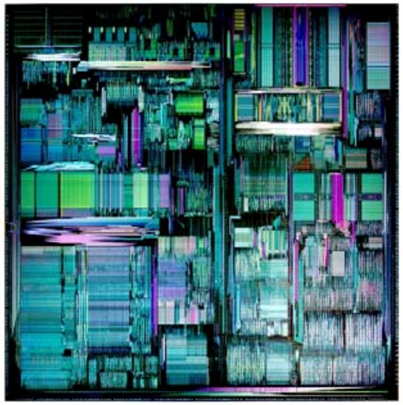
- ✓ *random* at the microscopic level, *but reproducible* (quasi deterministic) at the mesoscopic and macroscopic levels

Facilitating evolutionary innovation by development

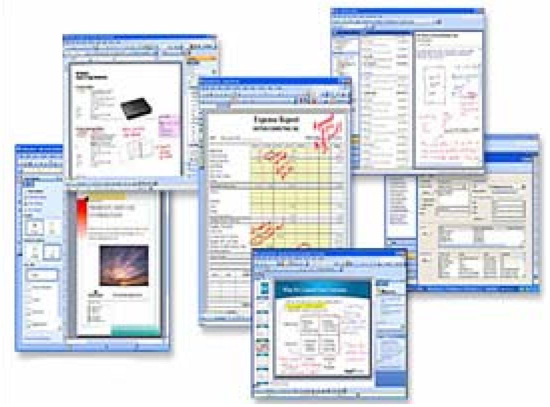
1. Toward self-organized *and* architectured systems
2. Biological development as a two-side challenge
   Heterogeneous motion vs. moving patterns
3. Embryomorphic engineering
   Morphogenesis as a multi-agent self-assembly process
4. Evo-devo engineering
   Evolutionary innovation by development
5. Extension to self-knitting network topologies

De facto complexity of engineering (ICT) systems

- Ineluctable breakup into myriads of modules/components,
  Desirable

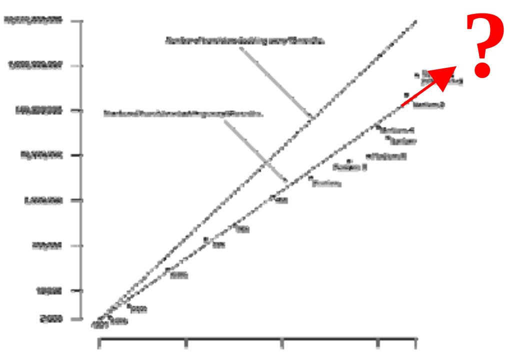


in hardware,

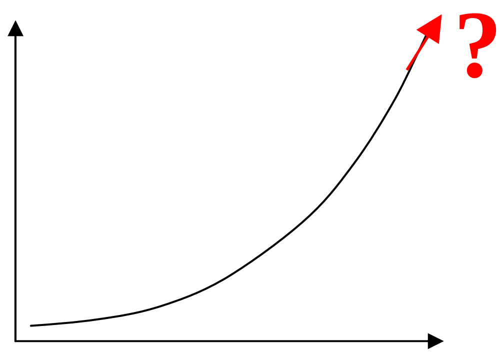


software,

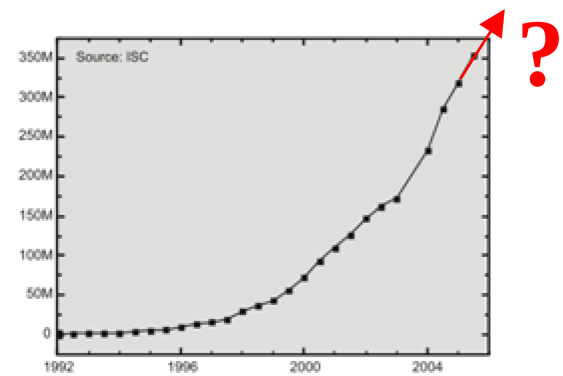
or networks, ...



number of transistors/year



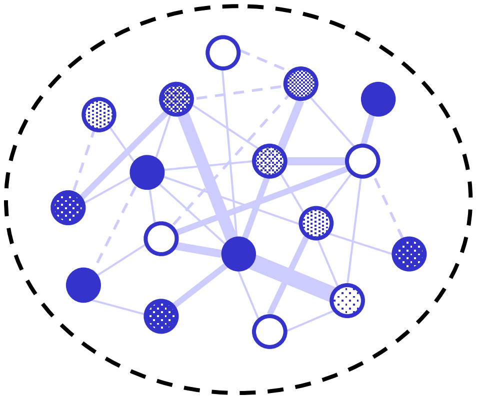
number of O/S lines of code/year



number of network hosts/year

Embracing complexity in design & design in complexity

➢ We are faced with complex systems in many domains

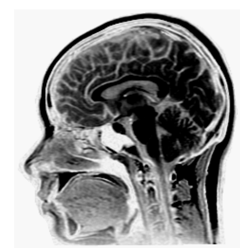


- large number of elementary **agents** interacting **locally**
- simple individual behaviors creating a complex **emergent** collective behavior
- *decentralized dynamics: no master blueprint or grand architect*

✓ physical, biological, technical, social systems (natural or artificial)

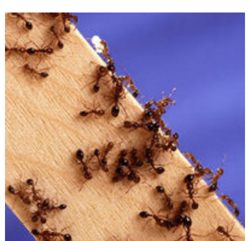
pattern formation
○ = matter

biological development
○ = cell



the brain & cognition
○ = neuron

insect colonies
○ = ant



Internet & Web
○ = host/page

social networks
○ = person

INSTITUT DES SYSTEMES COMPLEXES

Paris Ile-de-France

Complex systems: a vast archipelago

➢ Precursor and neighboring disciplines

complexity: measuring the length to describe, time to build, or resources to run, a system
- information theory (Shannon; entropy)
- computational complexity (P, NP)
- Turing machines & cellular automata

adaptation: change in typical functional regime of a system
- evolutionary methods
- genetic algorithms
- machine learning

→Toward a unified "complex systems" science

systems sciences: holistic (non-reductionist) view on interacting parts
- systems theory (von Bertalanffy)
- systems engineering (design)
- cybernetics (Wiener; goals & feedback)
- control theory (negative feedback)

dynamics: behavior and activity of a system over time
- nonlinear dynamics & chaos
- stochastic processes
- systems dynamics (macro variables)

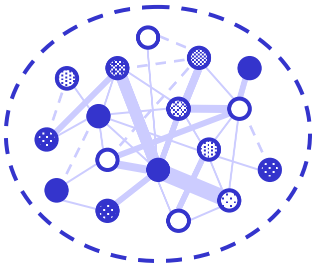
multitude: large-scale properties of systems
- graph theory & networks
- statistical physics
- agent-based modeling
- distributed AI systems

COMPLEX SYSTEMS

From natural CS to designed CS (and back)

- The challenges of complex systems (CS) research

Transfers
- among systems

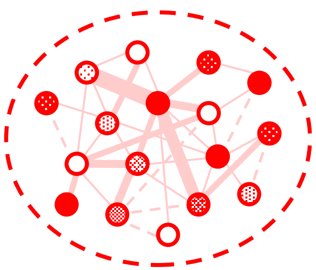


CS science: understanding "natural" CS

(spontaneously emergent, including human activity)

Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

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

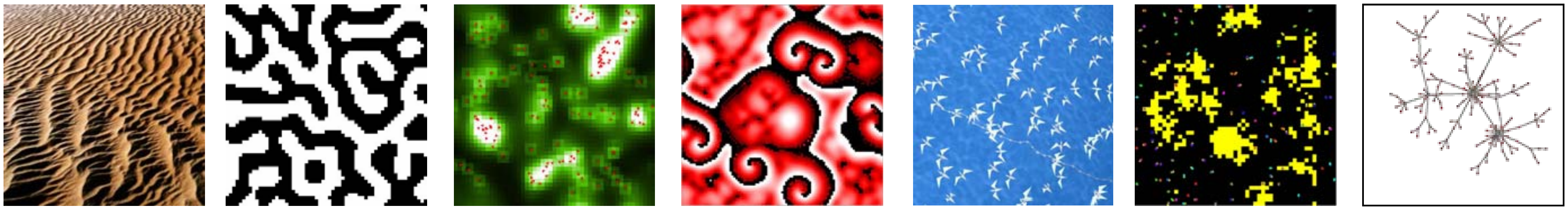


CS engineering: designing a new generation of "artificial" CS (harnessed & tamed, including nature)

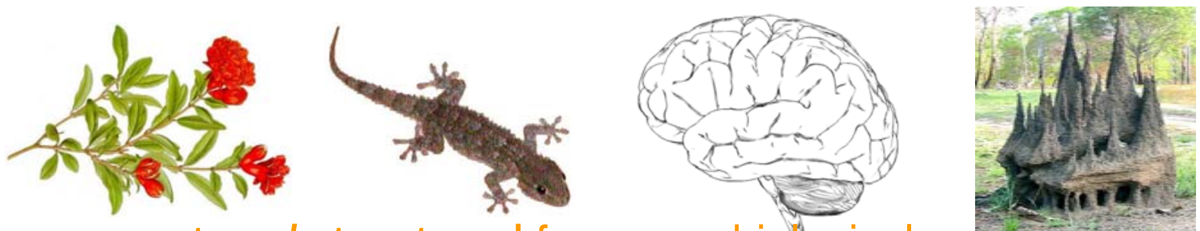
"Statistical" vs. "morphological" complex systems

(a) natural random self-organization

✓most **self-organized** systems form "**simple**" random patterns



(b) natural self-organized architectures



✓the only natural emergent *and* structured forms are biological

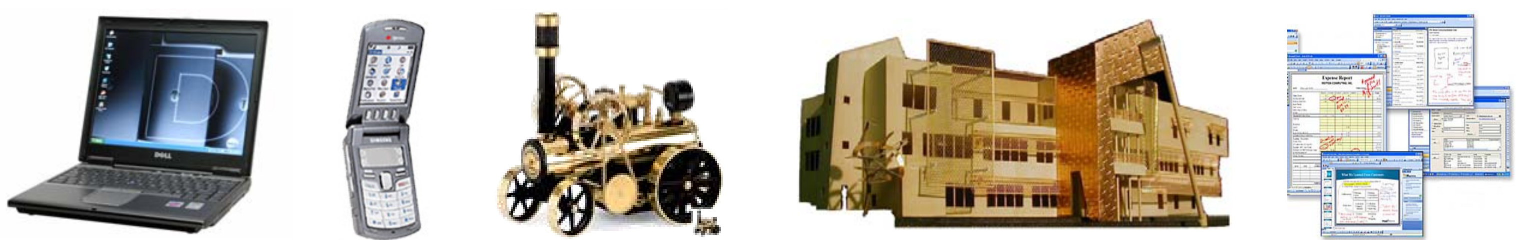
→*can we reproduce them in artificial systems?*

(c) engineered self-organization (bottom-up)

?? . .

. . ??

(d) direct design (top-down)



✓while "**complicated**" architectures are **designed** by humans

more architecture

natural

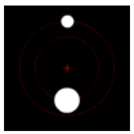
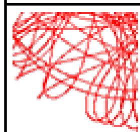
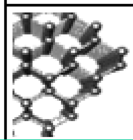
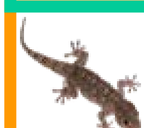
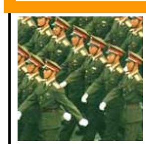
my research

artificial

more self-organization

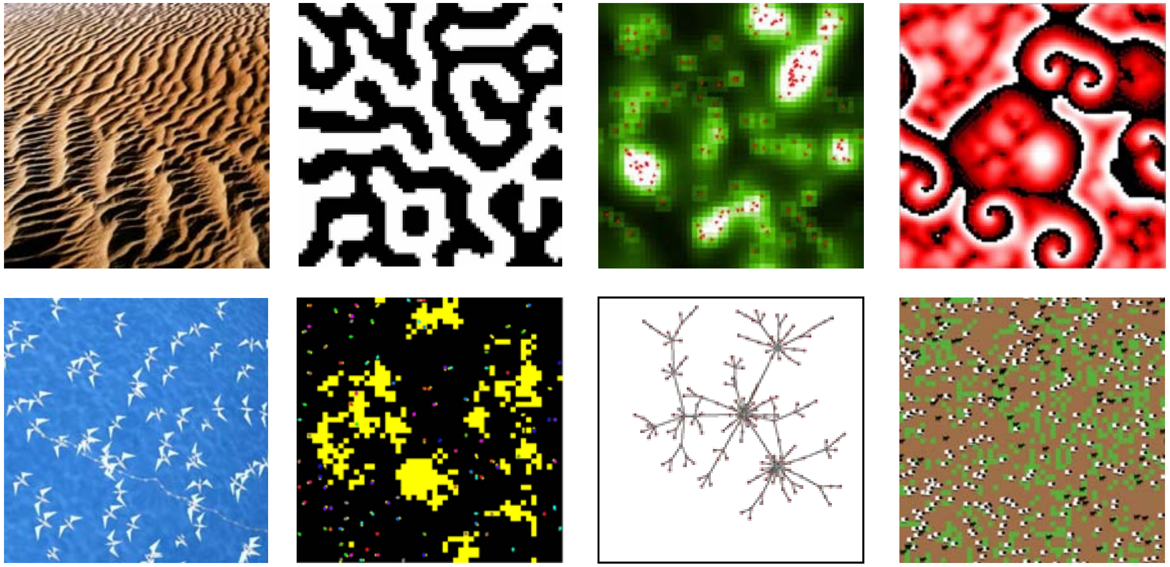
"Statistical" vs. "morphological" complex systems

➢ A brief taxonomy of systems

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

(a) 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.*



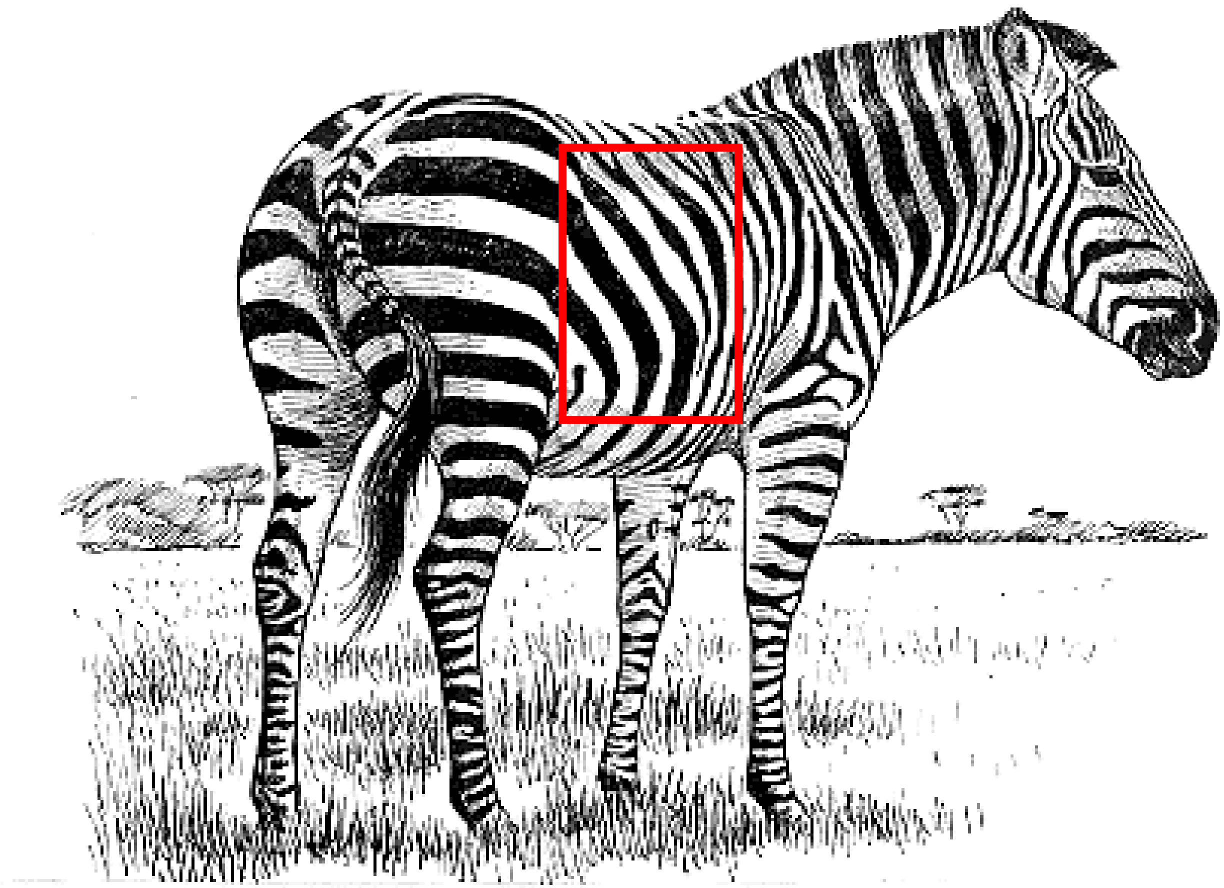
✓ yet, often like "textures": repetitive, statistically *uniform*, information-poor

✓ spontaneous order arising from amplification of *random* fluctuations

✓ *unpredictable* number and position of mesoscopic entities (spots, groups)

(b) Morphological (self-dissimilar) systems

compositional systems: pattern formation ≠ morphogenesis



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

"The stripes are easy, it's the horse part that troubles me"

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

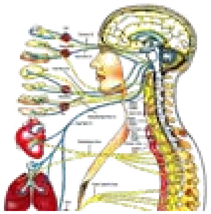
(b) Morphological (self-dissimilar) systems

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


plants


vertebrates

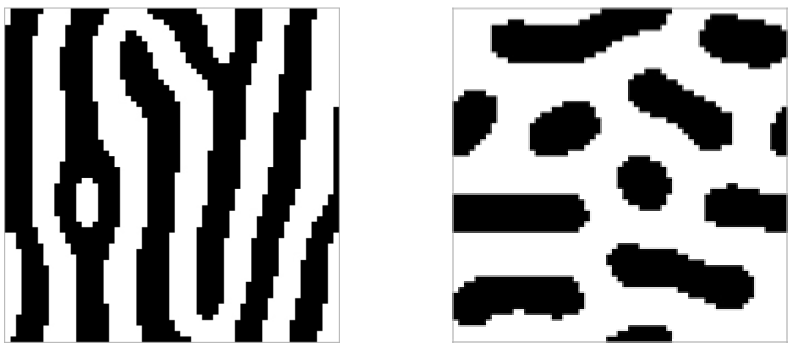

arthropods


humans

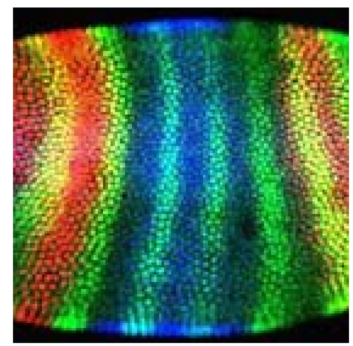
  - ✓ mesoscopic organs and limbs have intricate, *nonrandom* morphologies
  - ✓ development is highly *reproducible* in number and position of body parts
  - ✓ *heterogeneous* elements arise under information-rich genetic control
- **Biological organisms are self-organized *and* structured**
  - ✓ because the pieces of the puzzle (agent rules) are more "sophisticated" (than inert matter): depend on agent's *type* and/or *position* in the system
  - ✓ the outcome (development) is truly complex but, paradoxically, can also be more *controllable* and *programmable*

Statistical vs. morphological systems

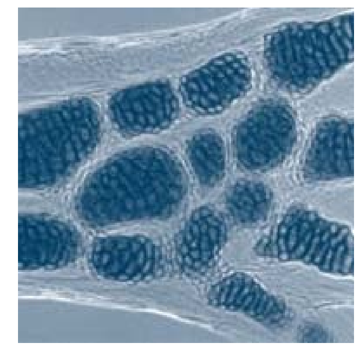
- Physical pattern formation is “free” –
  Biological (multicellular) pattern formation is “guided”



reaction-diffusion
with NetLogo



fruit fly embryo
Sean Caroll, U of Wisconsin



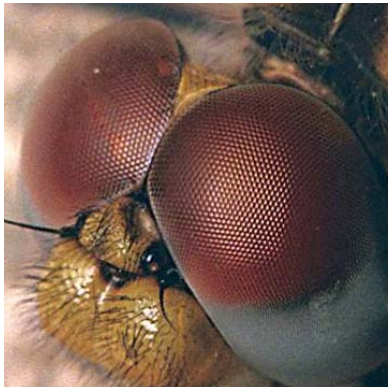
larval axolotl limb condensations
Gerd B. Müller

Statistical vs. morphological systems

- Multicellular forms = a bit of "free" + a lot of "guided"
  - ✓ domains of free patterning embedded in a guided morphology

unlike Drosophila's stripes, these pattern primitives are *not* regulated by different sets of genes depending on their position

spots, stripes in skin
angelfish, www.sheddaquarium.org



ommatidia in compound eye
dragonfly, www.phy.duke.edu/~hsg/54

  - ✓ repeated copies of a guided form, distributed in free patterns

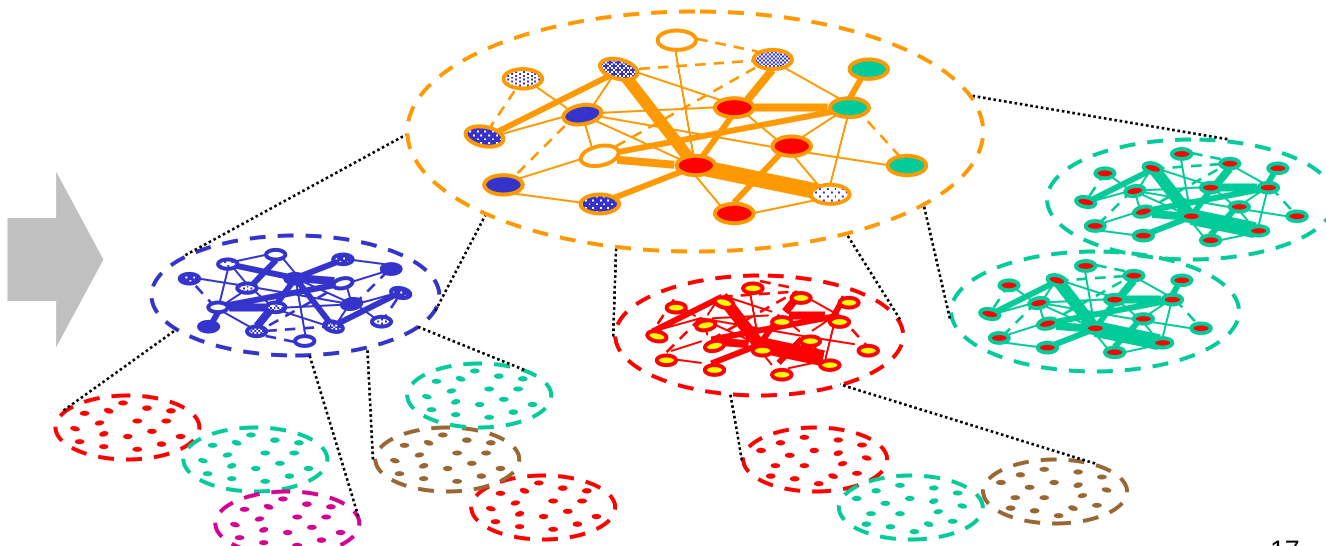
entire structures (flowers, segments) can become modules showing up in random positions and/or numbers

flowers in tree
cherry tree, www.phy.duke.edu/~fortney

segments in insect
centipede, images.encarta.msn.com

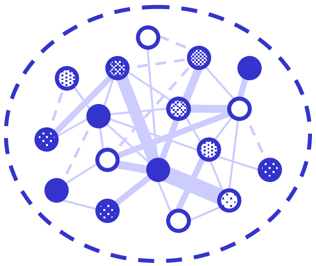
Beyond statistics: heterogeneity, modularity, reproducibility

