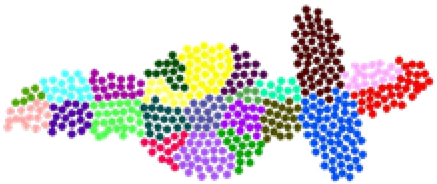
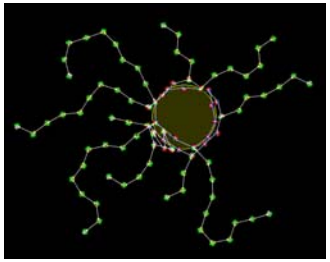


Embryomorphic Engineering:



From biological development to self-organized computational architectures

René Doursat

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

INSTITUT DES SYSTEMES COMPLEXES
PARIS ÎLE DE FRANCE

Systems that are self-organized *and* architectured

free self-organization

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

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

Peugeot Picasso

(evolutionary) design

make components evolve

decompose the system

Peugeot Picasso

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

---

➢ Architectured systems

- ✓ true *intrinsic structure*: 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

Embryomorphic Engineering

1. Toward self-organized *and* architectured systems

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

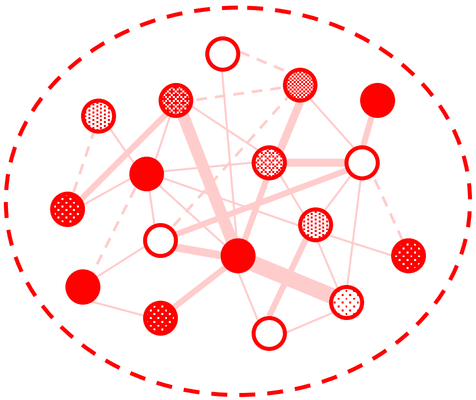
3. Embryomorphic engineering
   Morphogenesis as a multi-agent self-assembly process

4. Evo-devo engineering
   Evolutionary innovation by development

5. Extension to self-knitting network topologies

INSTITUT DES SYSTEMES COMPLEXES

Complex systems in many domains

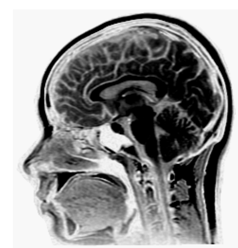


- large number of elementary **agents** interacting **locally**
- simple individual behaviors creating a complex **emergent** collective behavior
- *decentralized dynamics: no master blueprint or grand architect*

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

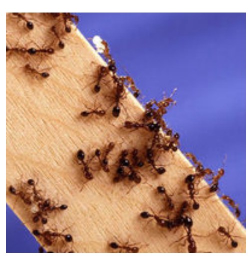
pattern formation
○ = matter

biological development
○ = cell

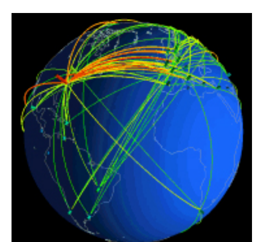


the brain & cognition
○ = neuron

insect colonies
○ = ant



Internet & Web
○ = host/page



social networks
○ = person

CS in geographical space (F)

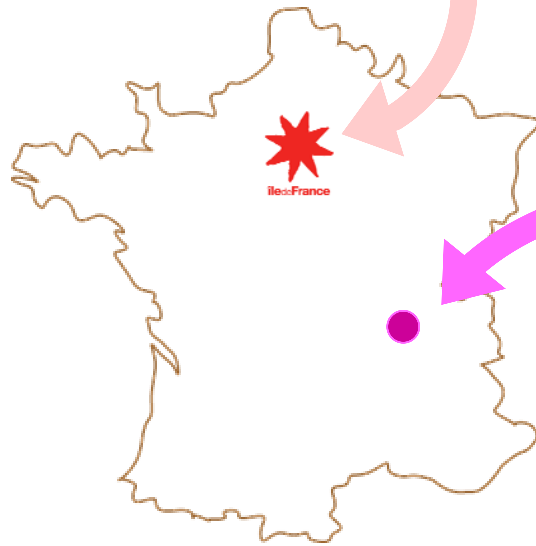
INSTITUT DES SYSTEMES COMPLEXES

Paris Ile-de-France

4th French Complex Systems Summer School, 2010

RNSC

National



IXXI

Lyon Rhône-Alpes

CS in conceptual space: 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 and engineering?*

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, statistics: large-scale properties of systems

- graph theory & networks
- statistical physics
- agent-based modeling
- distributed AI systems