- 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*

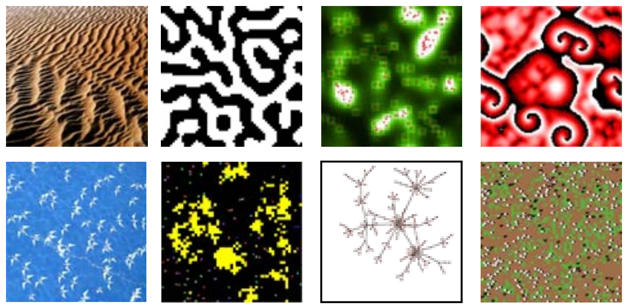


From natural CS to designed CS

- Transfer from morphological to technological systems

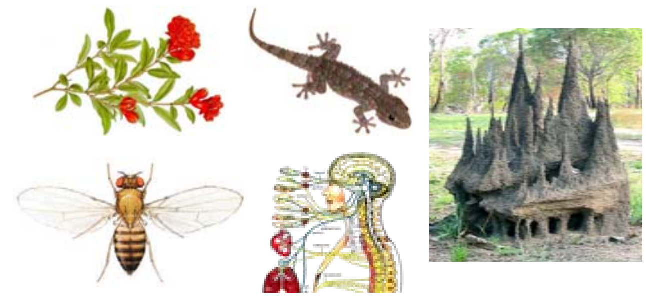


statistical systems

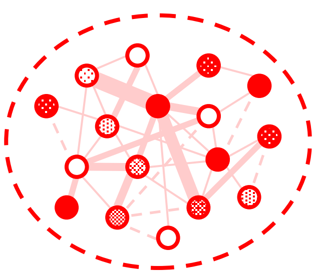


- uniform
- random
- unpredictable details

morphological systems



- heterogeneous
- programmable
- reproducible

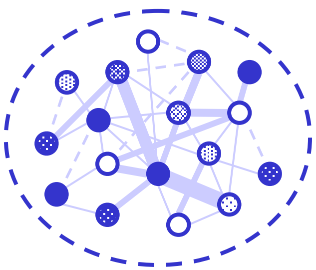


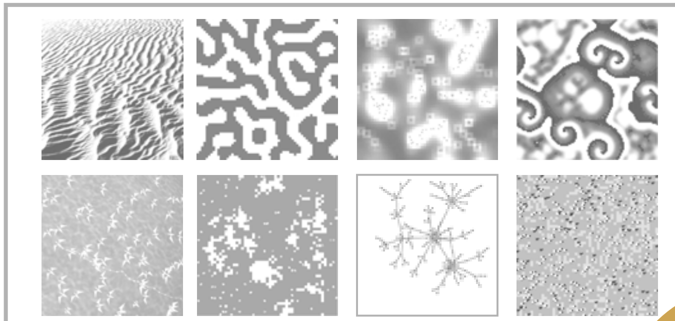
From natural CS to designed CS

➢ Transfer from morphological to technological systems

statistical systems

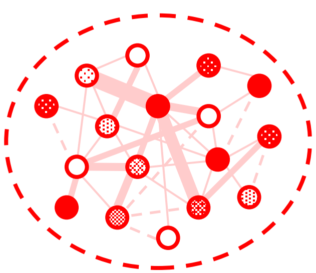
morphological systems

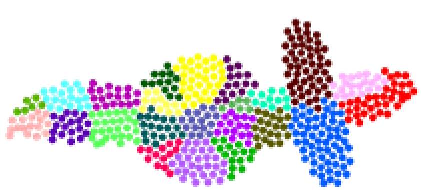


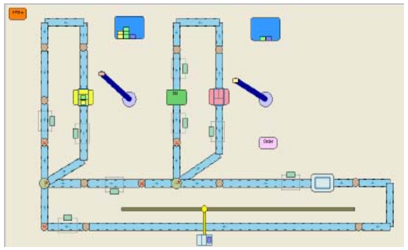


- uniform
- random
- unpredictable details

- heterogeneous
- programmable
- reproducible



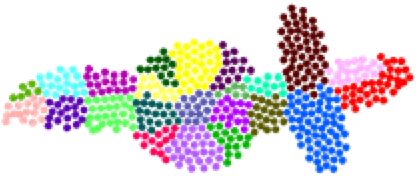


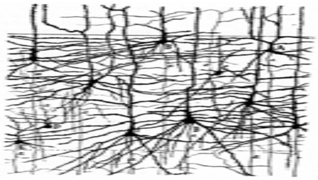


amorphous/spatial computing, autonomic networks, modular/swarm robotics, programmable matter

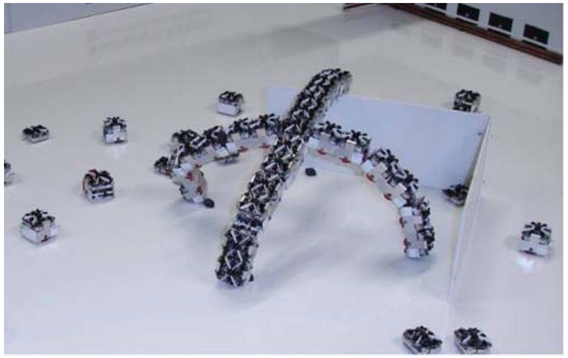
The need for morphogenetic abilities

- Self-architecturing in natural systems → artificial systems
  - ✓ morphogenetic abilities in biological modeling
    - organism development
    - brain development



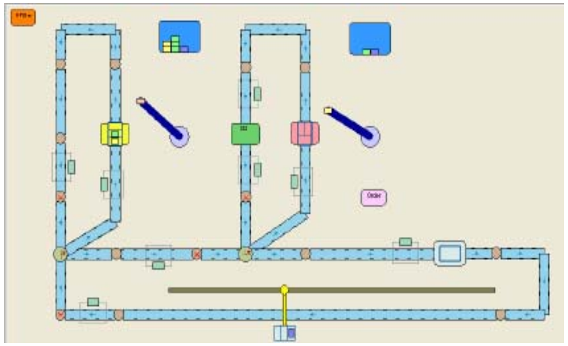


  - ✓ need for morphogenetic abilities in computer science & AI
    - self-forming robot swarm
    - self-architecturing software
    - self-connecting micro-components



http://www.symbrion.eu

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



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

Facilitating evolutionary innovation by development

1. Toward self-organized *and* architectured systems
2. **Biological development as a two-side challenge**
   Heterogeneous motion vs. moving patterns
3. Embryomorphic engineering
   Morphogenesis as a multi-agent self-assembly process
4. Evo-devo engineering
   Evolutionary innovation by development
5. Extension to self-knitting network topologies

Overview of morphogenesis

➢ An abstract computational approach to development

- ✓ as a fundamentally *spatial* phenomenon
- ✓ highlighting its *broad principles* and proposing a *computational* model of these principles

➢ Broad principles

1. *biomechanics* → collective motion → "sculpture" of the embryo
2. *gene regulation* → gene expression patterns → "painting" of the embryo

\+ *coupling* between shapes and colors

➢ Multi-agent models

- ✓ best positioned to integrate both
- ✓ account for heterogeneity, modularity, hierarchy
- ✓ each agent carries a combined set of *biomechanical* and *regulatory* rules

Morphogenesis couples assembly and patterning

➢ Sculpture → forms

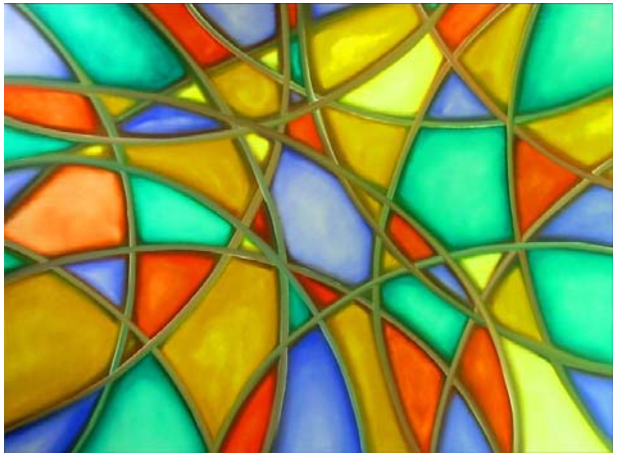
Ádám Szabó, *The chicken or the egg* (2005)
http://www.szaboadam.hu

“shape from patterning”

✓ the forms are “sculpted” by the self-assembly of the elements, whose behavior is triggered by the colors

Niki de Saint Phalle

➢ Painting → colors

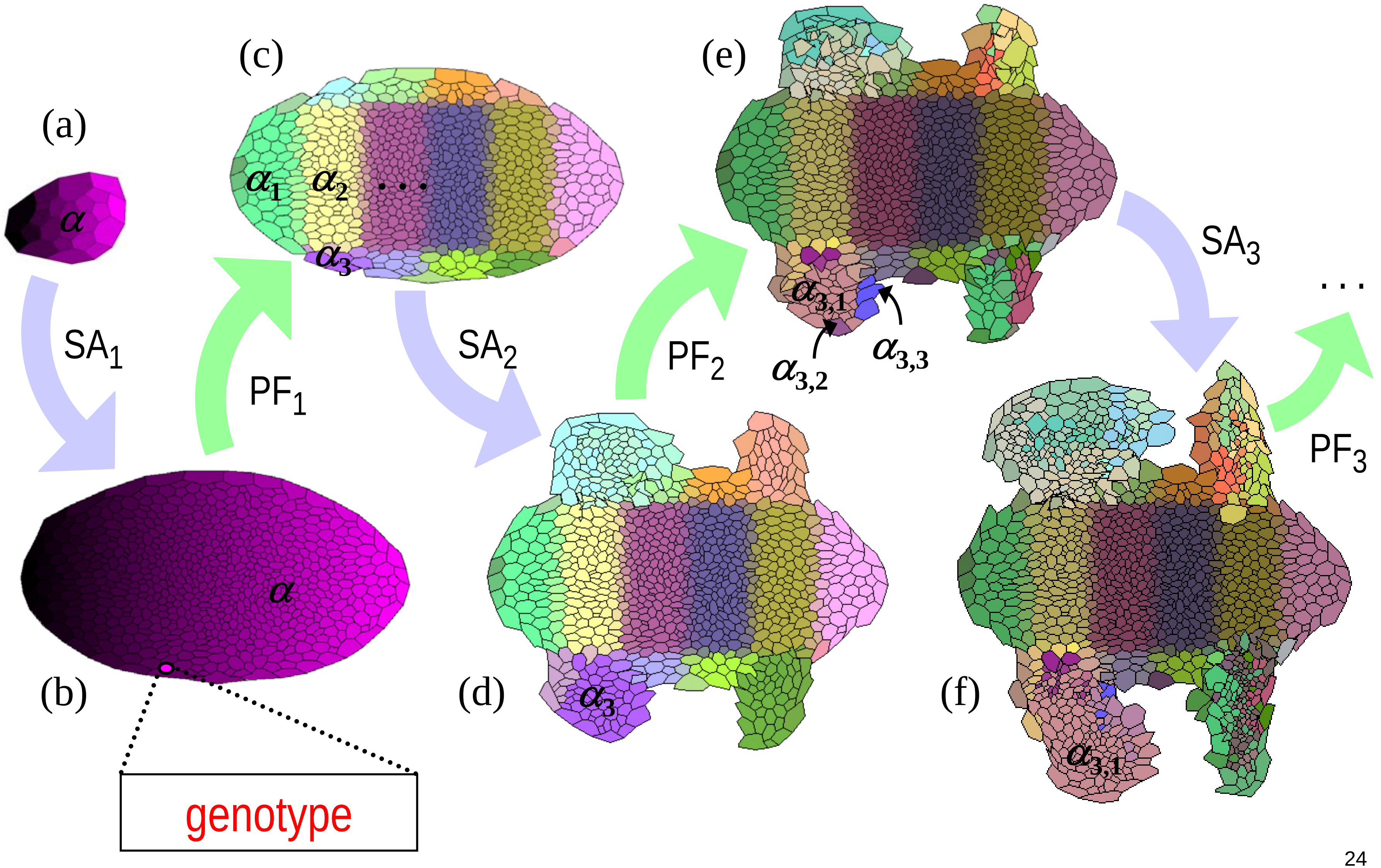


“patterns from shaping”

✓ new color regions appear (domains of genetic expression) triggered by deformations

Morphogenesis couples assembly and patterning

SA = self-assembly (“sculpture”)
PF = pattern formation (“painting”)

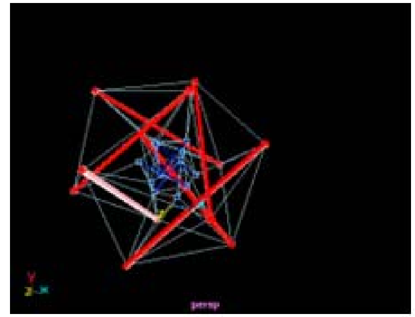


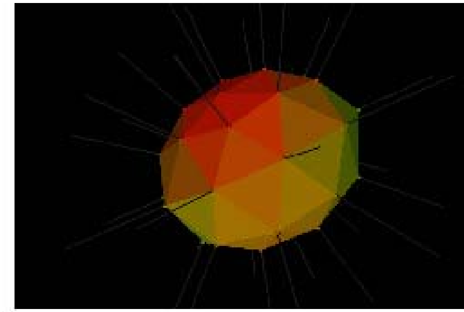
Morphogenesis couples mechanics and regulation

➢ Cellular mechanics

- ✓ adhesion
- ✓ deformation / reformation
- ✓ migration (motility)
- ✓ division / death

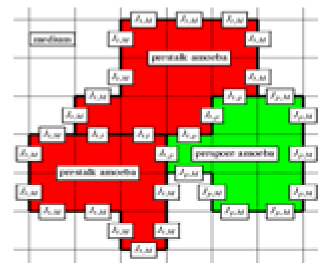
tensional integrity (Ingber)

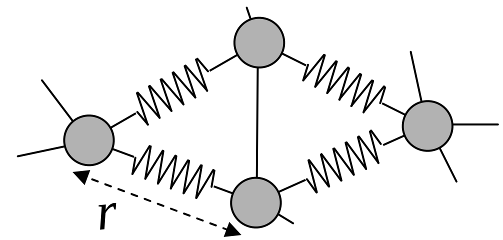




(Delile & Doursat)

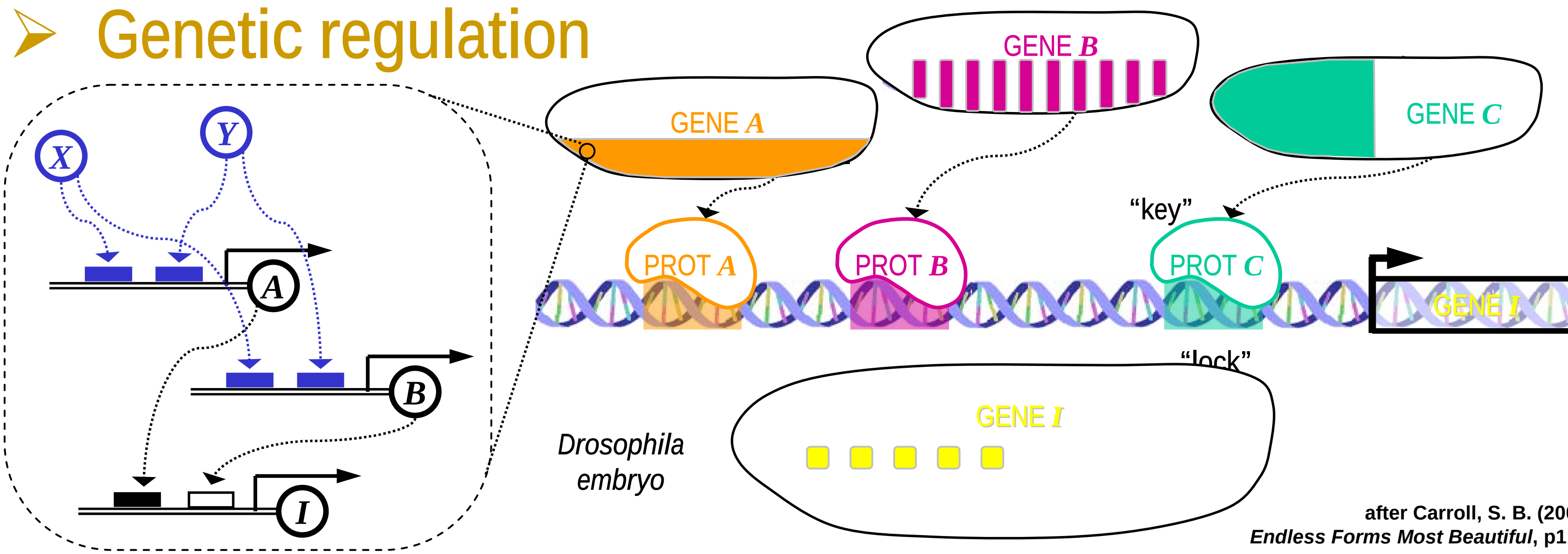
cellular Potts model (Graner, Glazier, Hogeweg)





(Doursat)

➢ Genetic regulation

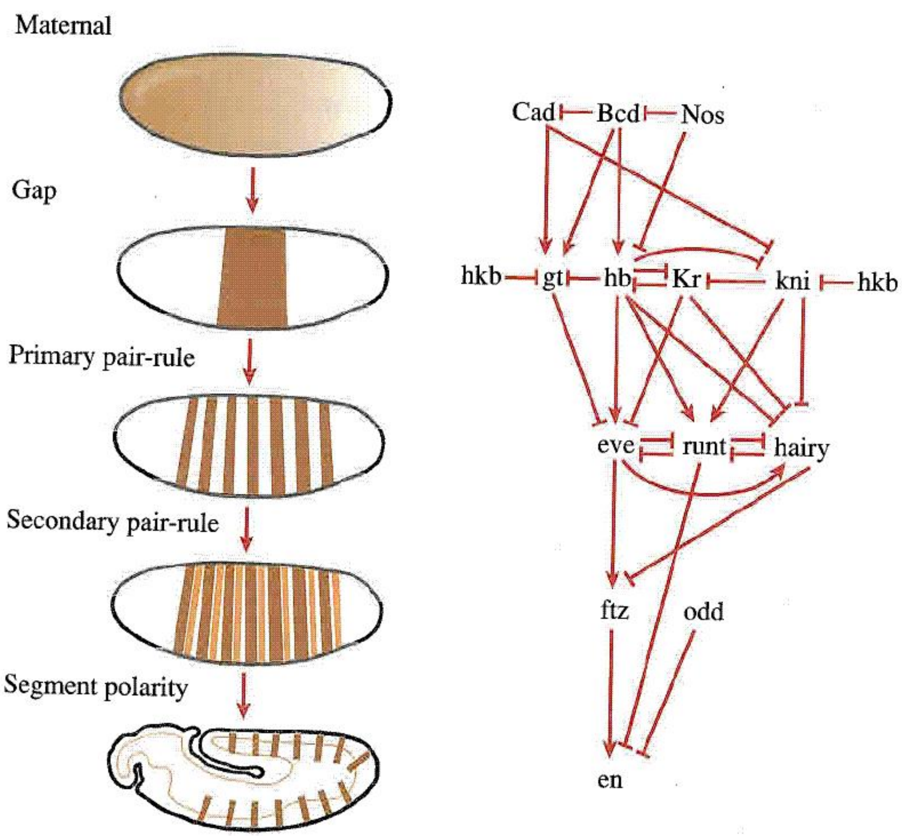


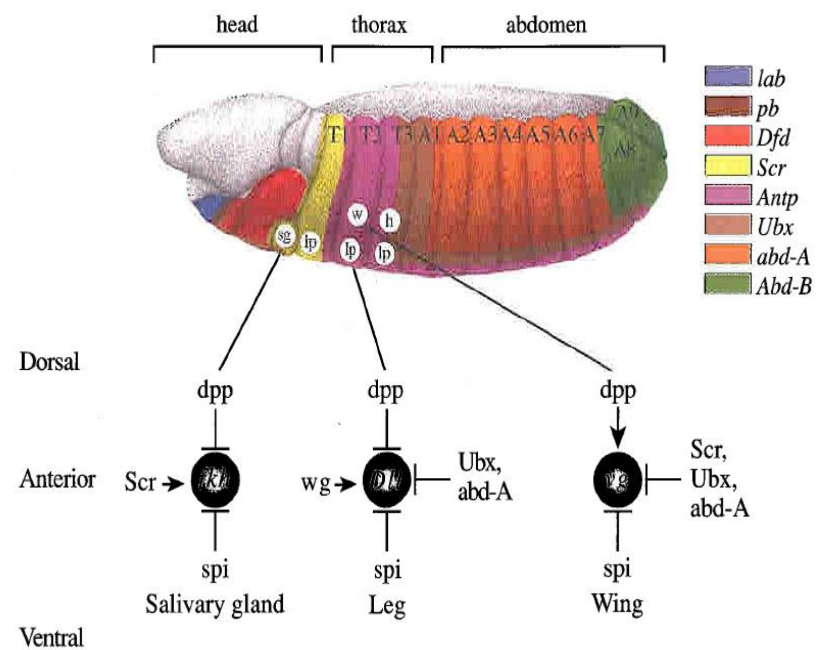
after Carroll, S. B. (2005) *Endless Forms Most Beautiful*, p117

Gene regulatory pattern formation

➢ 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.)



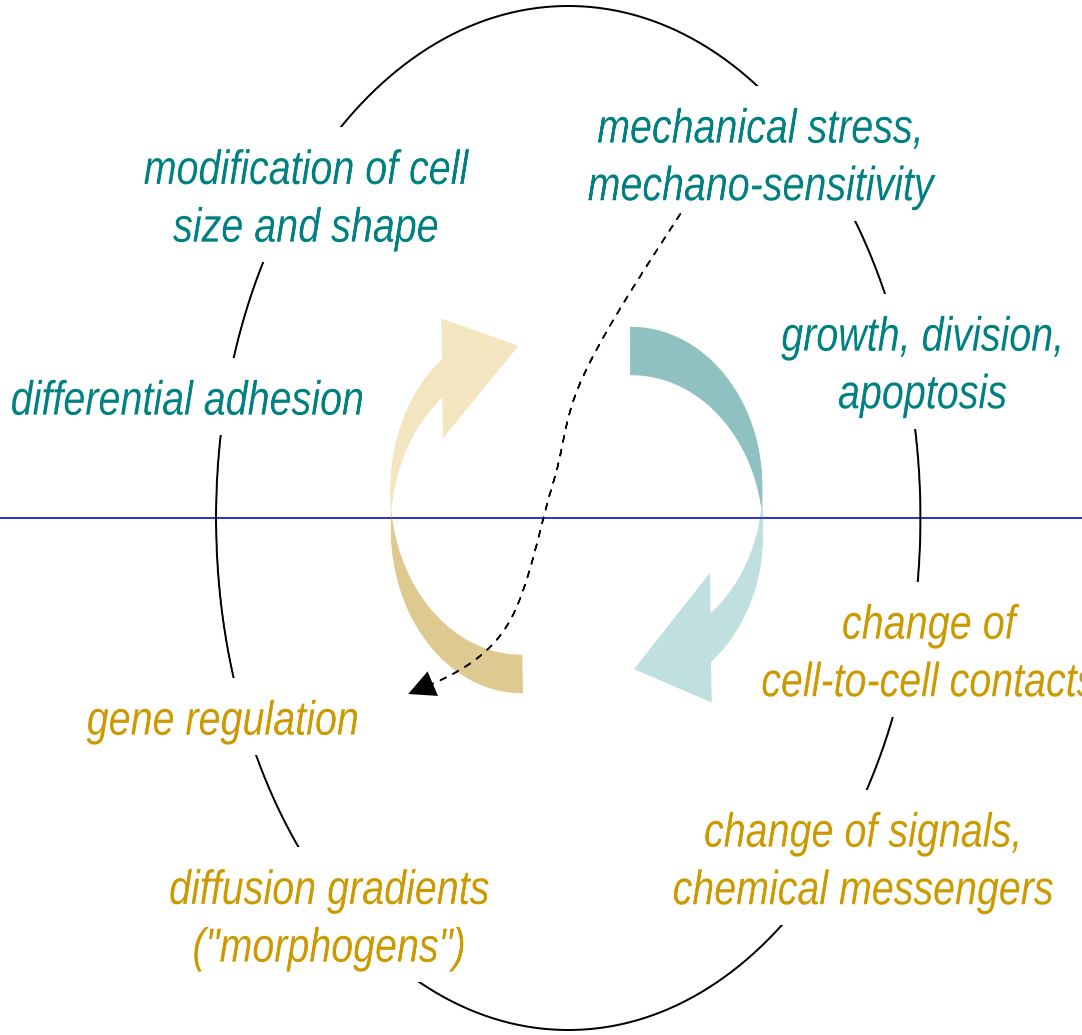


from Carroll, S. B., et al. (2001) *From DNA to Diversity*, p63

Morphogenesis couples mechanics and regulation

- Cellular mechanics

- Genetic regulation

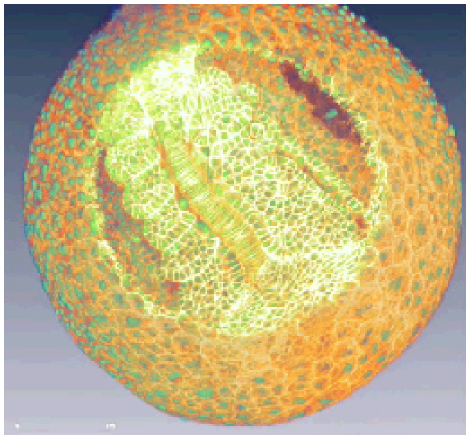


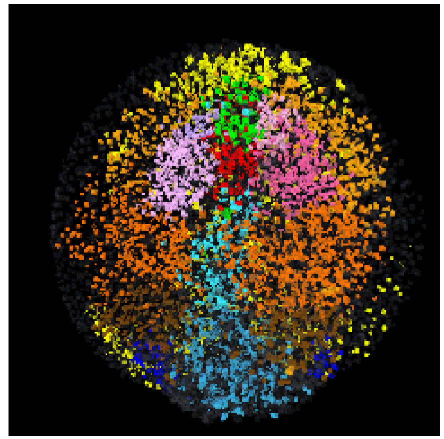
Morphogenesis couples motion and patterns

Collective motion regionalized into patterns

Nadine Peyriéras, Paul Bourgine, Thierry Savy, Benoît Lombardot, Emmanuel Faure et al.

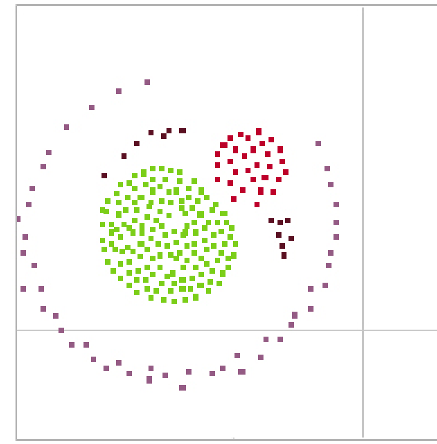
Embryomics & BioEmergences



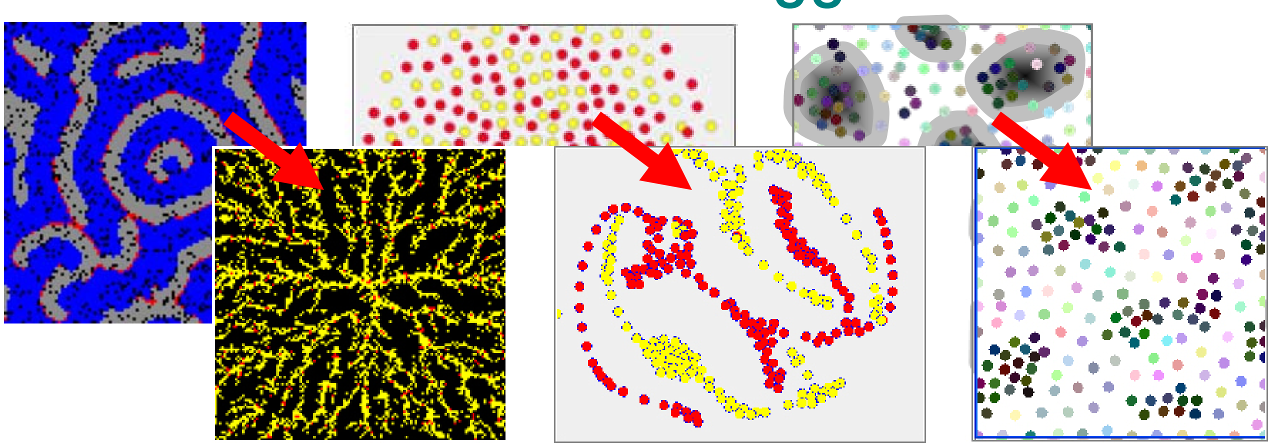


zebrafish

Hiroki Sayama (Swarm Chemistry) http://bingweb.binghamton.edu/~sayama/SwarmChemistry/

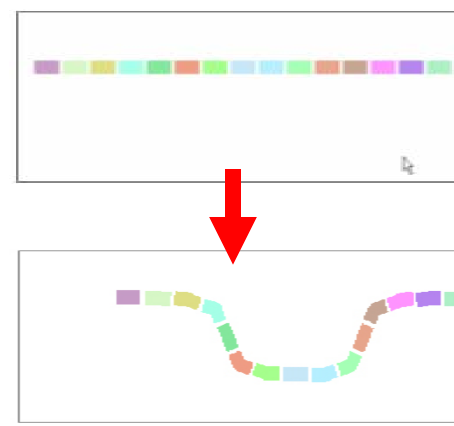


Pattern formation that triggers motion



http://zool33.uni-graz.at/schmickl

Doursat

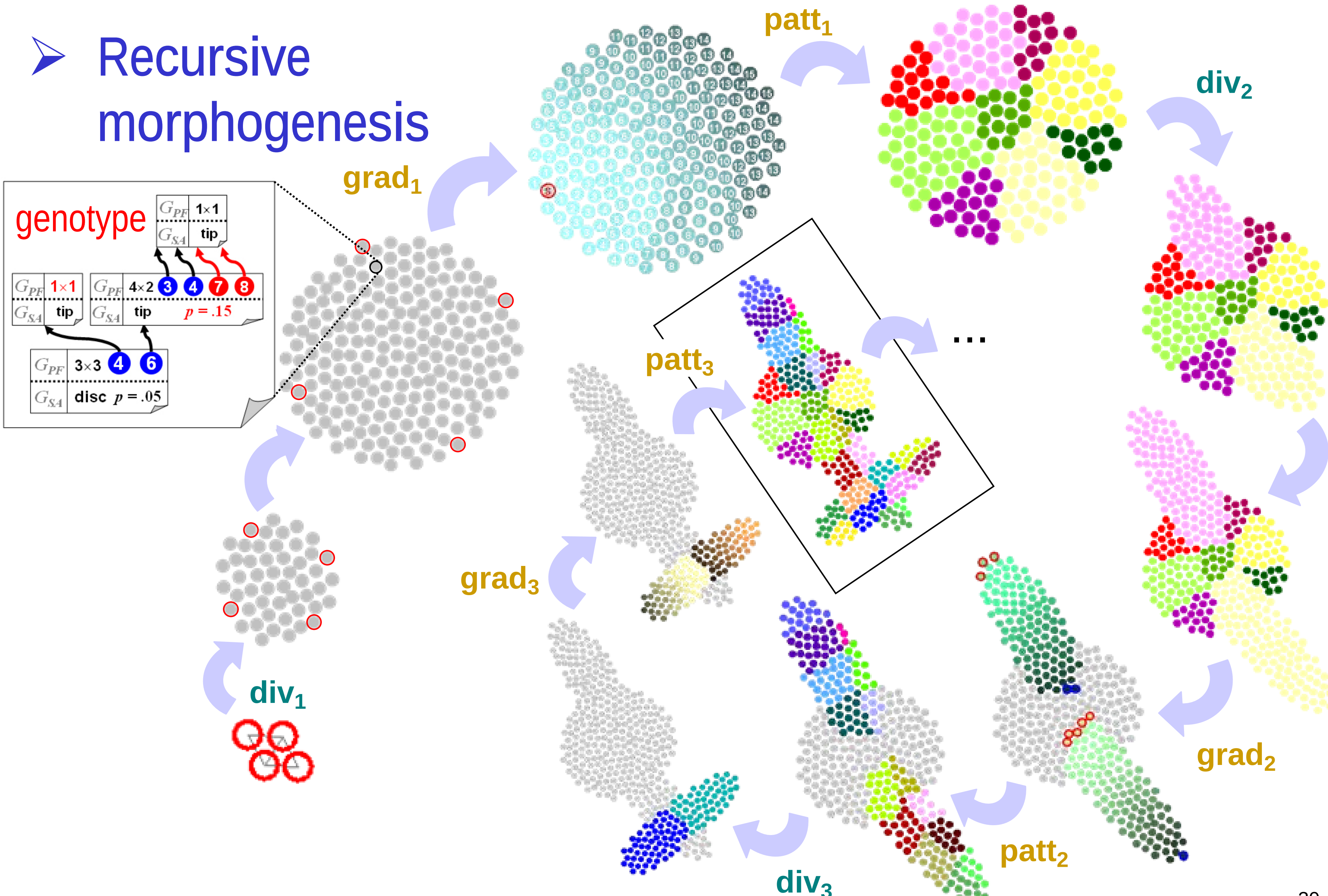


Facilitating evolutionary innovation by development

1. Toward self-organized *and* architectured systems
2. Biological development as a two-side challenge
   Heterogeneous motion vs. moving patterns
3. **Embryomorphic engineering**
   Morphogenesis as a multi-agent self-assembly process
4. Evo-devo engineering
   Evolutionary innovation by development
5. Extension to self-knitting network topologies

Overview of an embryomorphic system

➤ Recursive morphogenesis



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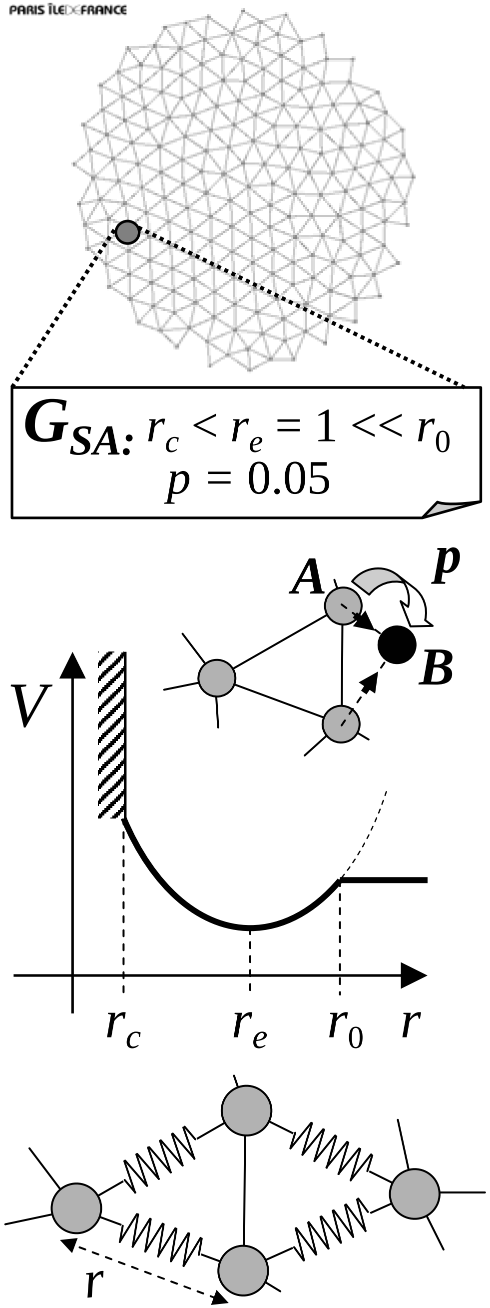

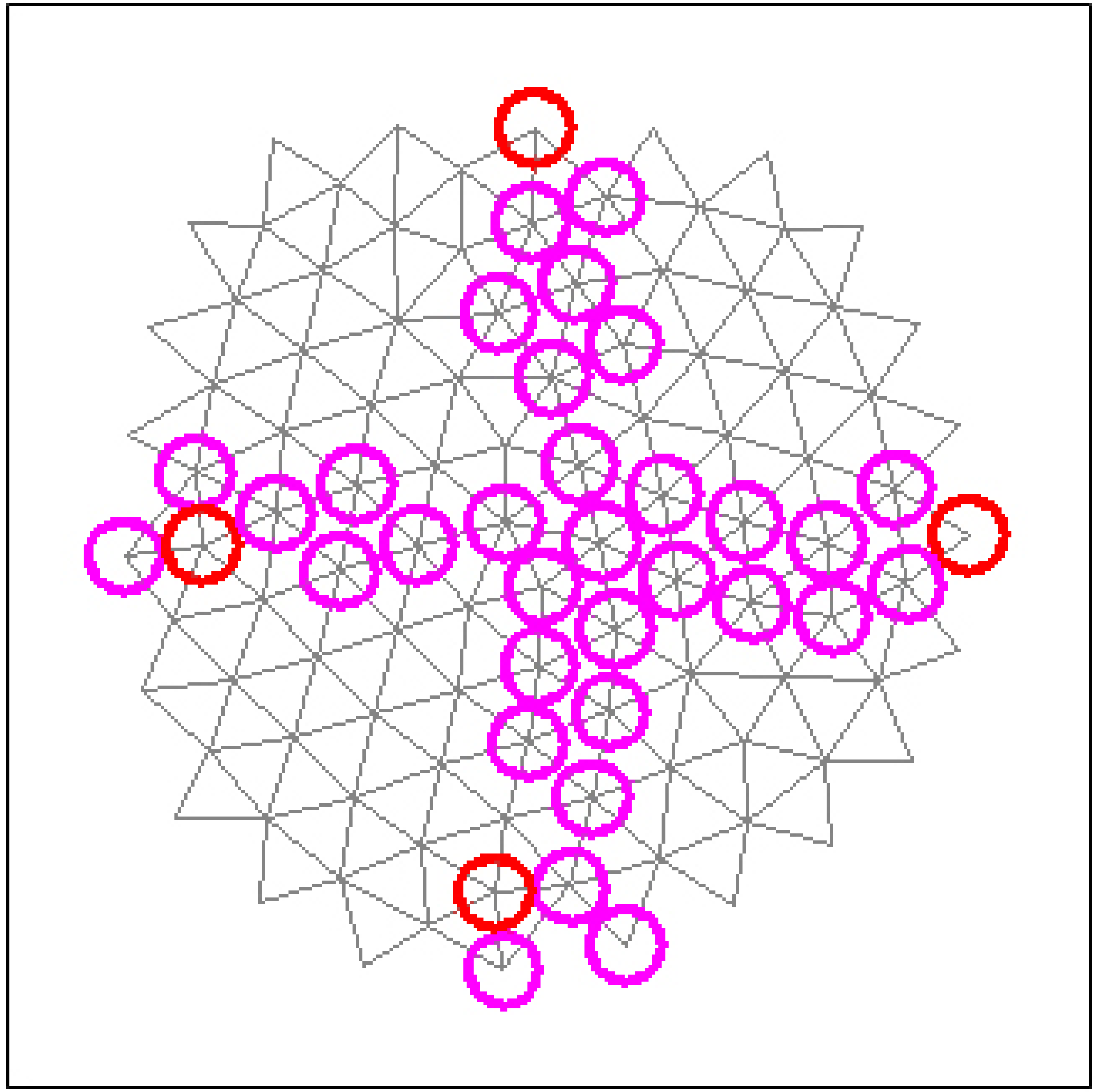

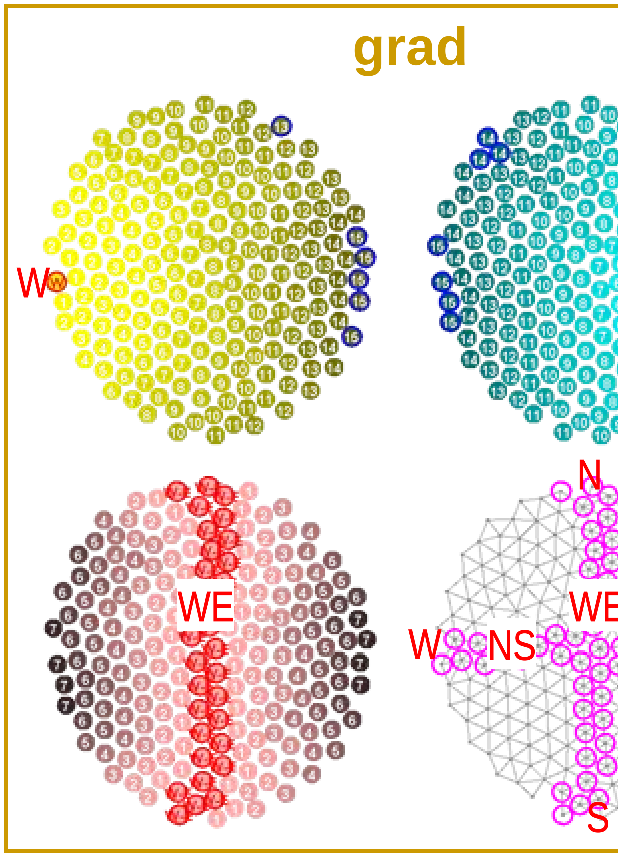
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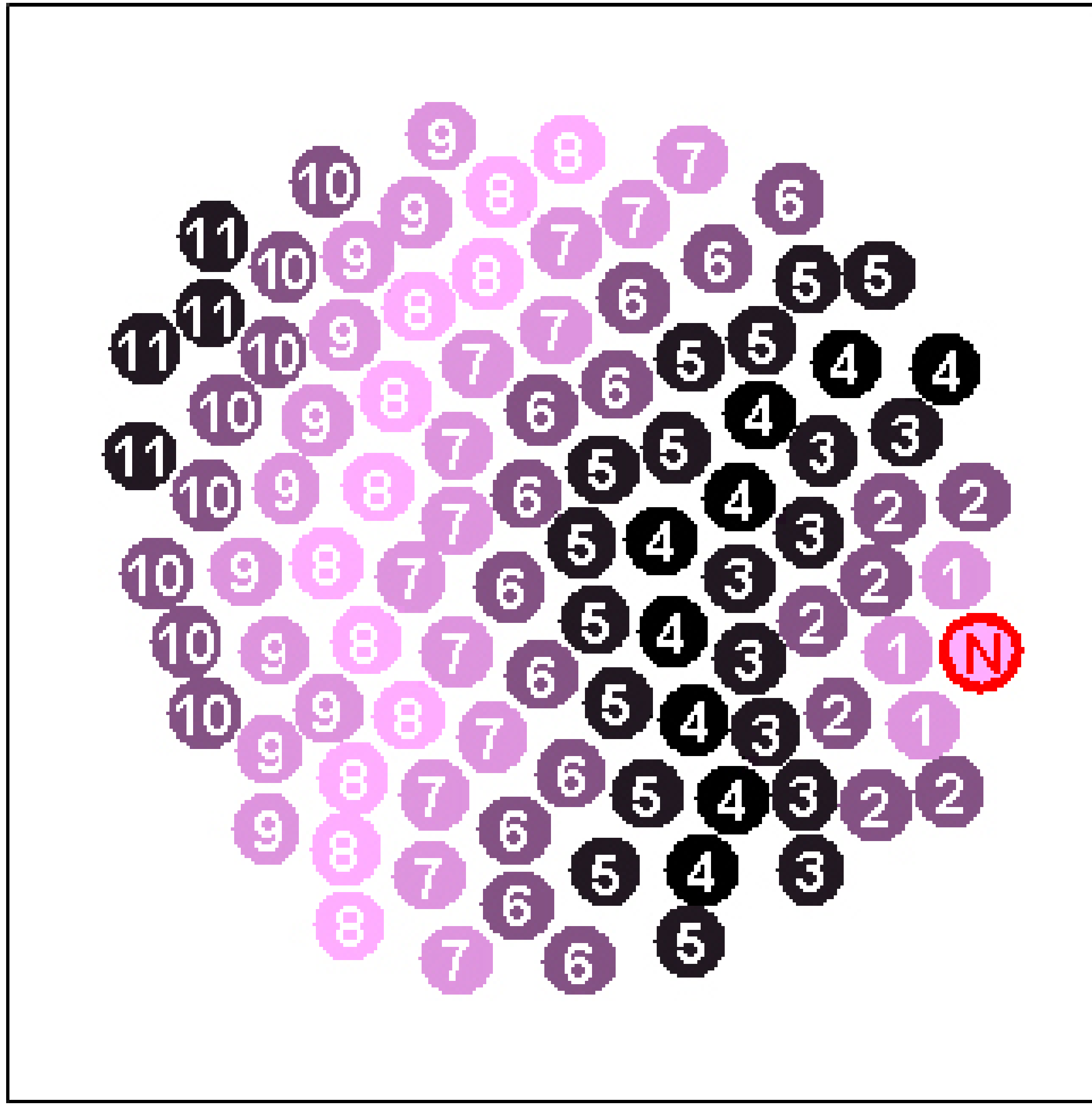
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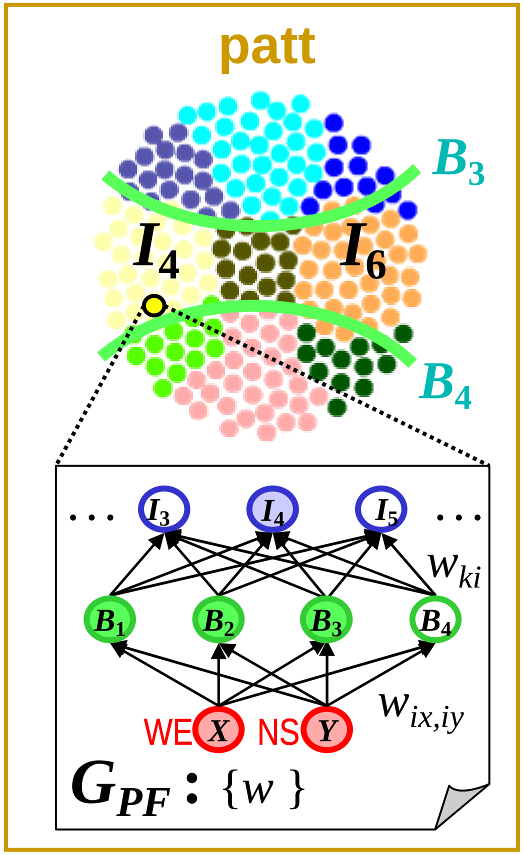
patt
B_3
I_4
I_6
B_4
I_3
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$w_{ix,iy}$
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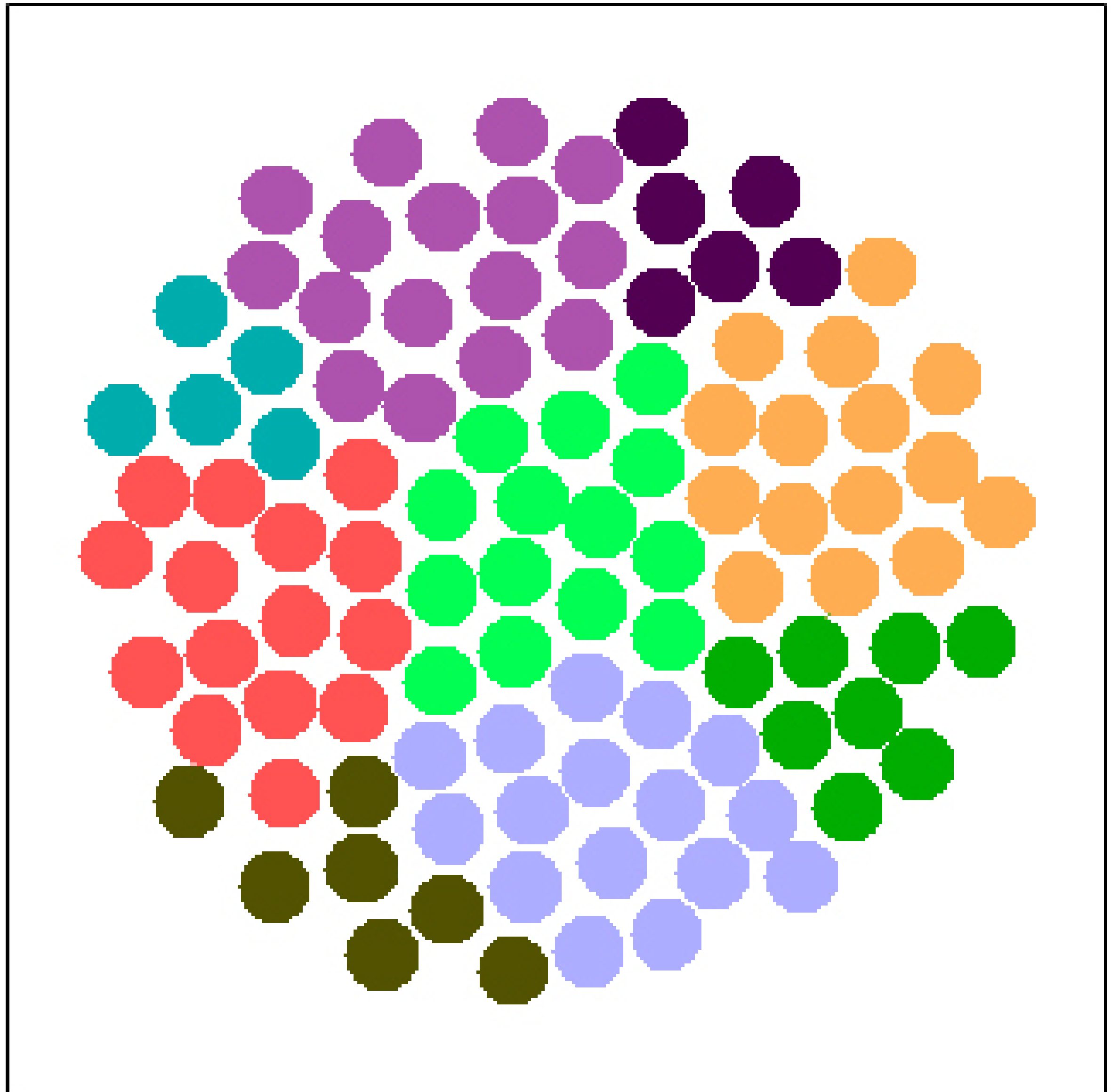
G_{PF} : {w }