COMPLEX SYSTEMS

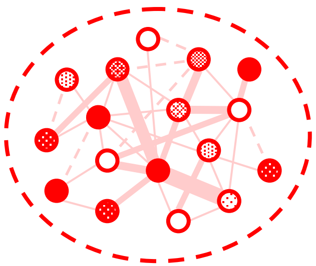
Emergence

- The system has properties that the elements do not have
  - ✓ ex: micro units form macro patterns: rolls, spiral waves, stripes, spots
  - ✓ ex: “ignorant” individuals make intelligent collective decisions: insect colonies, neurons, market traders(?)
- These properties cannot be easily inferred or deduced
  - ✓ ex: liquid water or ice emerging from H_2O molecules
  - ✓ ex: cognition and consciousness emerging from neurons
- Different properties can emerge from the same elements/rules
  - ✓ ex: the same molecules of water combine to form liquid or ice crystals
  - ✓ ex: the same cellular automaton rules change behavior with initial state
- Global properties make local (sophisticated) rules at a higher level
  - → *jumping from level to level through emergence*
- Counter-examples of emergence without self-organization
  - ✓ ex: well-informed leader (orchestra conductor, military officer)
  - ✓ ex: global plan (construction area), full instructions (orchestra)

From natural to engineered emergence (and back)

➢ The challenges of complex systems (CS) research

Transfers
- among systems



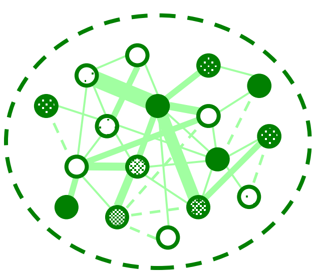
CS science: *understanding & modeling "natural" CS*

(spontaneously emergent, including human-made):

morphogenesis, neural dynamics, cooperative co-evolution, swarm intelligence

Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

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



CS engineering: *designing a new generation of "artificial" CS*

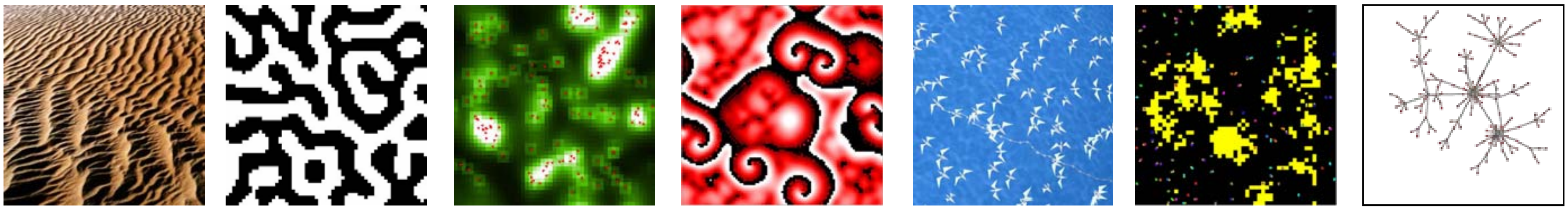
(harnessed & tamed, including nature):

collective robotics, synthetic biology, energy networks

From “statistical” to “morphological” CS

➢ Most self-organized systems form “simple”/random patterns

(a) simple/random SO: pattern formation (spots, stripes), swarms (clusters, flocks), complex networks (hubs)...



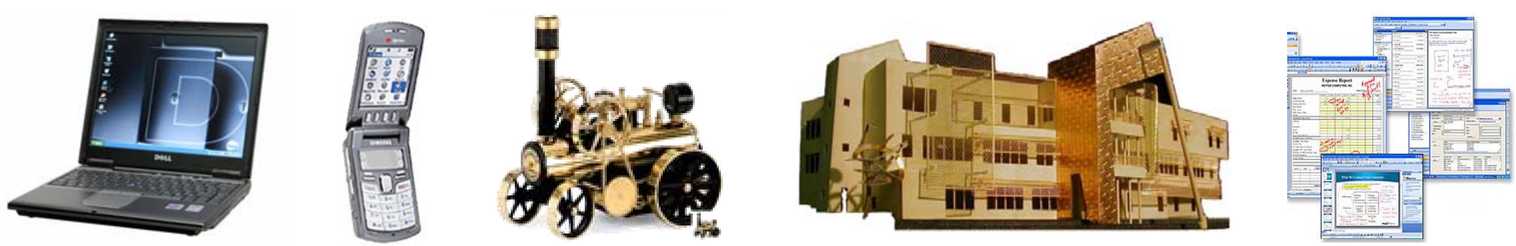
texture-like order: repetitive, statistically **uniform**, information-poor – arising from amplification of fluctuations: **unpredictable** number/position of mesoscopic entities (spots, groups) – OR **determined** by the environment (trails)

more architecture

gap to fill

... while “complicated” architectures are designed by humans

(d) direct design (top-down)



more self-organization

From “statistical” to “morphological” ... *to artificial CS*

(a) natural random self-organization

➢ the only natural emergent and structured forms are biological

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

(b) natural self-organized architectures

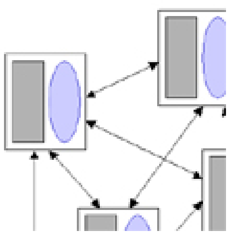
natural

MESOBIONICS

artificial

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

. . . .