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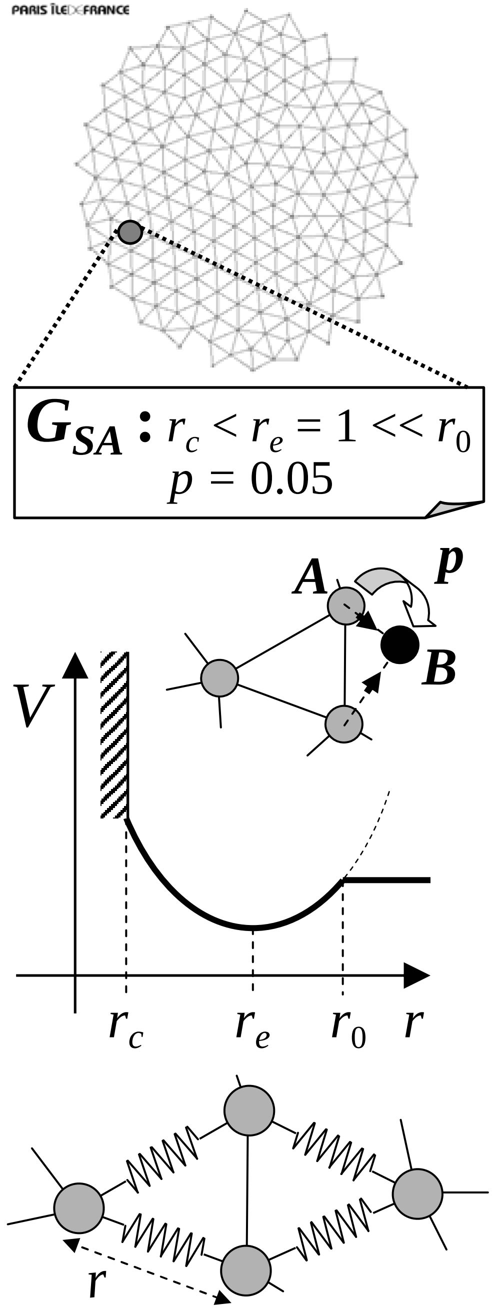

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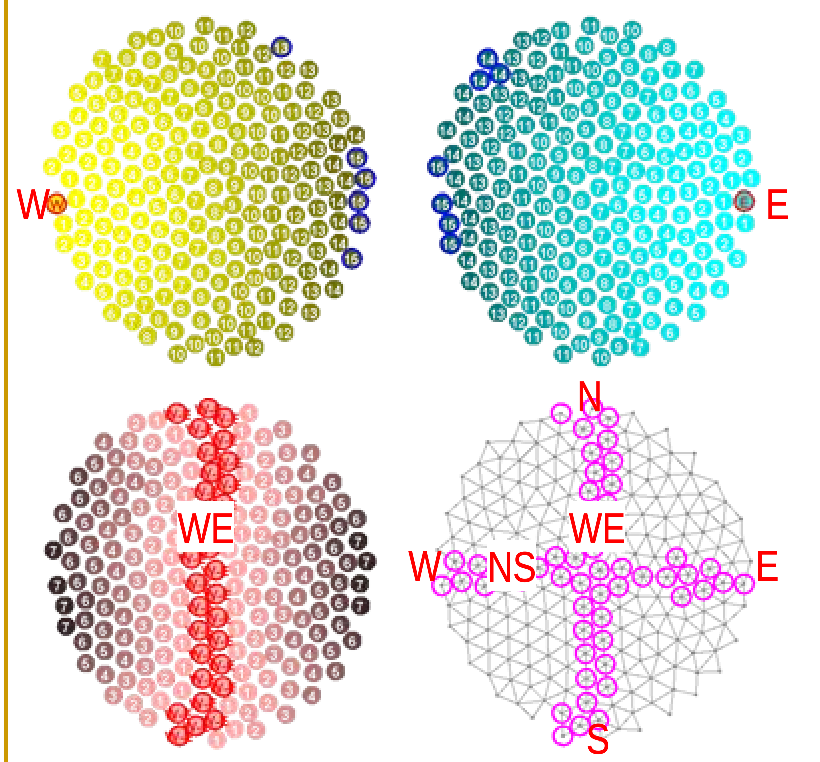

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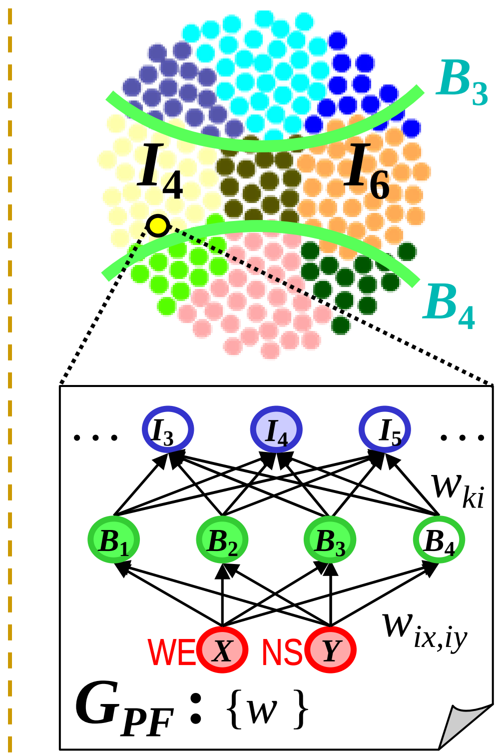
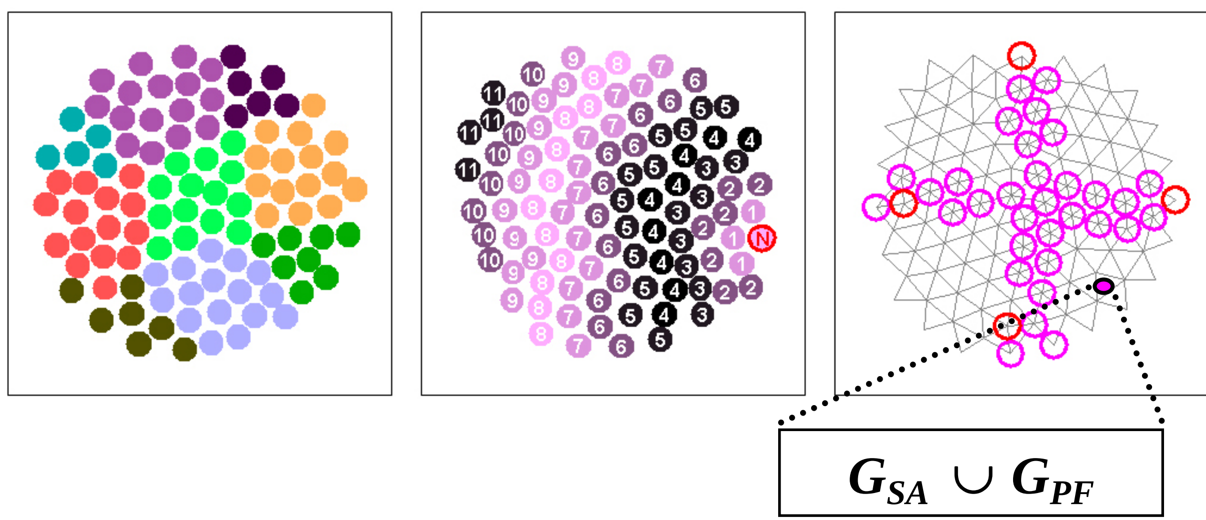
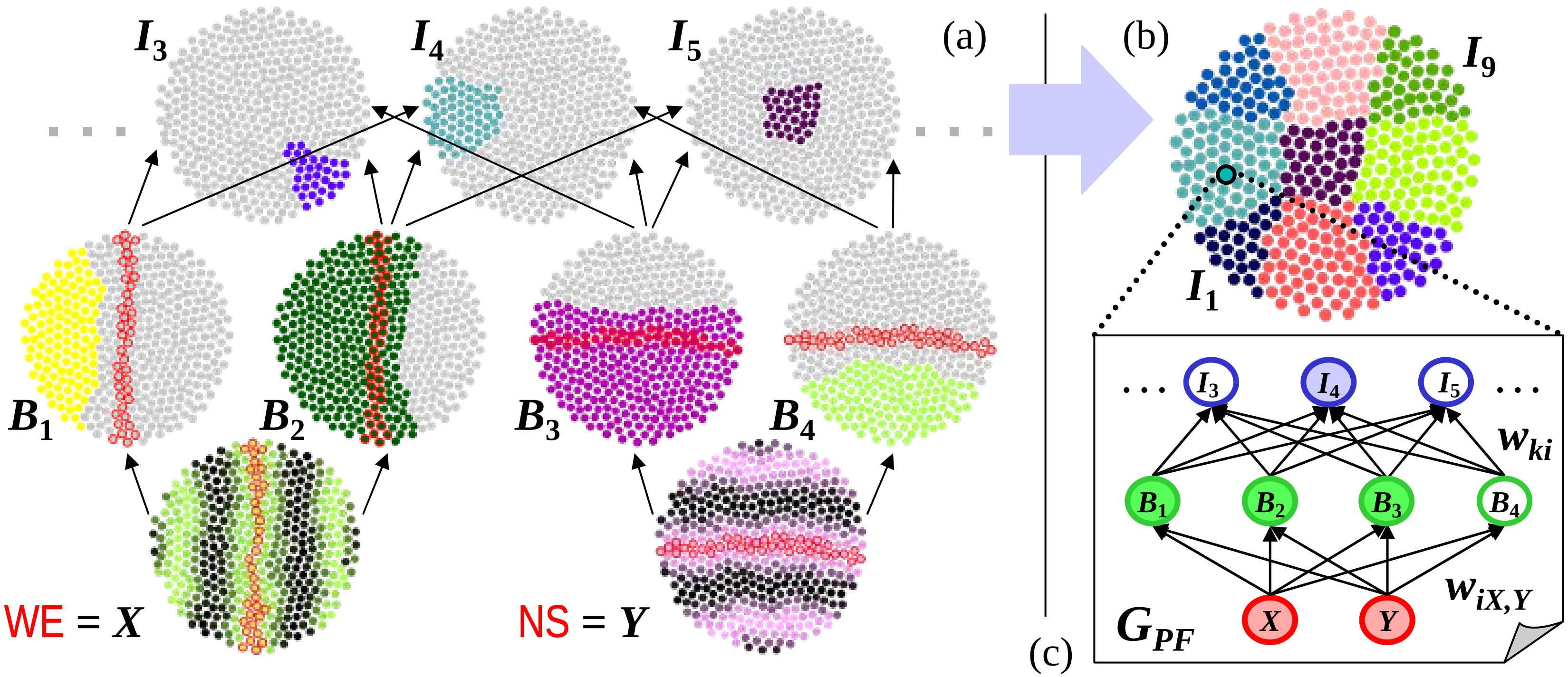




Virtual gene atlas

- Programmed patterning (patt): 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 $k = 1...9$
  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.



Hierarchical morphogenesis

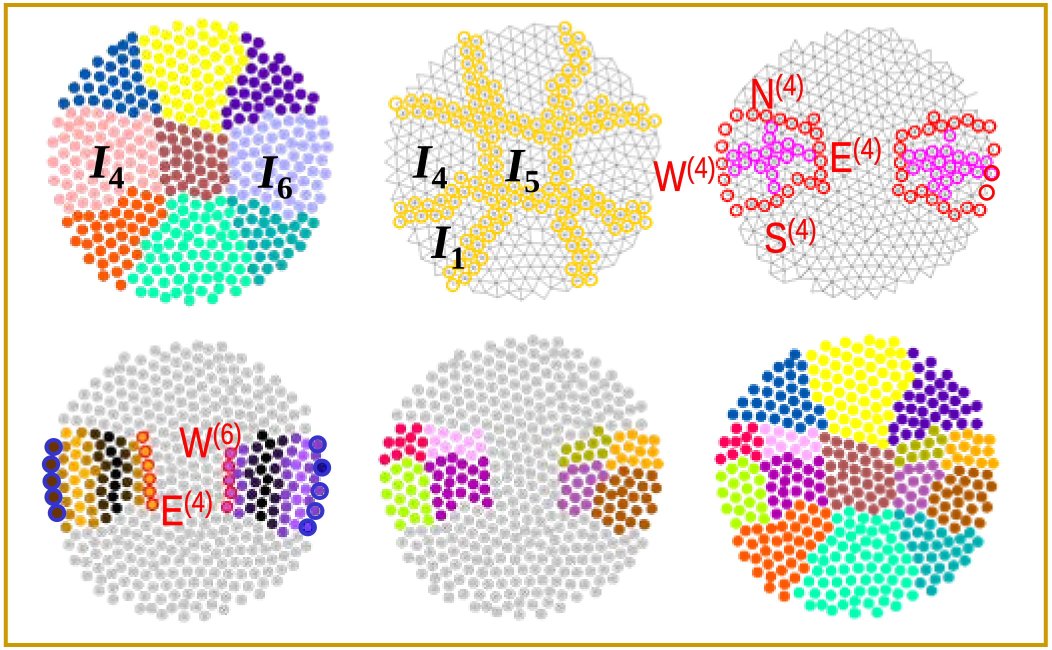
➢ Morphological refinement by iterative growth

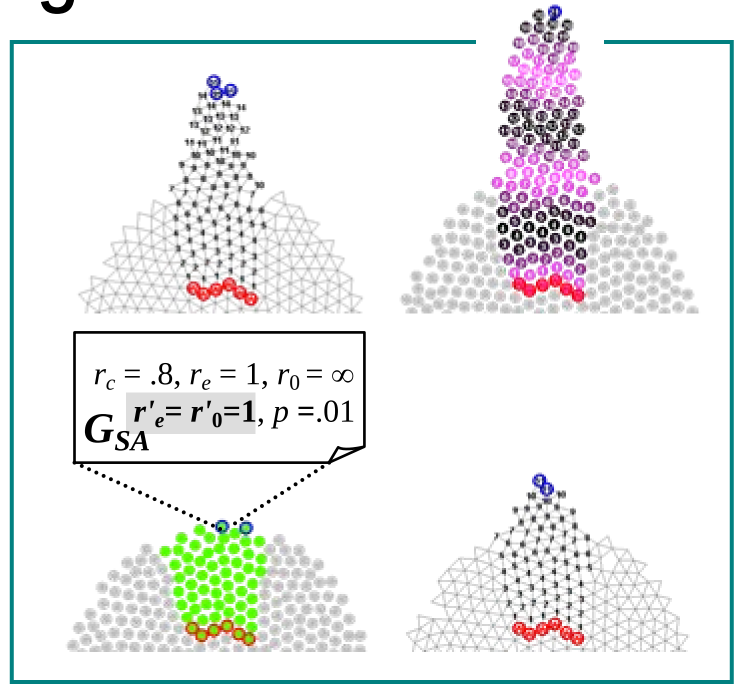
- ✓ details are not created in one shot, but gradually added. . .

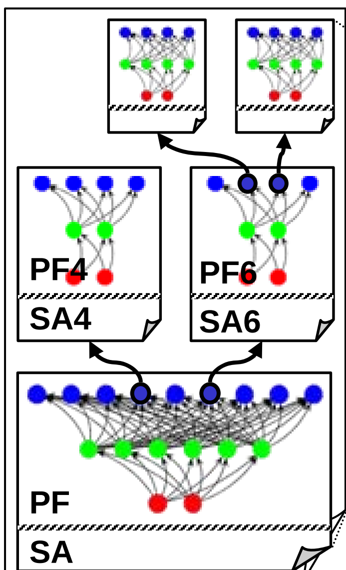
- ✓ . . . while, at the same time, the canvas grows

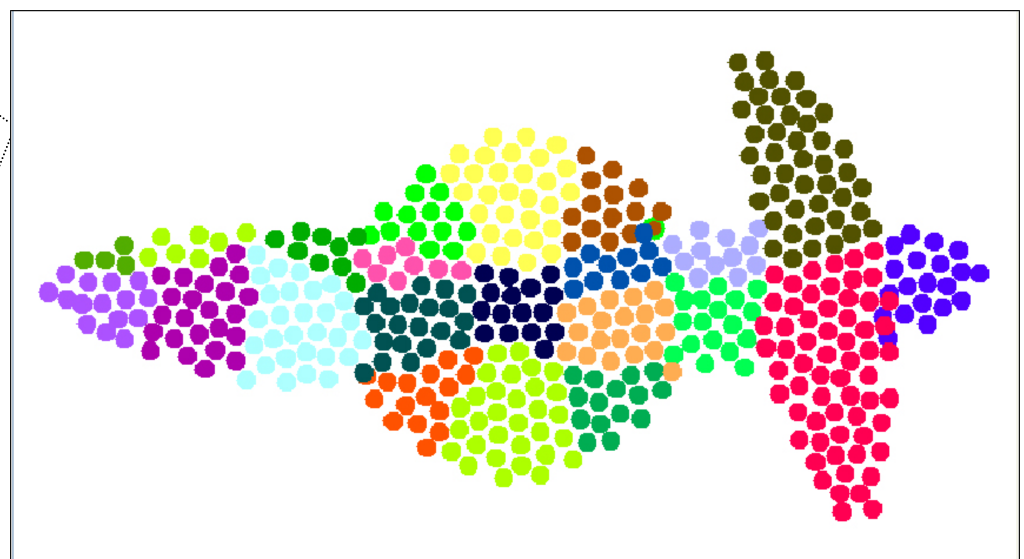
from Coen, E. (2000)
The Art of Genes, pp131-135

Hierarchical embryogenesis

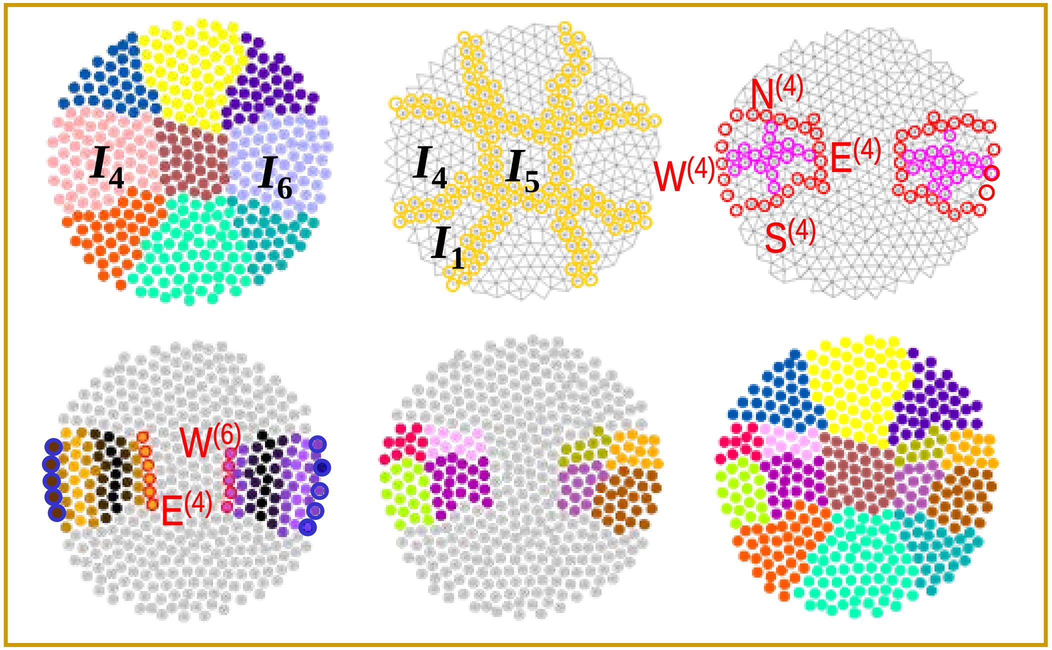


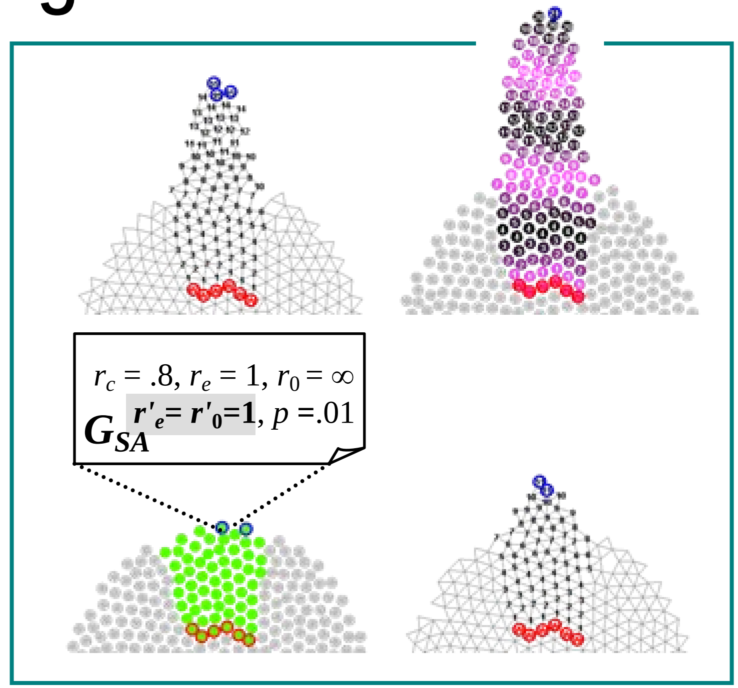


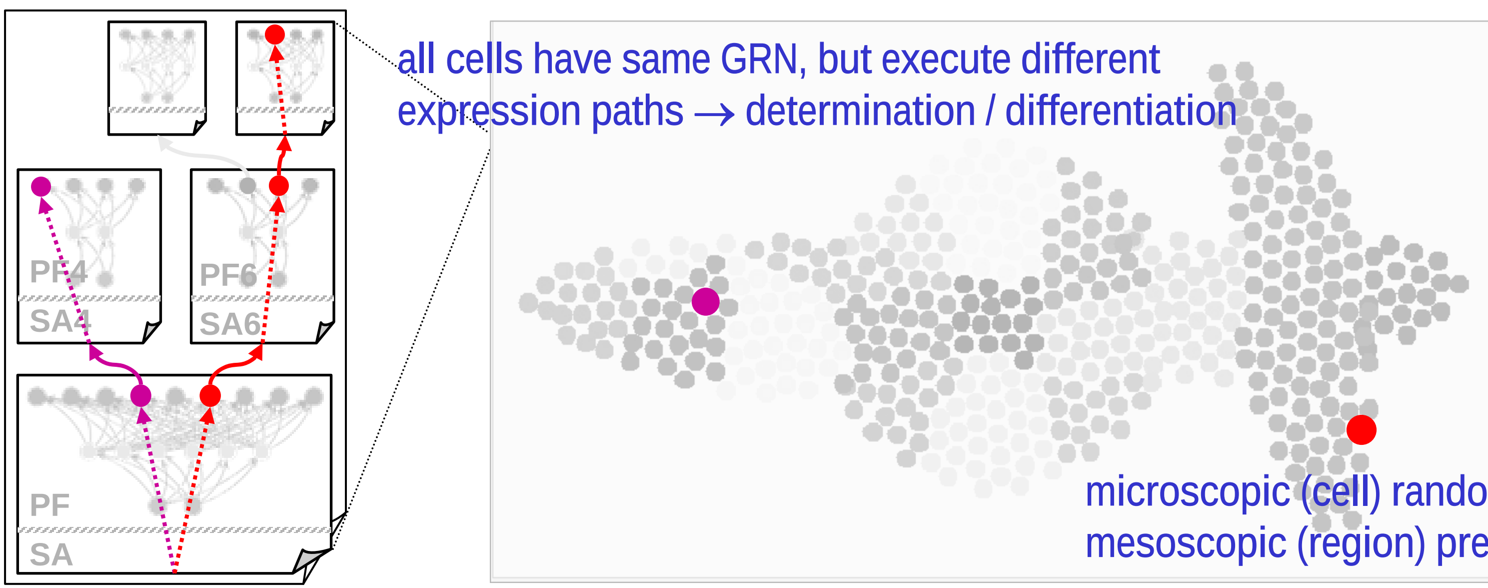




Hierarchical embryogenesis







all cells have same GRN, but execute different expression paths → determination / differentiation

microscopic (cell) randomness, but mesoscopic (region) predictability

Facilitating evolutionary innovation by development

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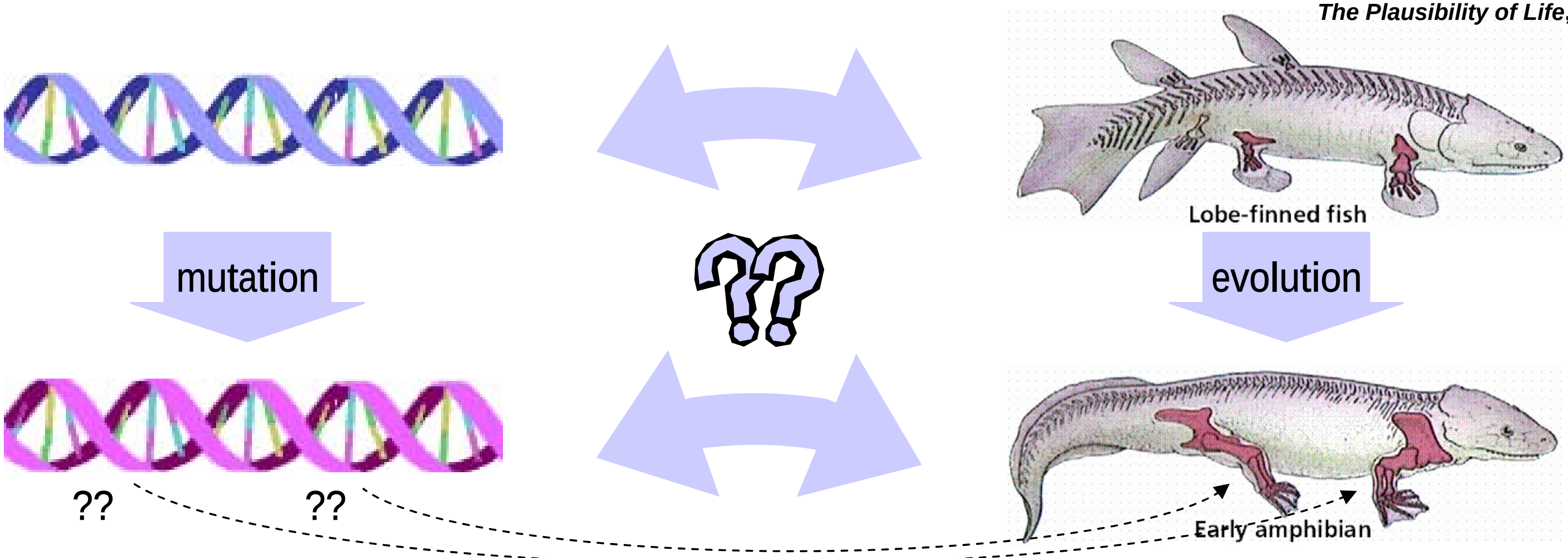
Evolutionary innovation by development

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

"When Charles Darwin proposed his theory of evolution by variation and selection, explaining selection was his great achievement. He could not explain variation. That was Darwin's dilemma."

"To understand novelty in evolution, we need to understand organisms down to their individual building blocks, down to their deepest components, 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*

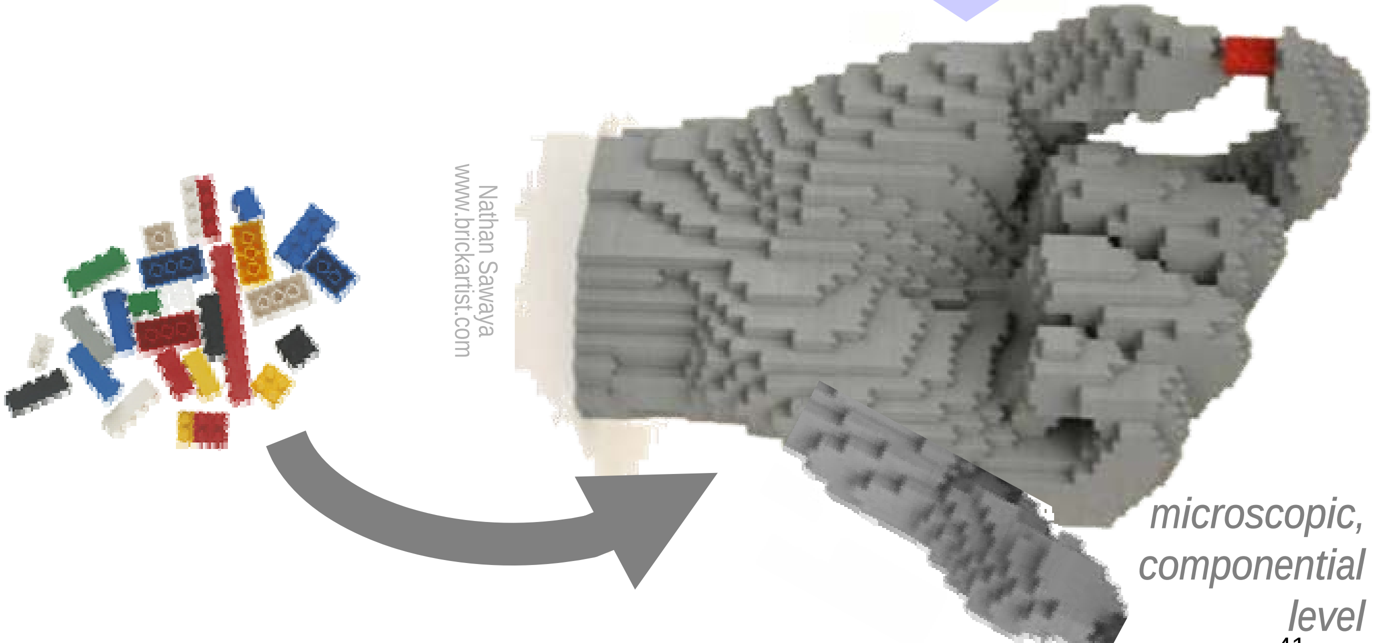
The self-made puzzle of “evo-devo” engineering

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

Amy L. Rawson
www.thirdroar.com

macroscopic, emergent level

“To understand novelty in evolution, we need to understand organisms down to their individual building blocks, down to their deepest components, for these are what undergo change.”



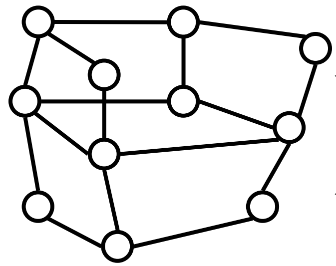
Nathan Sawaya
www.brickartist.com

microscopic, componential level

The self-made puzzle of “evo-devo” engineering

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

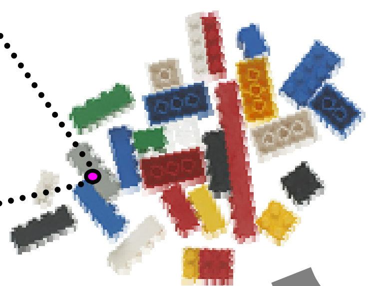
more or less direct representation

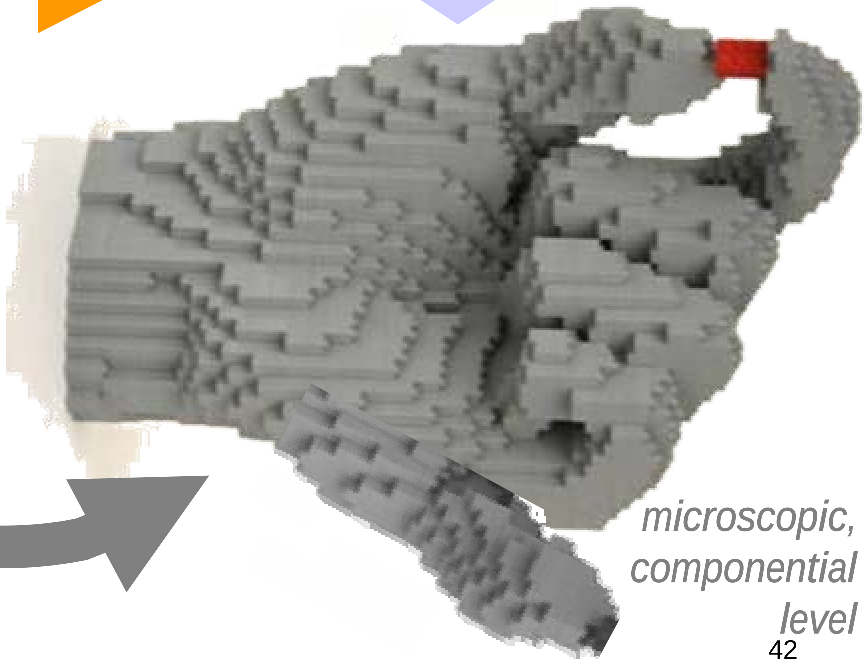
≈ () ≈

macroscopic, emergent level

Genotype — “Transformation” → Phenotype

generic elementary rules of **self-assembly**



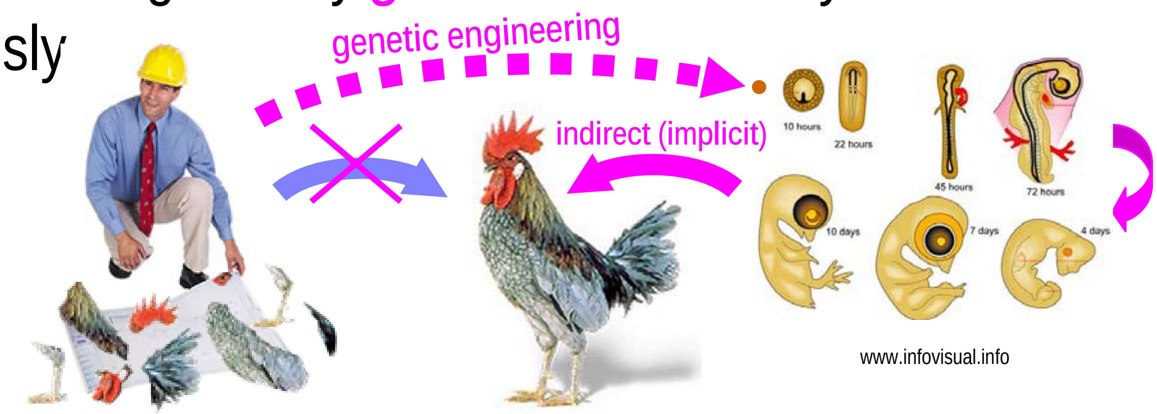


microscopic, componential level

Toward “evo-devo” engineering

➢ ... and of Evolutionary Computation: toward “meta-design”

- ✓ organisms endogenously *grow* but artificial systems *are built* exogenously

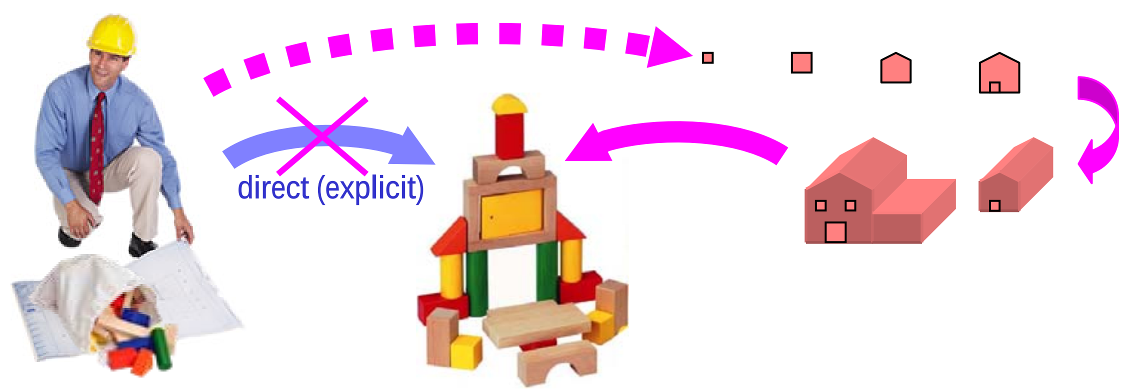


systems design

systems "meta-design"

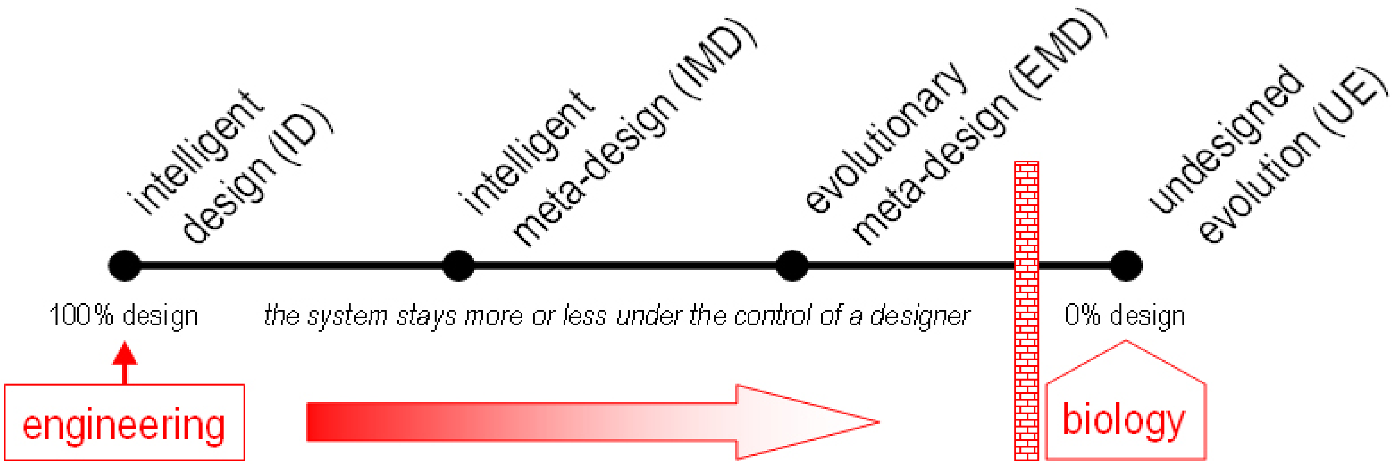
- ✓ could engineers “step back” from their creation and only set *generic* conditions for systems to self-assemble?

instead of building the system from the top (phenotype), <u>program the components</u> from the bottom (genotype)



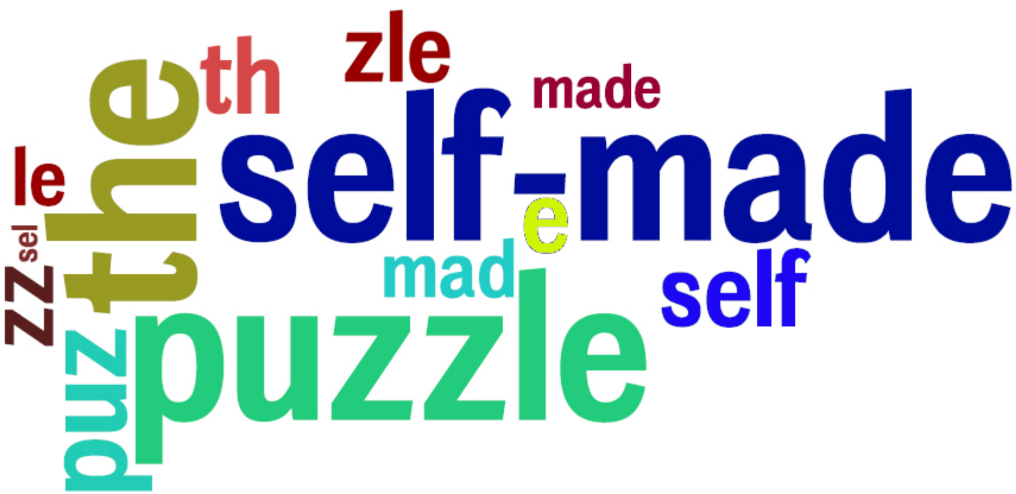
The meta-design of complexity

➢ Pushing design toward evolutionary biology



intelligent "hands-on" design		intelligent & evolutionary "meta-design"
heteronomous order	▪	autonomous order
centralised control	▪	decentralised control
designer as a micromanager	▪	designer as a lawmaker
rigidly placing components	▪	allowing fuzzy self-placement
sensitive to part failures	▪	insensitive to part failures
need to control and redesign	▪	prepare for adaptation & evolution
complicated systems: planes, computers	▪	*complex* multi-component systems

The evolutionary "self-made puzzle" paradigm



a. Construe systems as *self-assembling (developing) puzzles*

b. Design and *program their pieces* (the "genotype")

c. Let them evolve by ***variation* of the pieces** and *selection* of the architecture (the "phenotype")

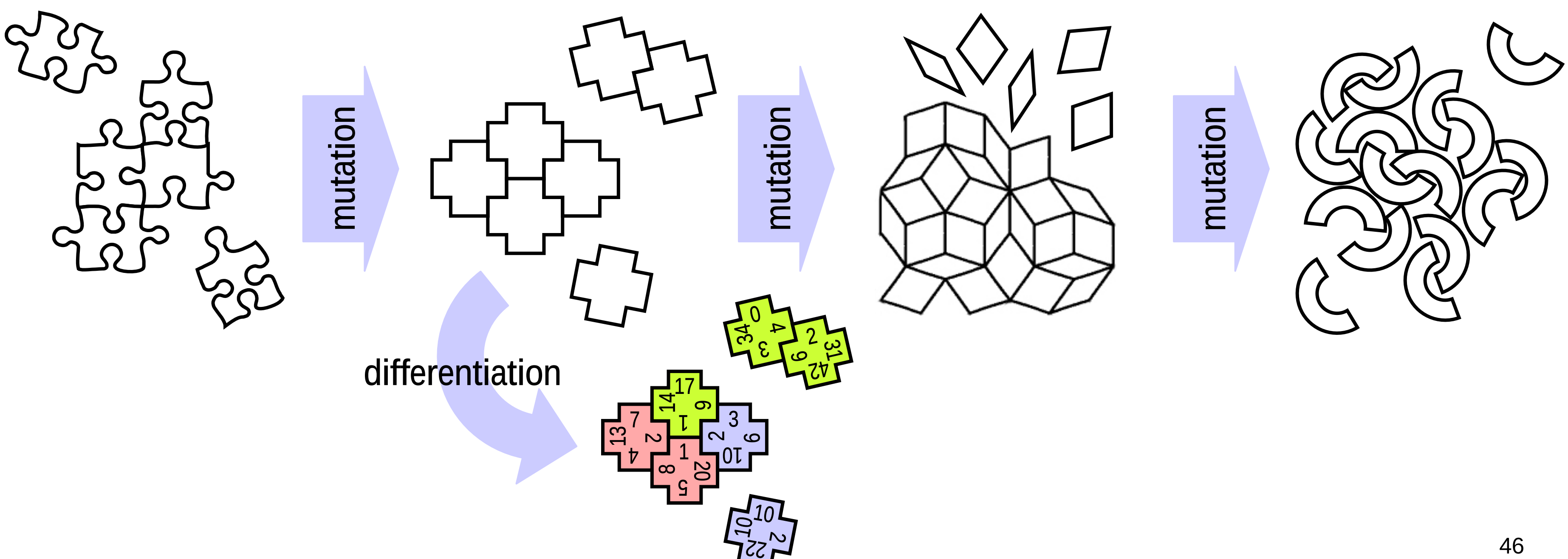
- **Genotype: rules at the *micro* level of agents**
  - ✓ ability to *search* and *connect* to other agents
  - ✓ ability to *interact* with them over those connections
  - ✓ ability to *modify* one's internal state (differentiate) and rules (evolve)
  - ✓ ability to provide a specialized local *function*
- **Phenotype: collective behavior, visible at the *macro* level**

The evolutionary “self-made puzzle” paradigm

a. Construe systems as ***self-assembling*** *(developing)* ***puzzles***

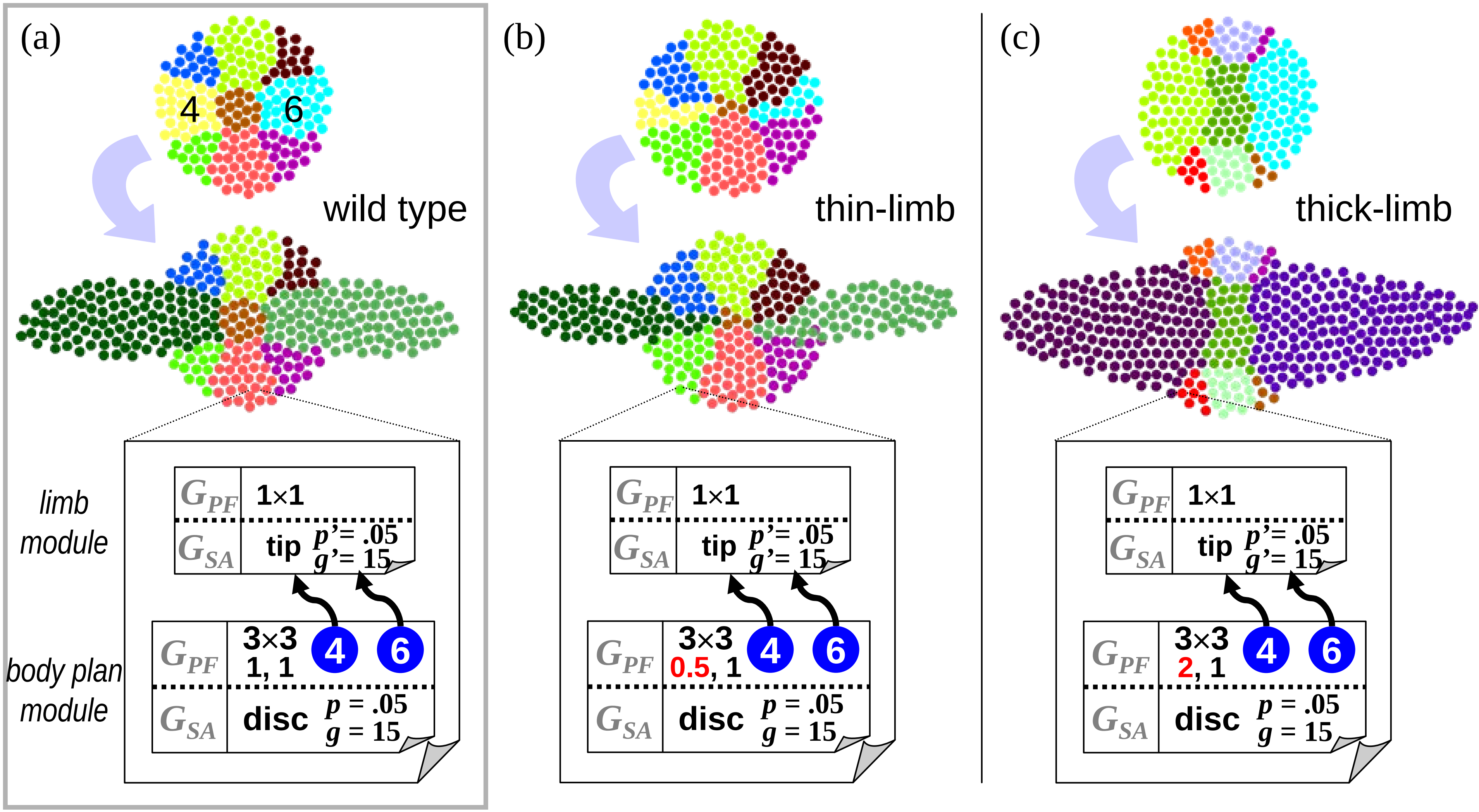
b. Design and ***program their pieces*** (the “genotype”)

c. Let them evolve by ***variation*** of the pieces and ***selection*** of the architecture (the “phenotype”)