. . . .

more architecture

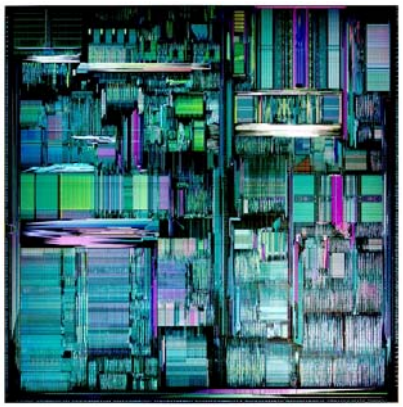
more self-organization

(d) direct design (top-down)

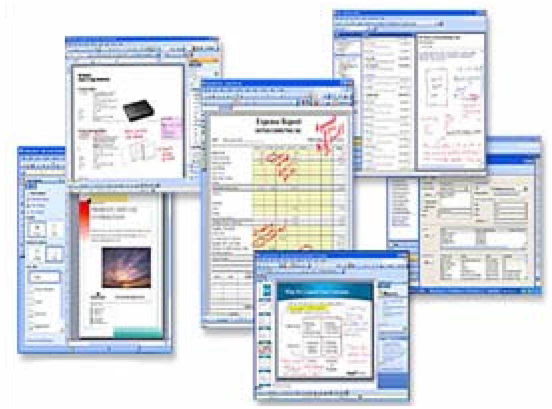
→ *can we reproduce them in artificial systems?*

De facto complexity of engineering (ICT) systems

- Ineluctable breakup into myriads of modules/components,

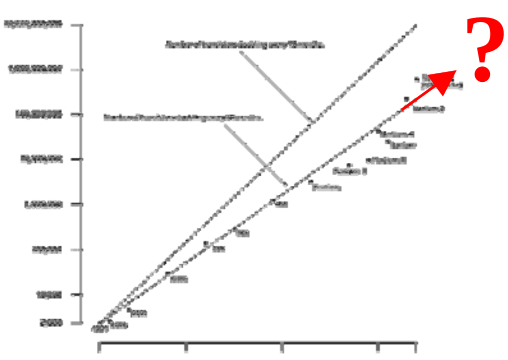


in hardware,

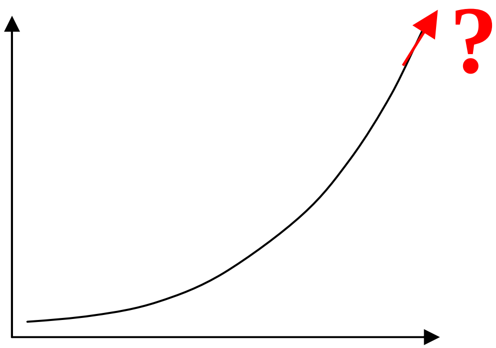


software,

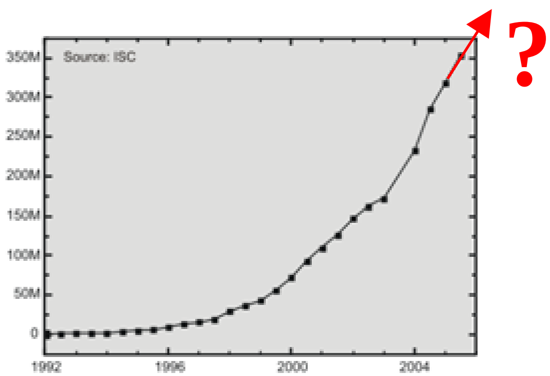
or networks, ...



number of transistors/year



number of O/S lines of code/year



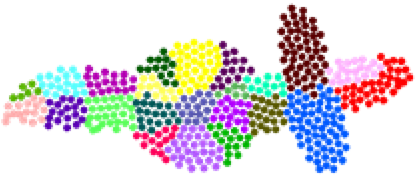
number of network hosts/year

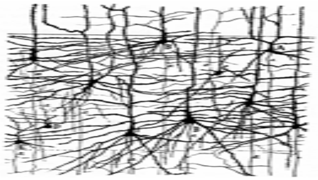
Taming complex ICT toward morphogenetic abilities

➢ Self-architecturing in natural systems → artificial systems

✓ morphogenetic abilities in biological modeling

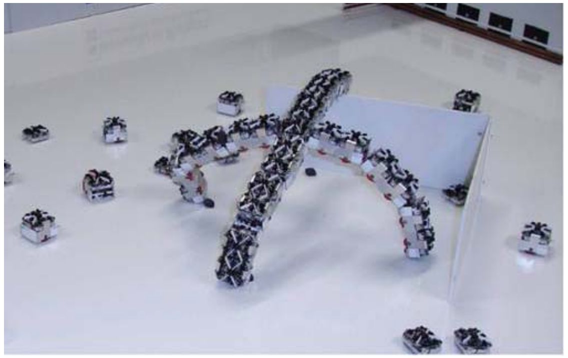
- organism development
- brain development





✓ need for morphogenetic abilities in computer science & AI

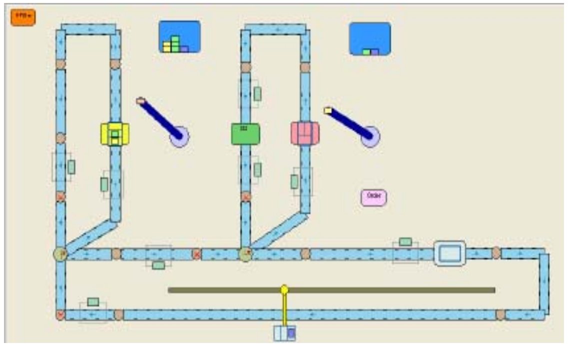
- self-forming robot swarm
- self-architecturing software
- self-connecting micro-components



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

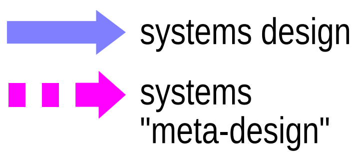


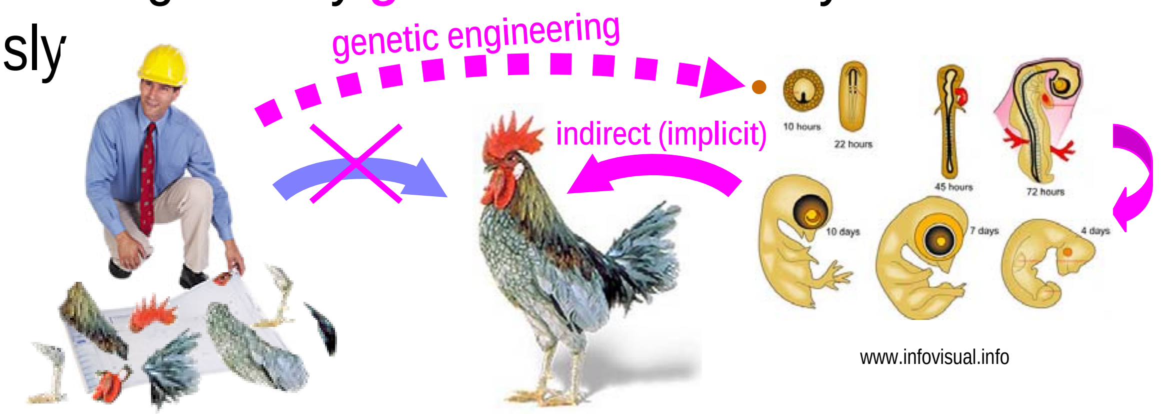
MAST agents, Rockwell Automation Research Center
{pvrba, vmarik}@ra.rockwell.com

Toward “evo-devo” engineering

➢ From design to “meta-design”

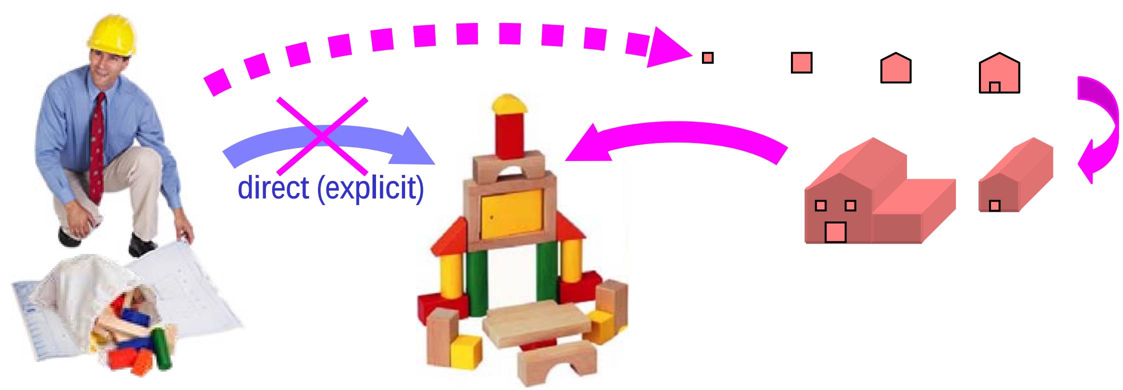
- ✓ organisms endogenously *grow* but artificial systems *are built* exogenously