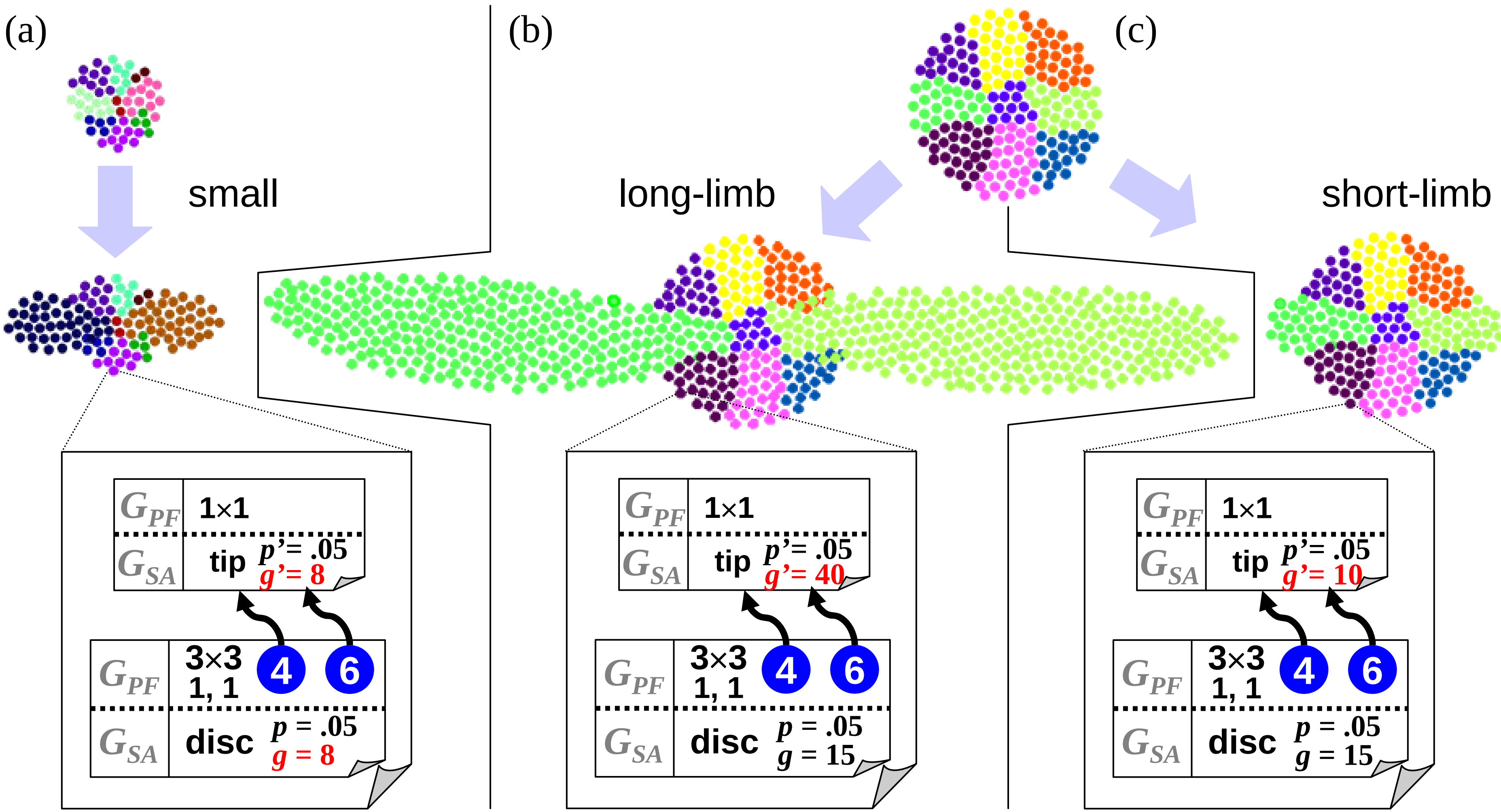
Multi-agent evolutionary development (evo-devo)

➤ Quantitative mutations: limb thickness



Multi-agent evolutionary development (evo-devo)

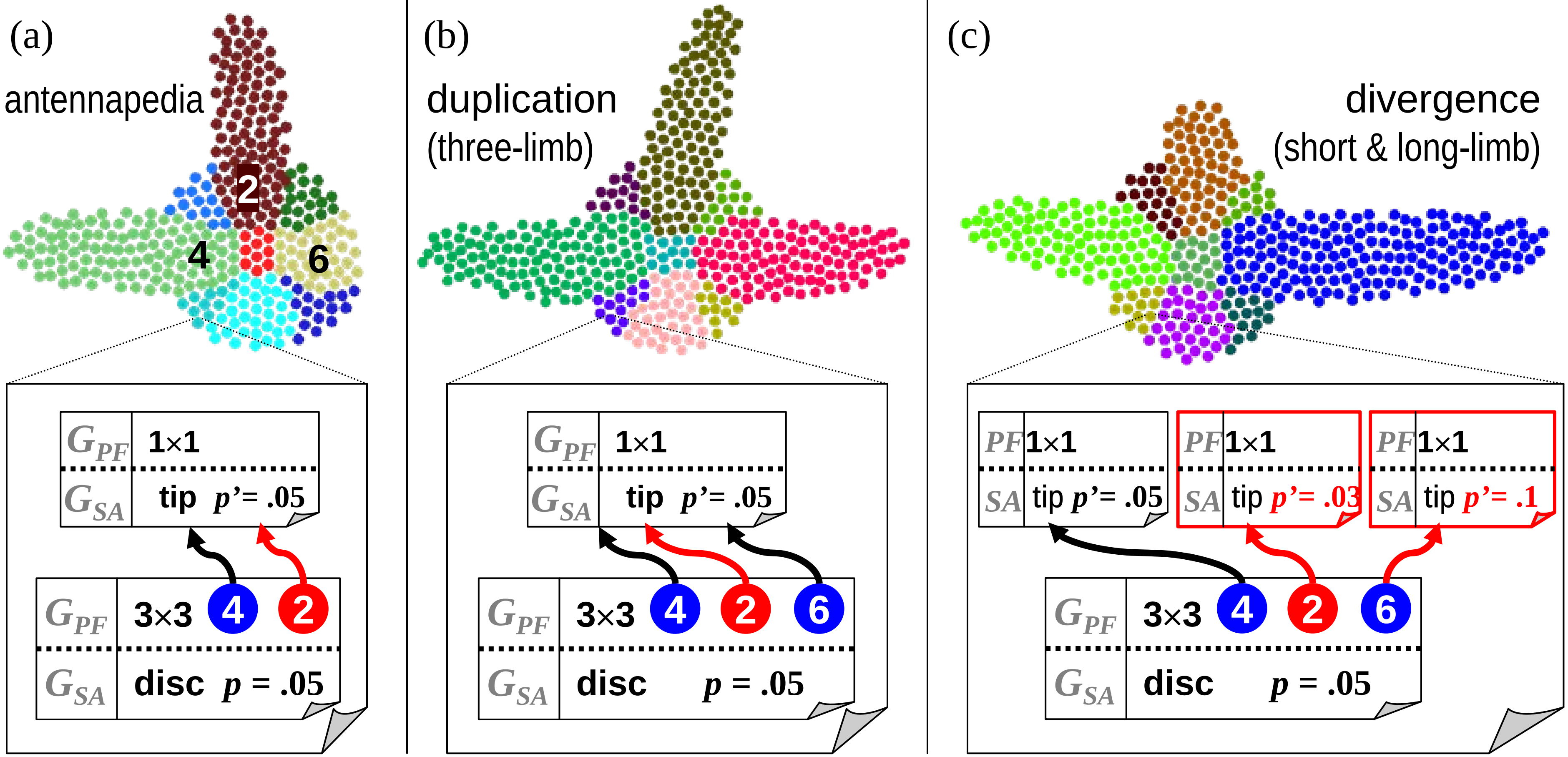
➢ Quantitative mutations: body size and limb length



Multi-agent evolutionary development (evo-devo)

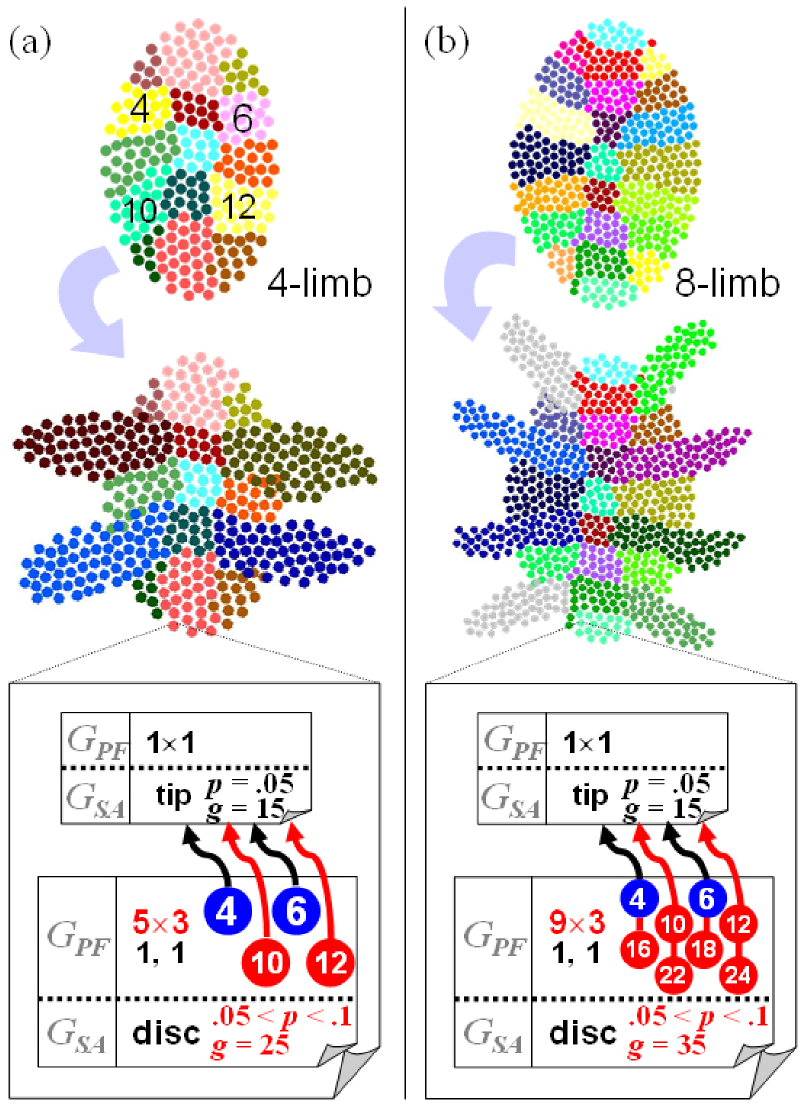
➢ Qualitative mutations: limb position and differentiation

antennapedia | *homology* by *duplication* | *divergence* of the homology



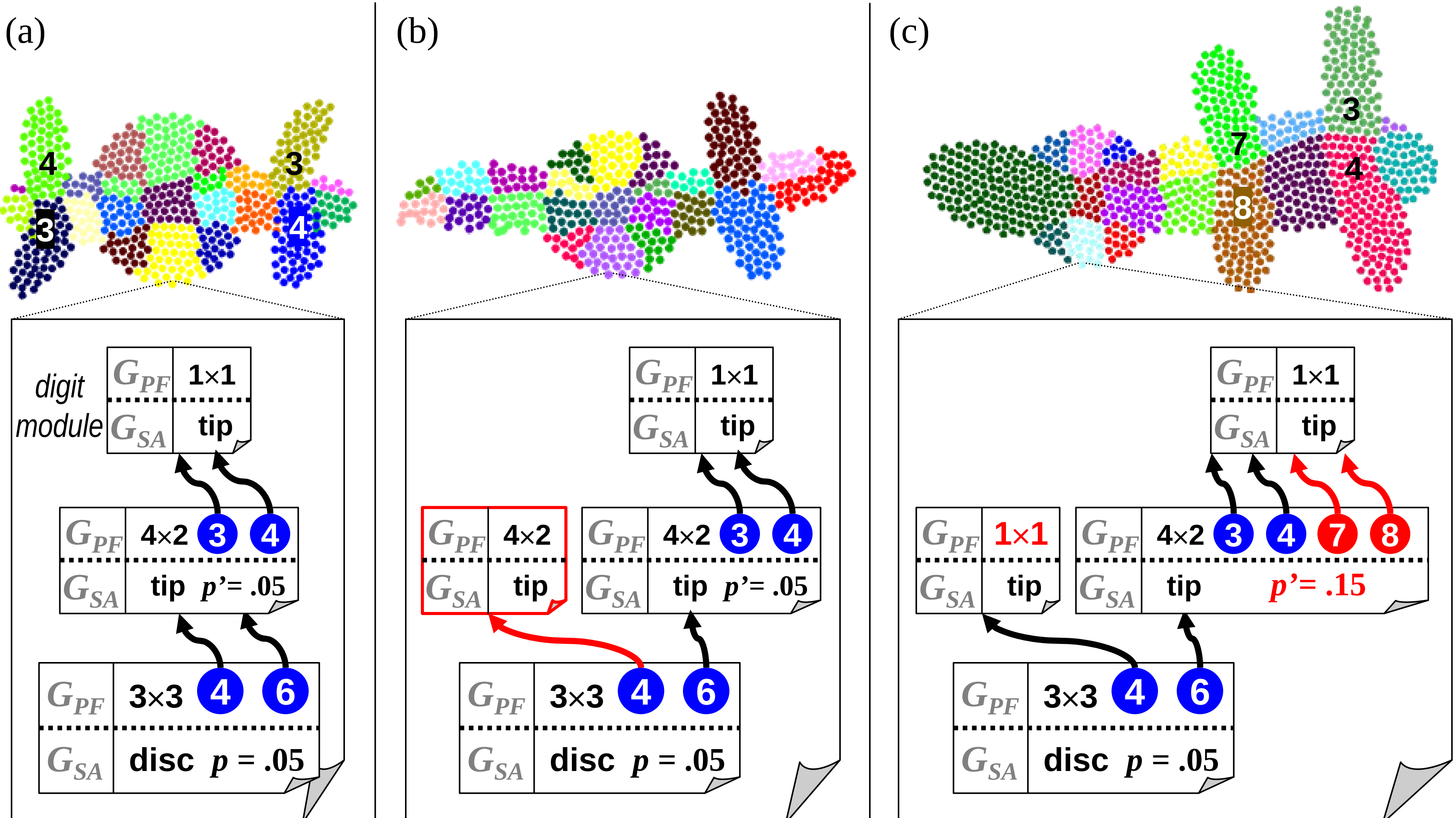
Multi-agent evolutionary development (evo-devo)

- Qualitative mutations: number of limbs



Multi-agent evolutionary development (evo-devo)

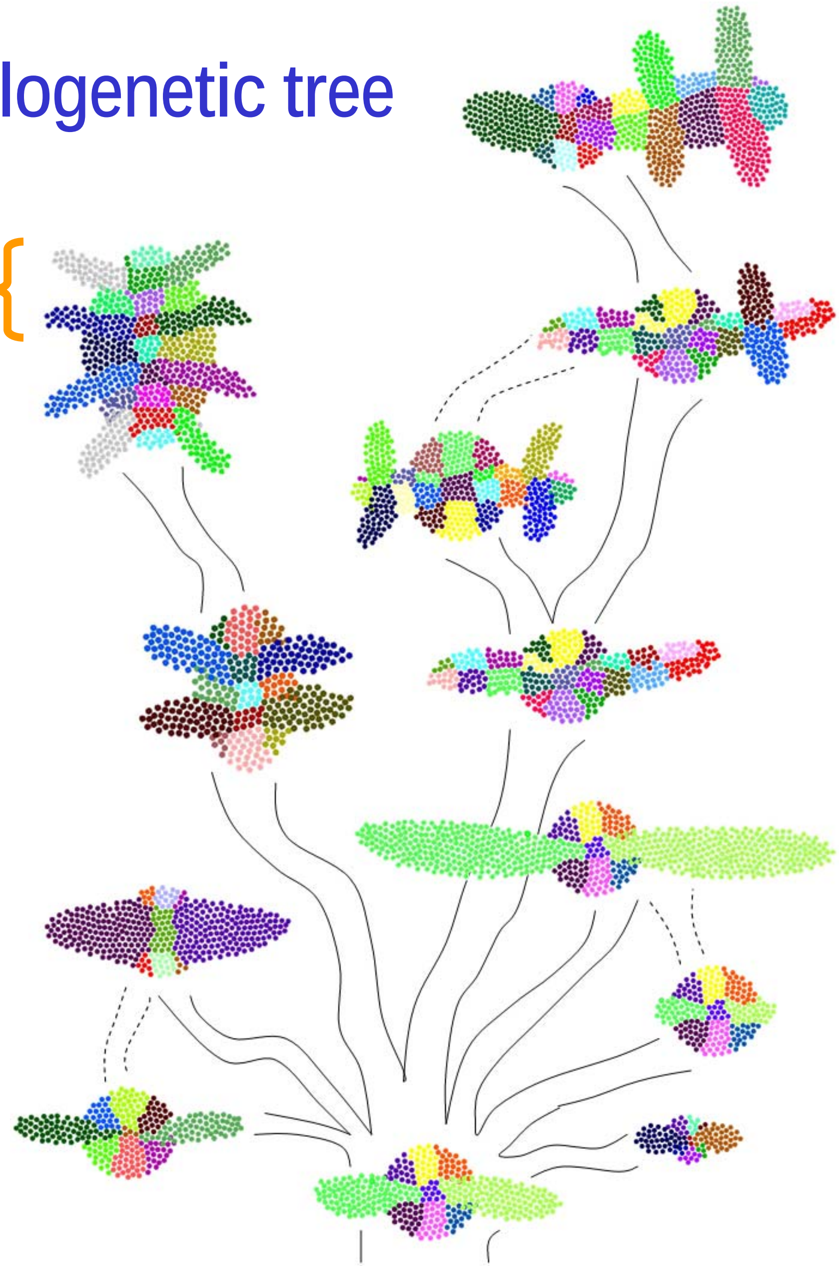
- Qualitative mutations: 3rd-level digits



Multi-agent evolutionary development (evo-devo)

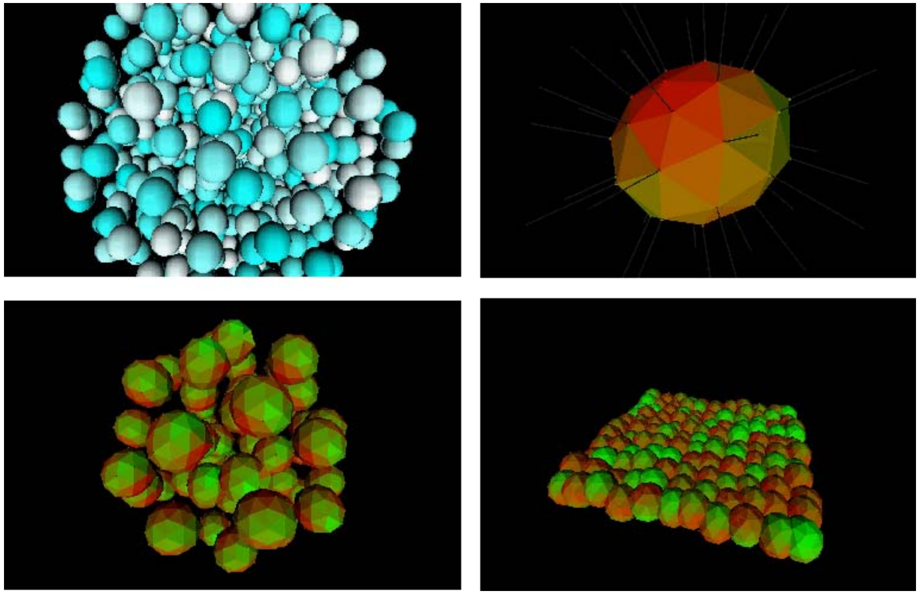
- Artificial phylogenetic tree

production of structural innovation



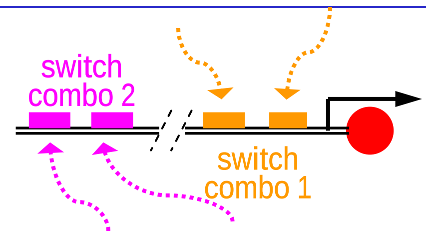
Work toward more accurate biological modeling

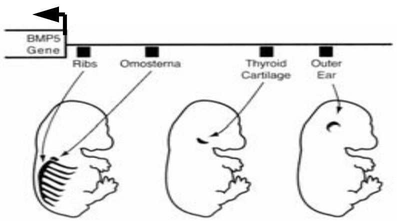
- More accurate mechanics
  - ✓ 3-D
  - ✓ individual cell shapes
  - ✓ collective motion, migration
  - ✓ adhesion



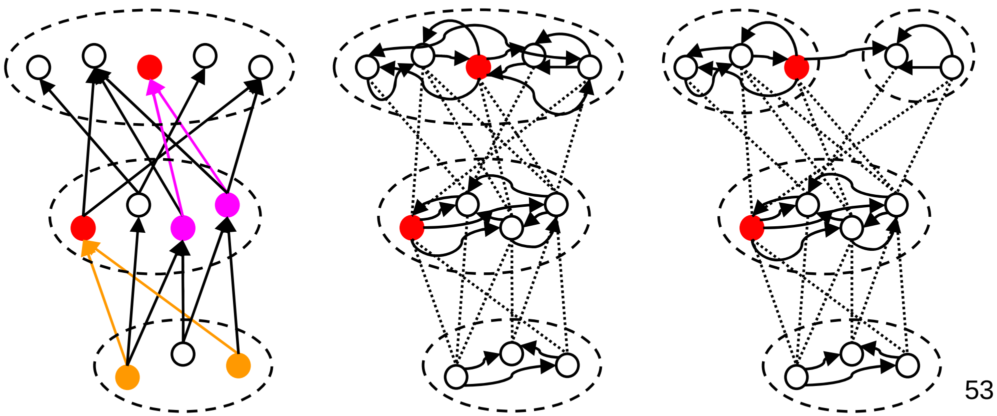
(Delille, Doursat, Peyrieras)

- Better gene regulation
  - ✓ recurrent links
  - ✓ gene reuse
  - ✓ kinetic reaction ODEs
  - ✓ attractor dynamics





after David Kingsley, in Carroll, S. B. (2005) *Endless Forms Most Beautiful*, p125



More work toward functional EC

➢ What is missing...

1. the *function/purpose/behavior* of a developed organism
   - depending on the problem domain
   - 2-D/3-D modular robotics: move, grab, build, etc.
   - N-D networks: communication dynamics, collective computation
2. a *fitness measure*
   - assessing the value of the above function
3. a *systematic exploration*
   - by random, automated mutations
   - with statistics over many runs
4. a *comparison*
   - with other, non-developmental (or non-self-organized) approaches
   - on the same problems or benchmarks

Discussion

Questions that need to be addressed...