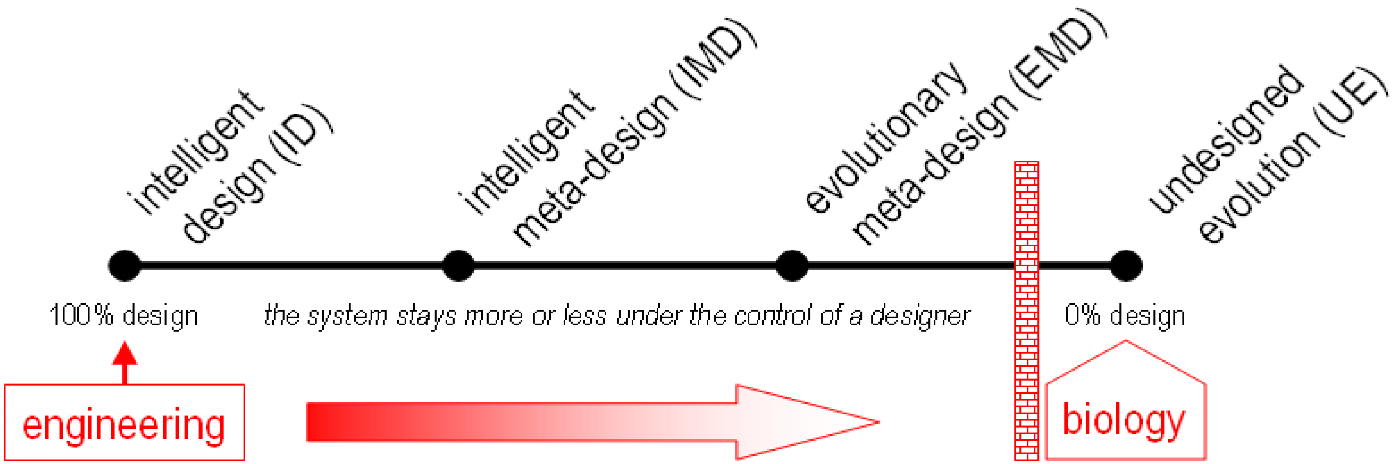
- ✓ could engineers “step back” from their creation and only set *generic* conditions for systems to self-assemble?

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")

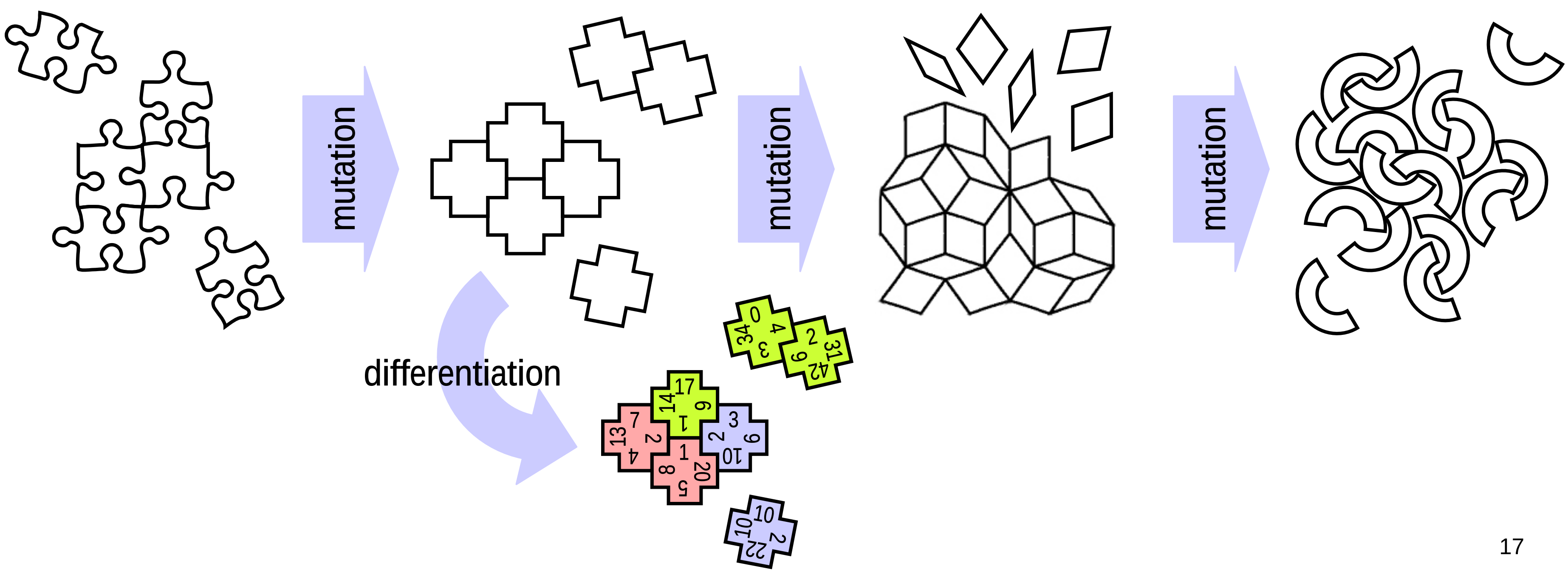
- Genotype: rules at the *micro* level of agents
  - ✓ ability to *search* and *connect* to other agents
  - ✓ ability to *interact* with them over those connections
  - ✓ ability to *modify* one's internal state (differentiate) and rules (evolve)
  - ✓ ability to provide a specialized local *function*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