- *modularity?*
  - modularity of the genotype vs. phenotype
- *compactness?*
  - repetitiveness: reuse of genes and gene regulation modules
  - vs. heterogeneity and uniqueness of structures
- *innovation?*
  - how fine-grained development fosters the emergence of new structures
- *open-ended evolution?*
  - don't set a specific goal, harvest from surprising organisms

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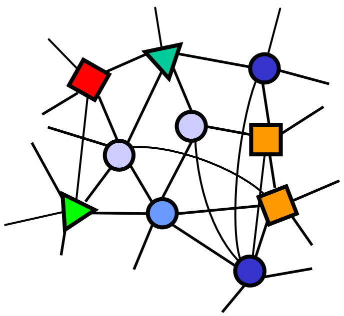
Programmable techno-social networks

➢ Harnessing complex networks

ubiquitous computing & communication capabilities create entirely *new myriads of user-device interactions* from the bottom up

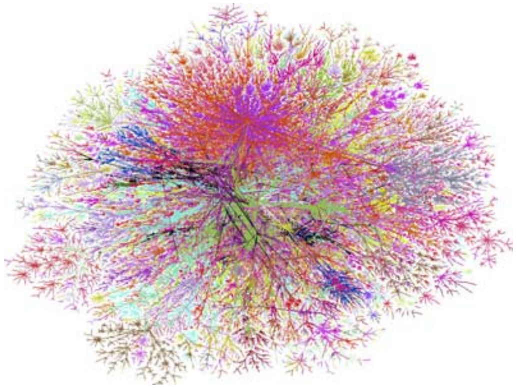


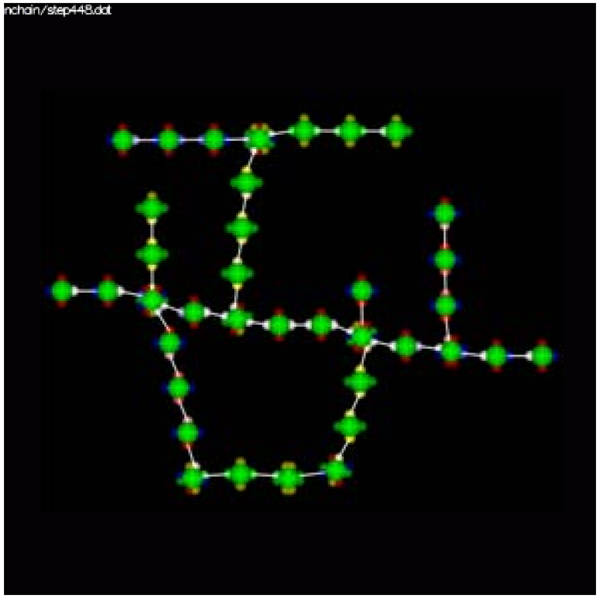
explosion in size and complexity of techno-social networks in all domains: energy, education, healthcare, business, defense

de facto complex systems with spontaneous collective behavior that we don’t quite understand or control yet

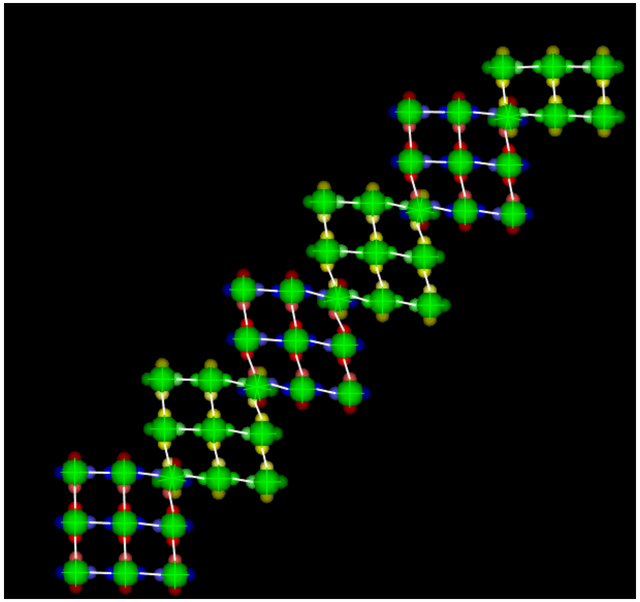
time to design new collaborative technologies to harness this decentralisation and emergence

From "scale-free" to architectured networks

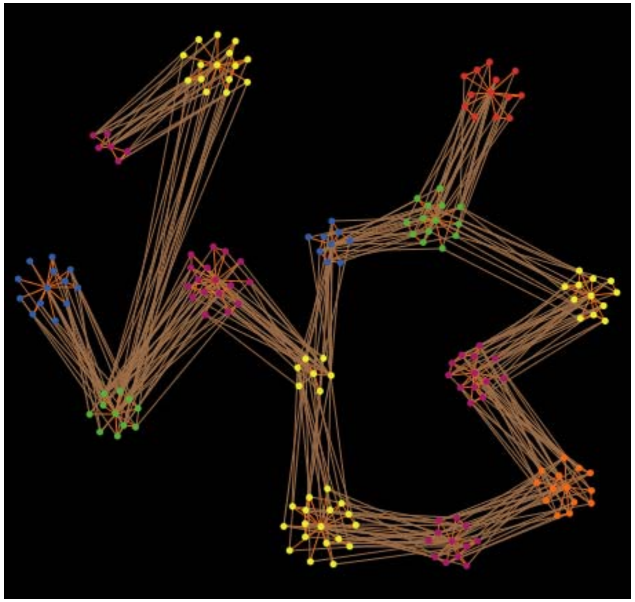




single-node
composite branching



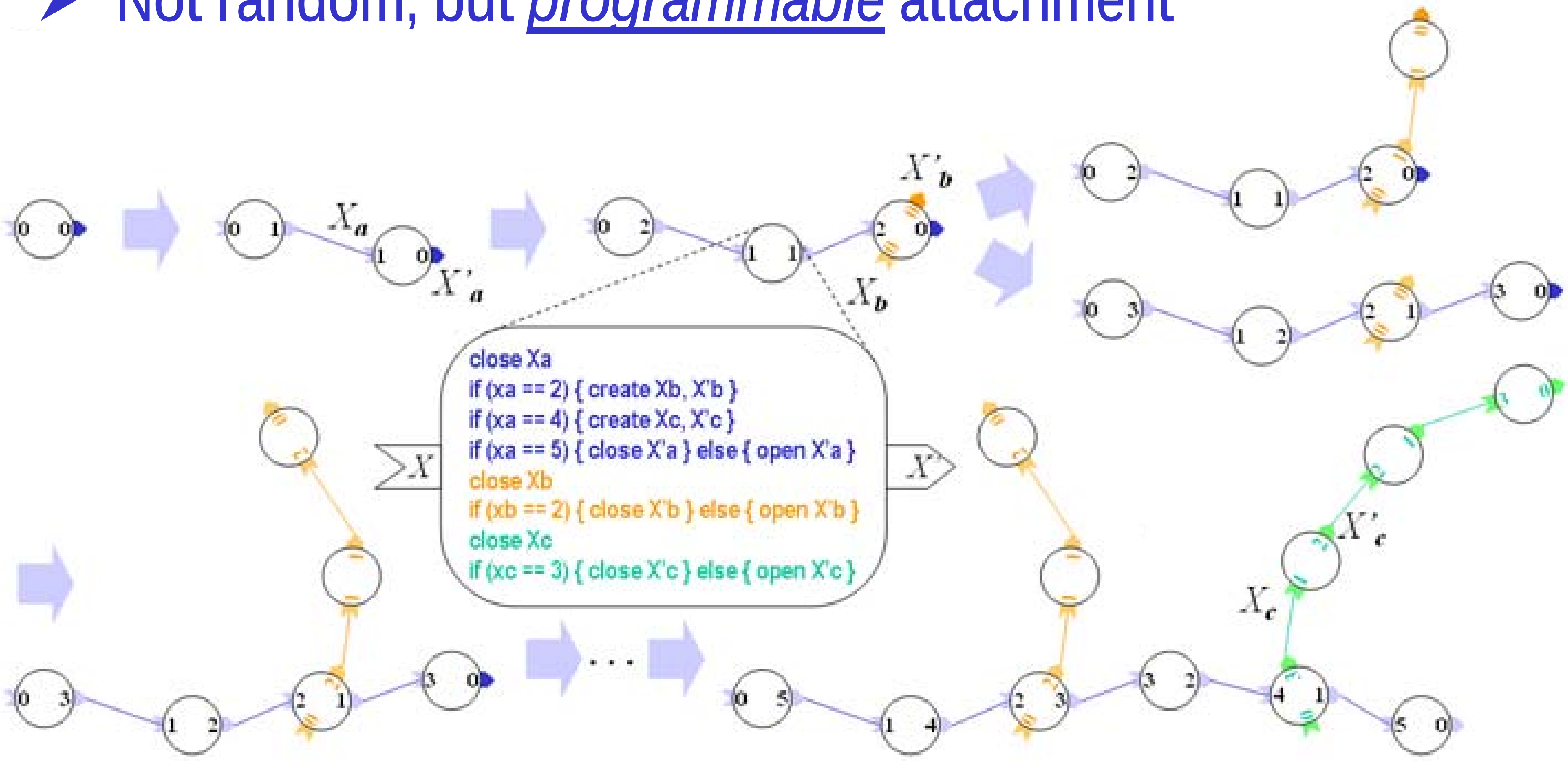
iterative lattice pile-up



clustered
composite branching

Self-knitting networks

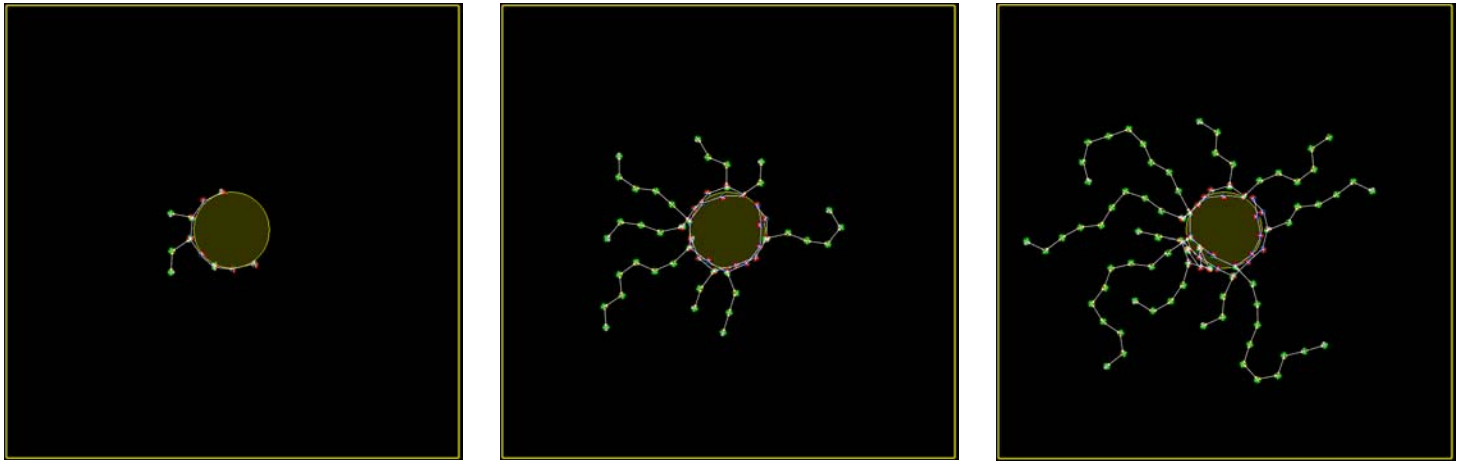
➢ Not random, but *programmable* attachment

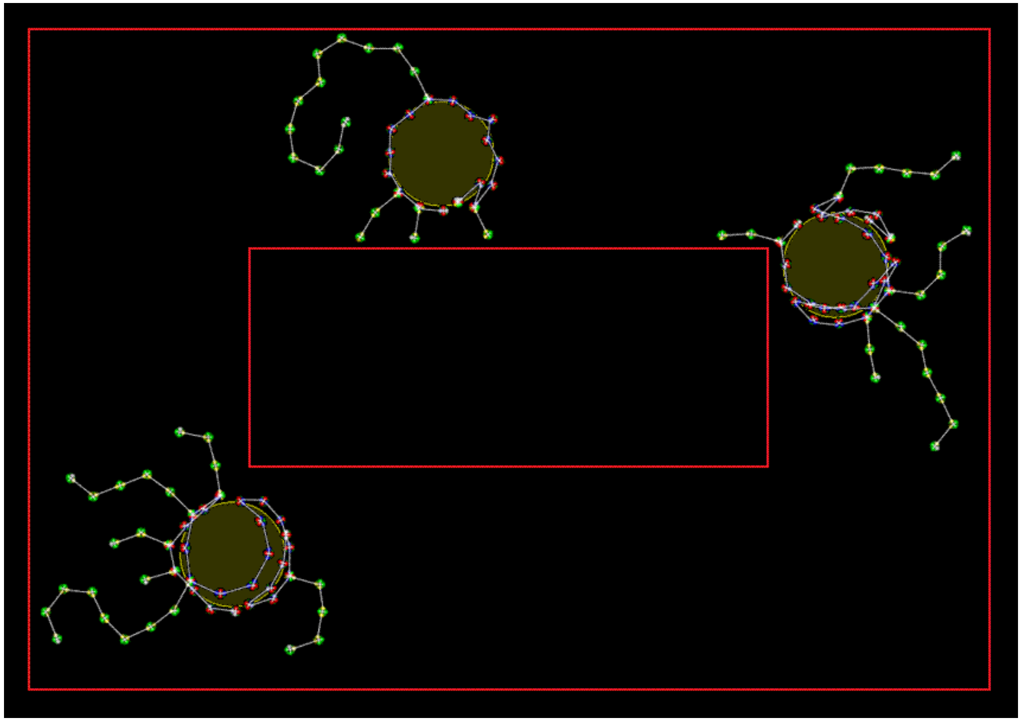


✓ a generalisation of morphogenesis in *n* dimensions

✓ the node routines are the *"genotype"* of the network

Order influenced (not imposed) by the environment

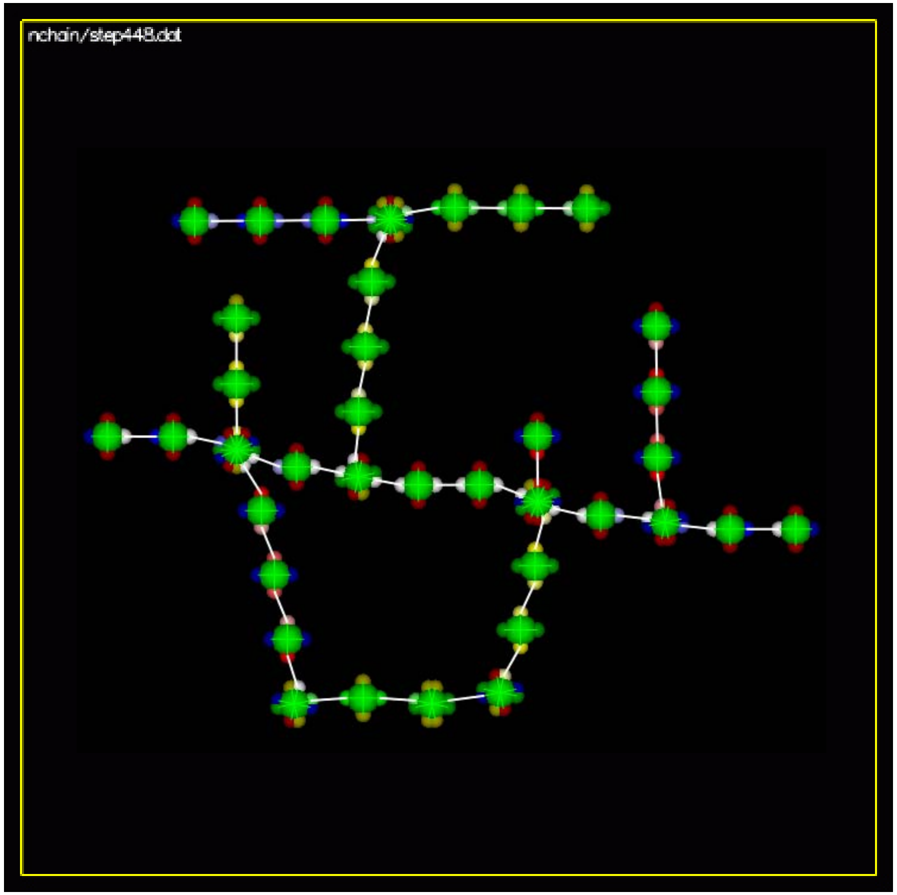




Abstract model of self-made network

➢ Formation of a specific, reproducible structure

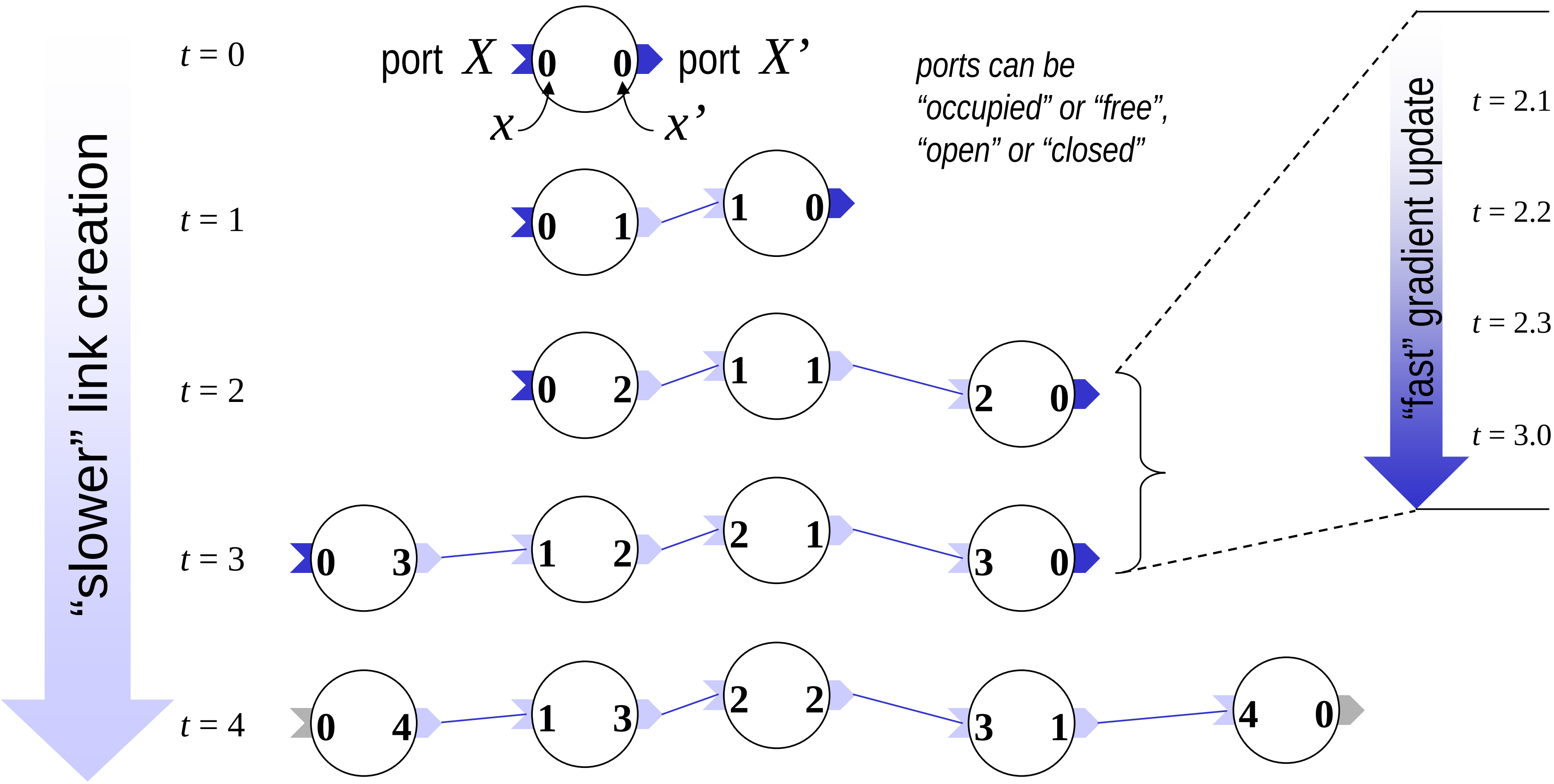
✓ nodes attach randomly, but only to a few available ports



1. Chains
2. Lattices
3. Clusters
4. Modules

Abstract model of self-made network

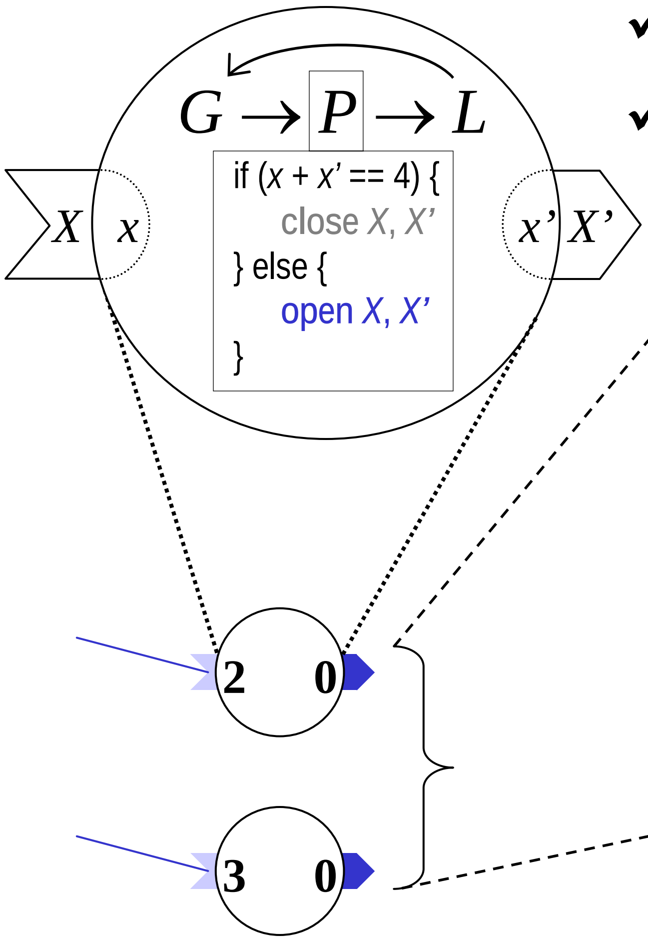
- Simple chaining
  - ✓ link creation (L) by programmed port management (P)