Embryomorphic Engineering

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

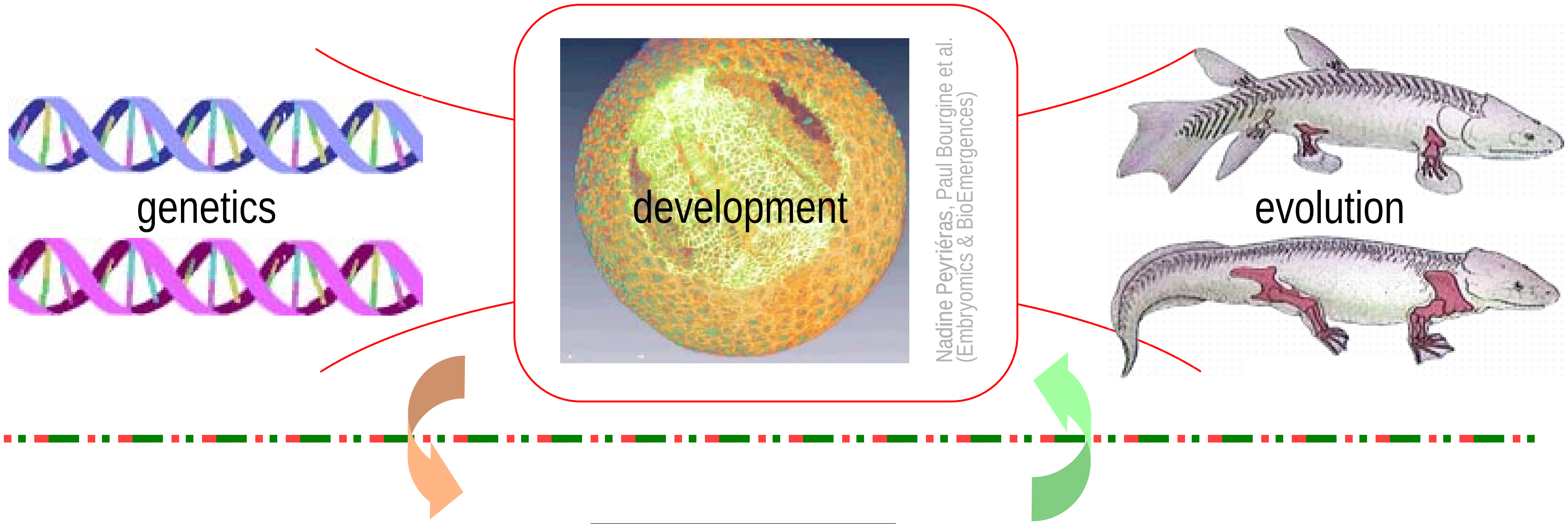
4. Evo-devo engineering
   Evolutionary innovation by development

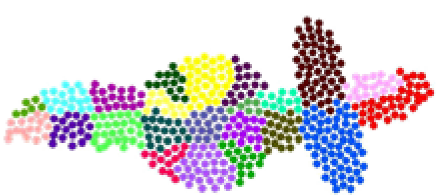
5. Extension to self-knitting network topologies

Devo-inspired engineering

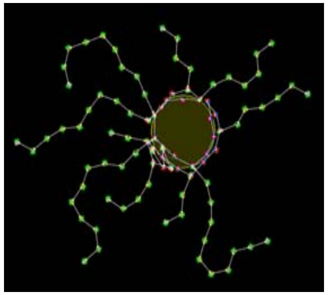
➢ Replacing biological development in the center

✓ *Computational, spatially explicit models of development and evolution with possible outcomes toward hyperdistributed, decentralized engineering systems*

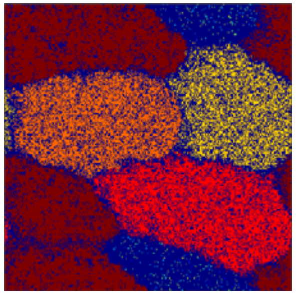




DEVO



PROGNET



EVOSPACE

From “statistical” to “morphological” CS

in social insect constructions

more intrinsic, sophisticated architecture

http://taos-telecommunity.org/epow/epow-archive/archive_2003/EPOW-030811_files/matabele_ants.jpg

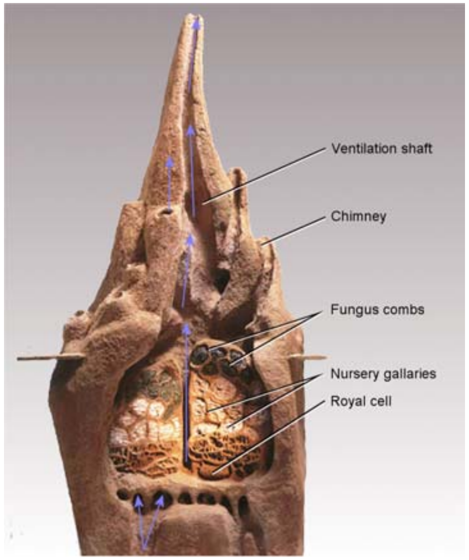
ant trail

http://picasaweb.google.com/tridentoriginal/Ghana

network of ant trails