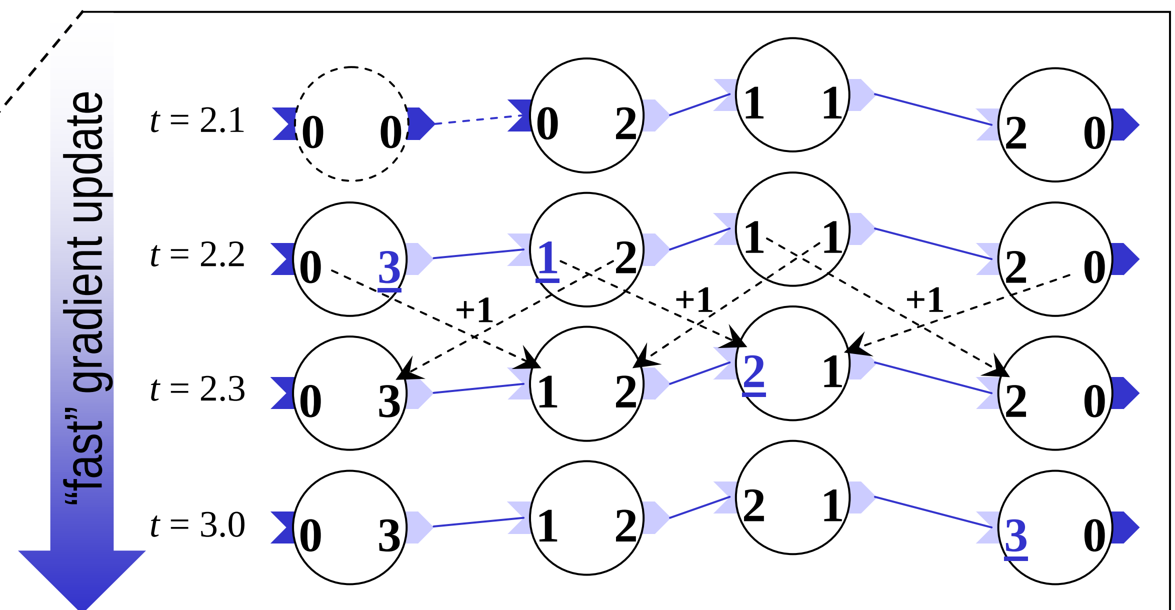


Abstract model of self-made network

Simple chaining

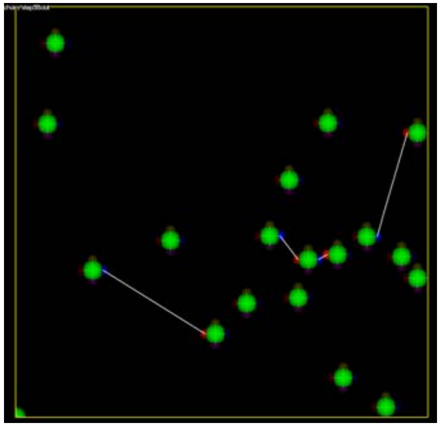
- ✓ port management (P) relies on gradient update (G)
- ✓ each node executes G, P, L in a loop
- ✓ P contains the logic of programmed attachment

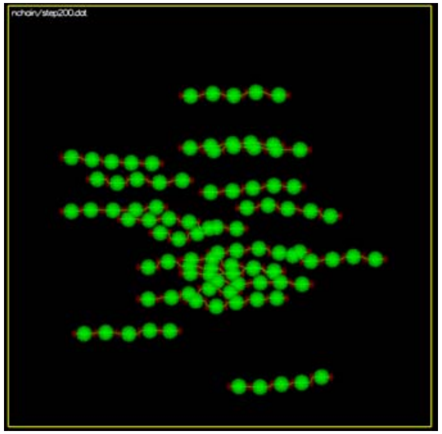




Abstract model of self-made network

- Simple chaining

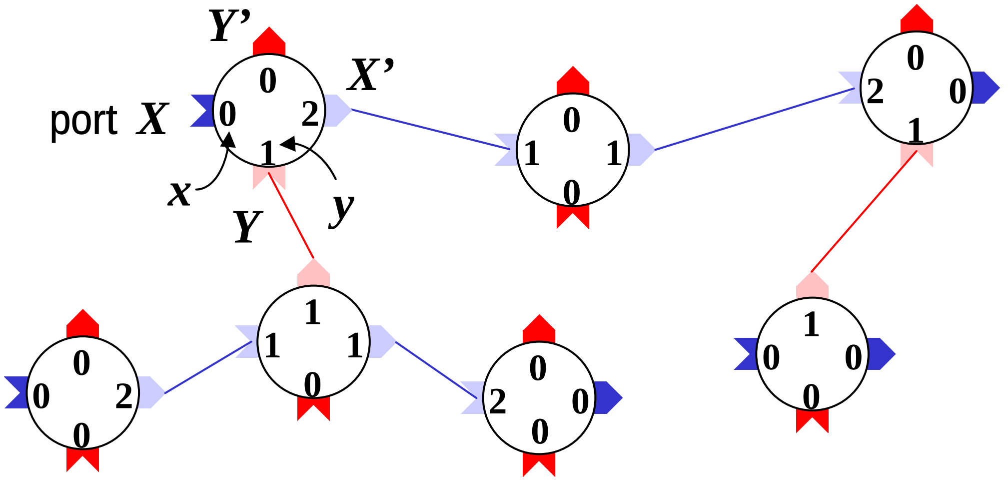




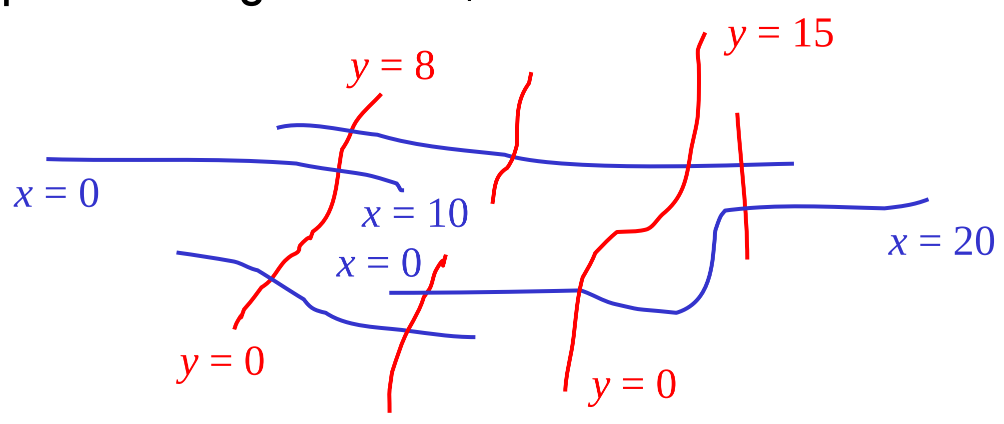
Abstract model of self-made network

➢ Lattice formation by guided attachment

- ✓ *two* pairs of ports: (X, X') and (Y, Y')

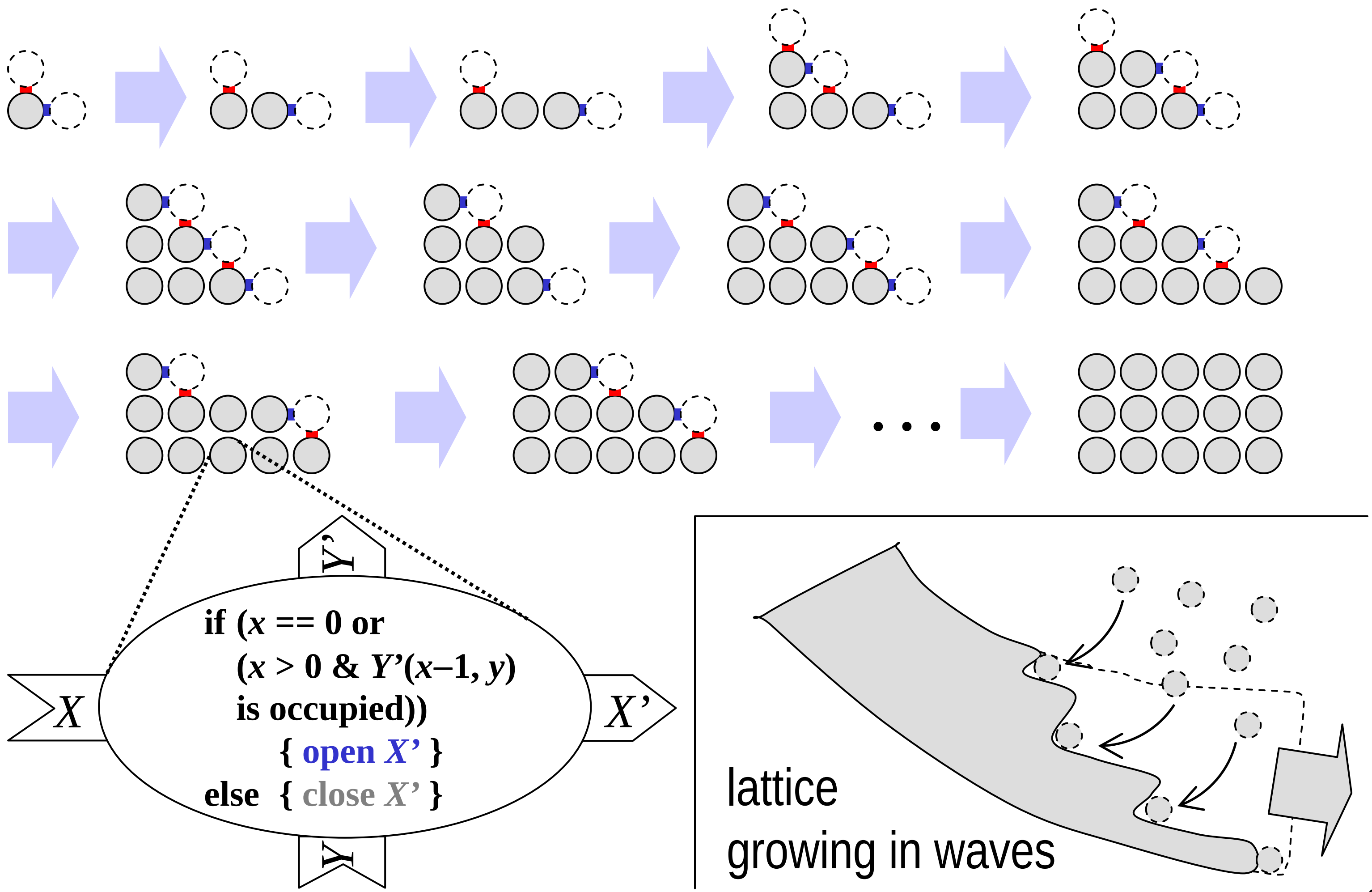


- ✓ without port management *P*, chains form and intersect randomly



Abstract model of self-made network

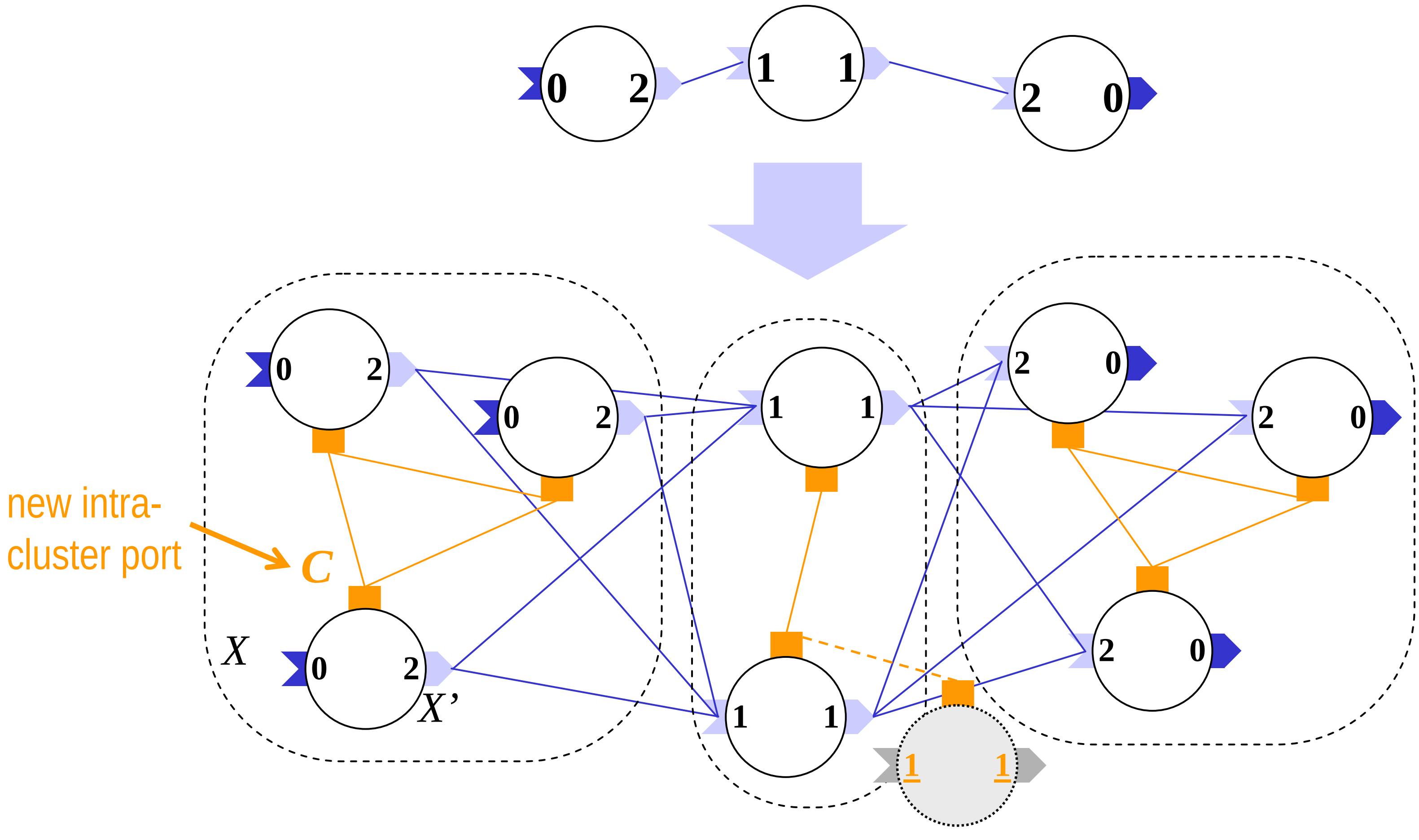
- Lattice formation by guided attachment
  - ✓ only specific spots are open, similar to beacons on a landing runway



Abstract model of self-made network

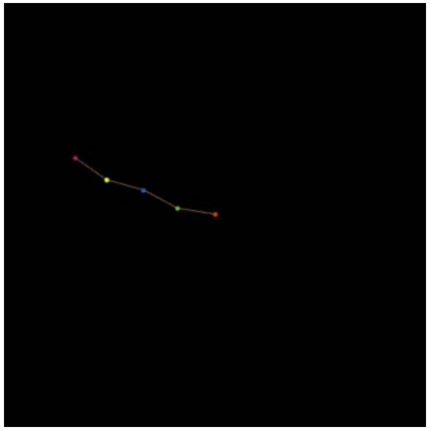
➢ Cluster chains and lattices

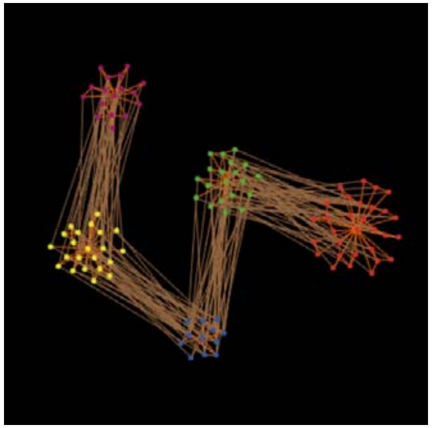
✓ several nodes per location: reintroducing randomness but only within the constraints of a specific structure



Abstract model of self-made network

- Cluster chains and lattices

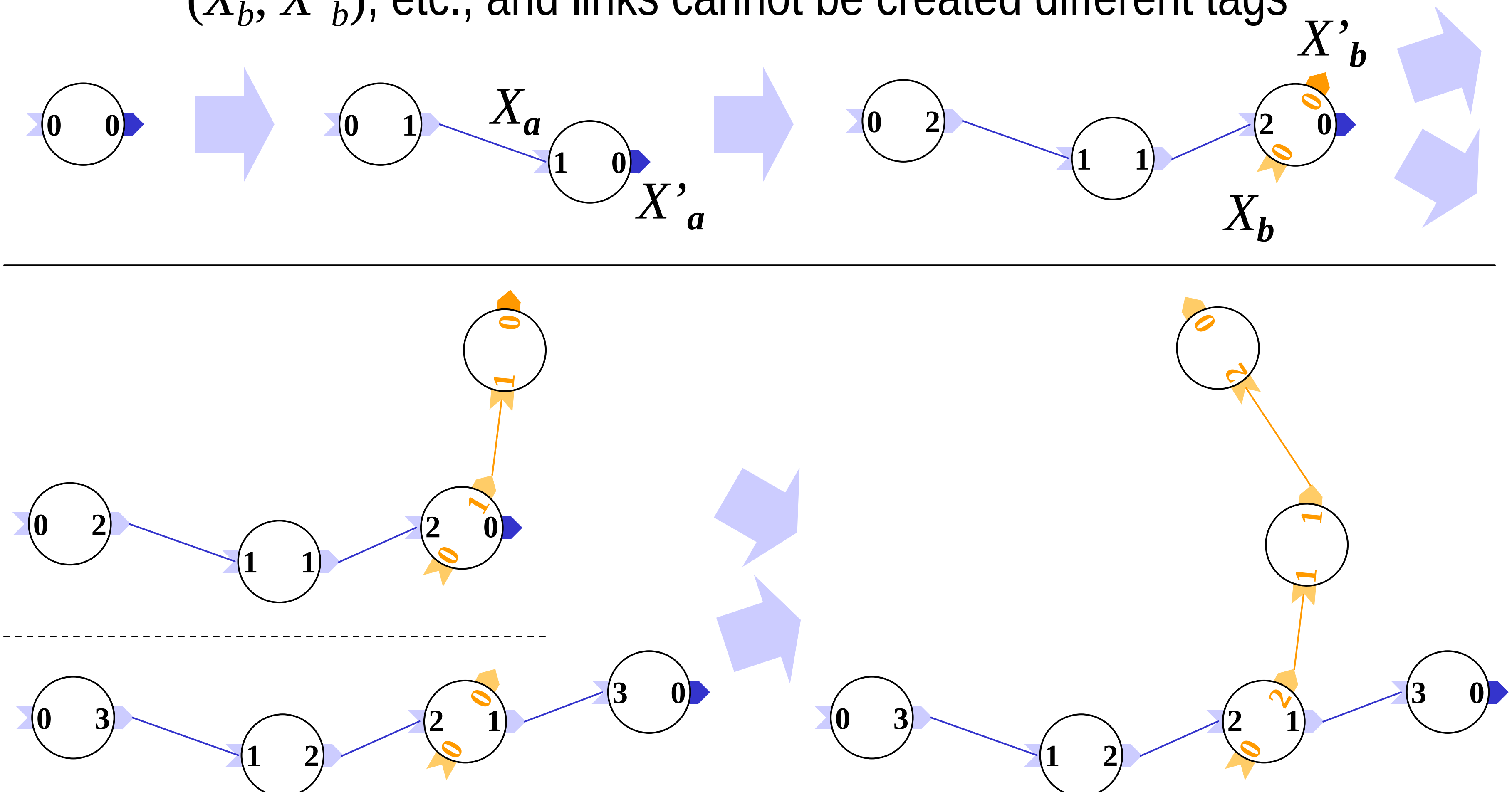




Abstract model of self-made network

➢ Modular structures by local gradients

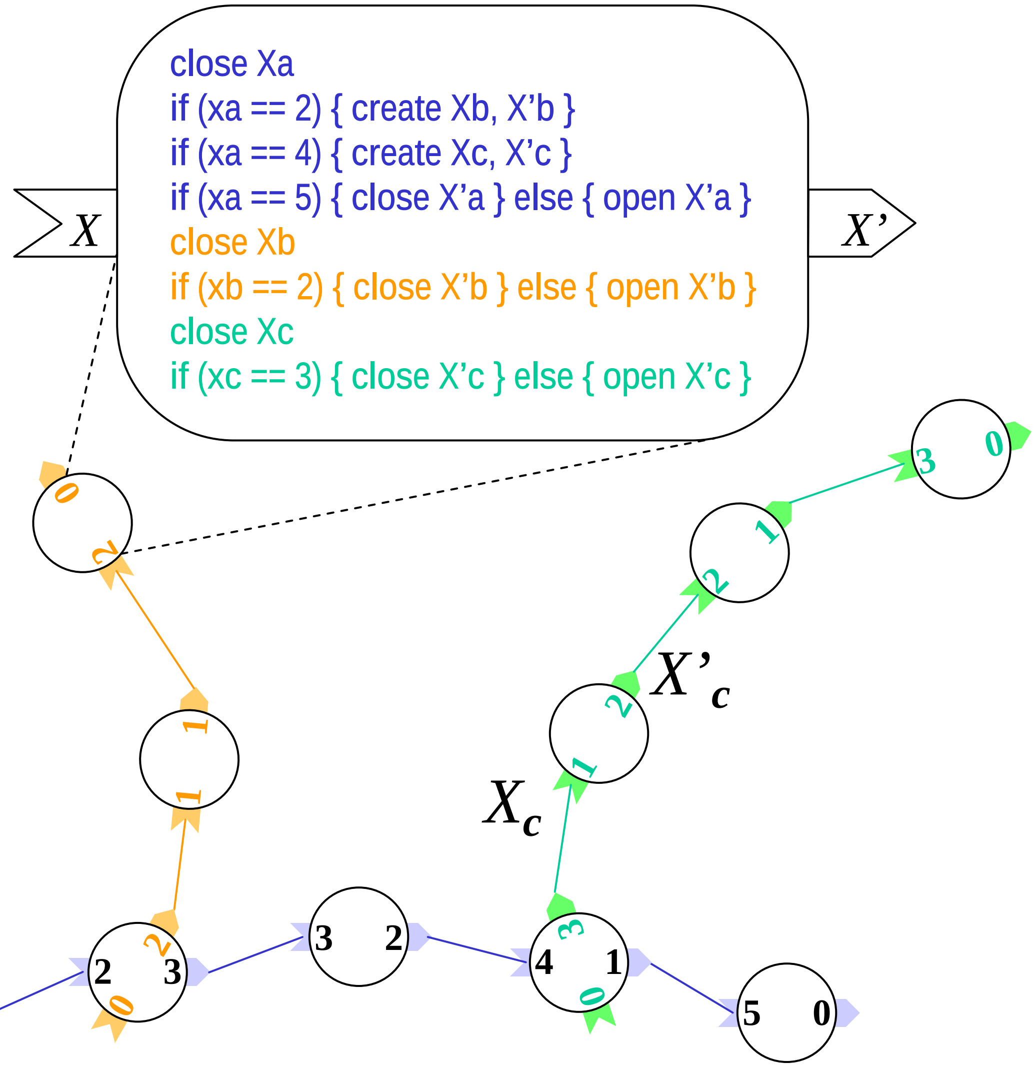
- ✓ modeled here by different coordinate systems, (X_a, X'_a), (X_b, X'_b), etc., and links cannot be created different tags

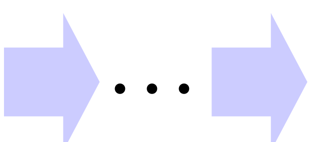


Abstract model of self-made network

➢ Modular structures by local gradients

- ✓ the node routines are the *“genotype”* of the network

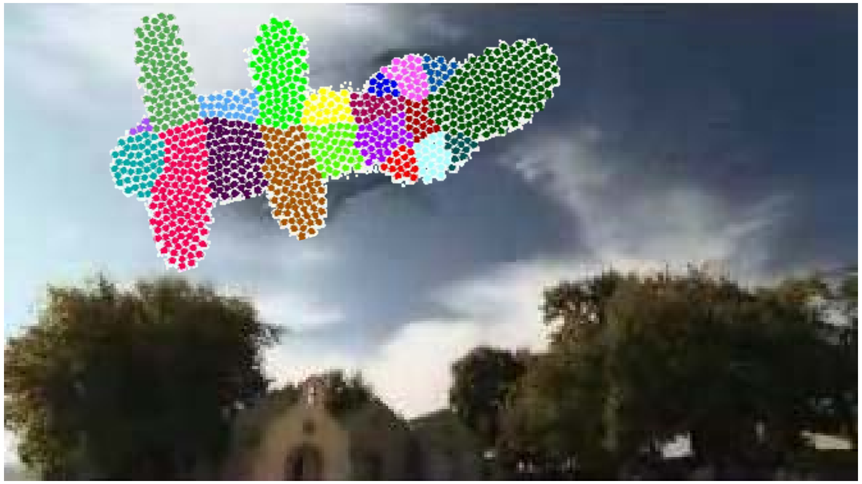




http://iridia.ulb.ac.be/ants2010

→ Special Session on Morphogenetic Engineering

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



Thank you

Facilitating evolutionary innovation by development

1. Toward self-organized *and* architectured systems

2. Biological development as a two-side challenge
   Heterogeneous motion vs. moving patterns

3. Embryomorphic engineering
   Morphogenesis as a multi-agent self-assembly process

4. Evo-devo engineering
   Evolutionary innovation by development

5. Extension to self-knitting network topologies