http://www.bio.fsu.edu/faculty-tschinkel.php

ant nest

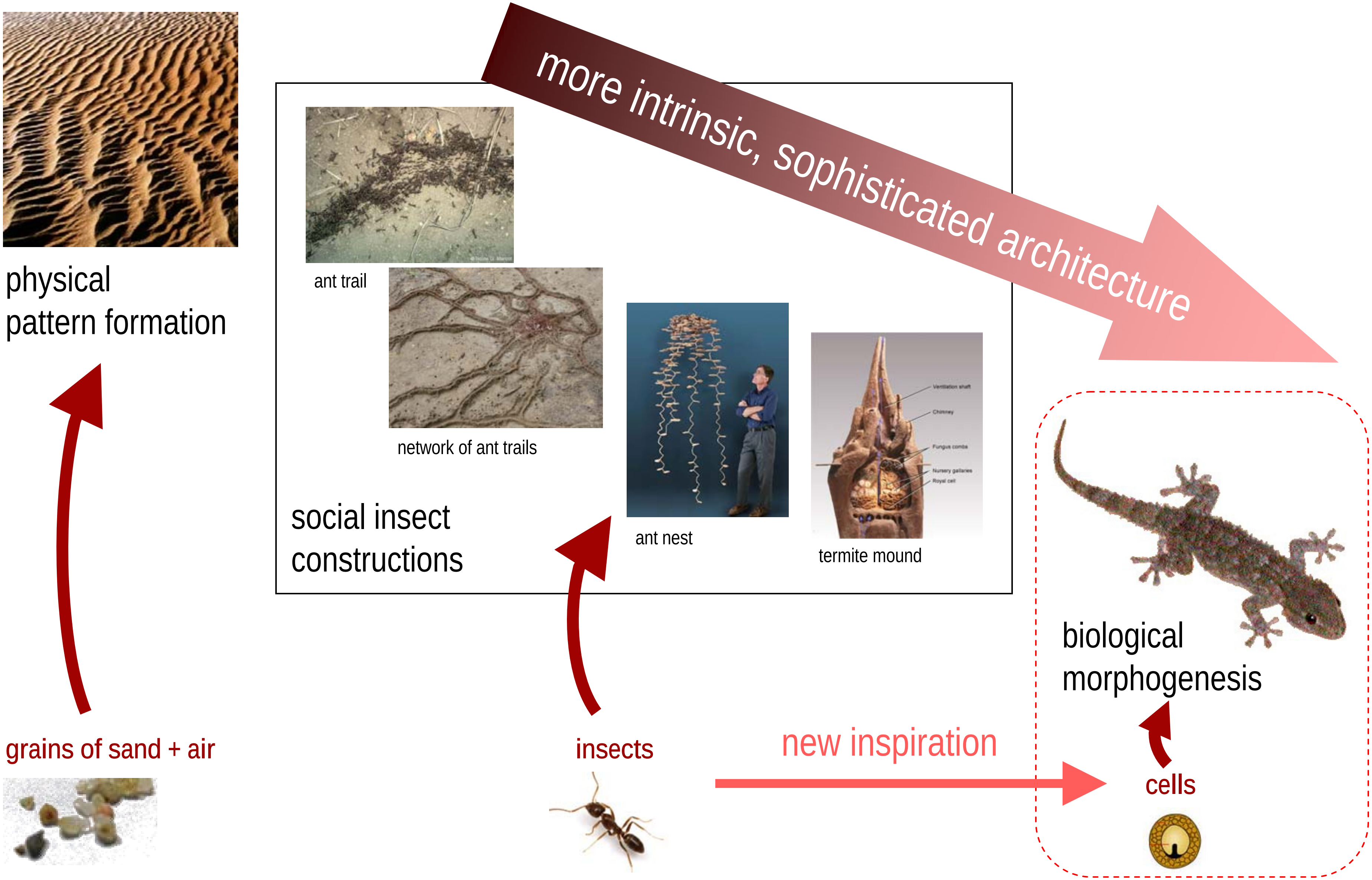


http://cas.bellarmine.edu/tietjen/TermiteMound%20CS.gif

termite mound

From “statistical” to “morphological” CS

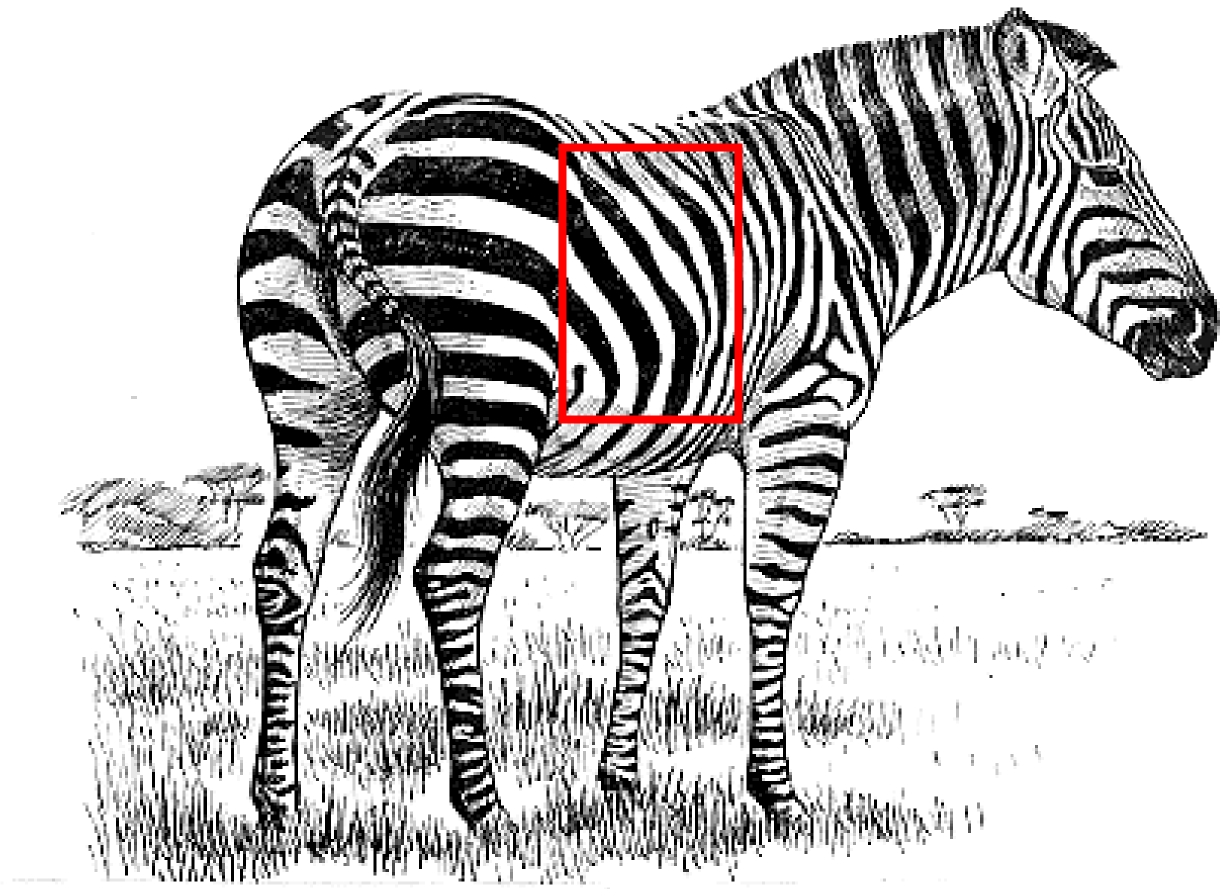
in inert matter / insect constructions / multicellular organisms



ISC PARIS ÎLE-DE-FRANCE

Morphological (self-dissimilar) systems

compositional systems: pattern formation ≠ morphogenesis

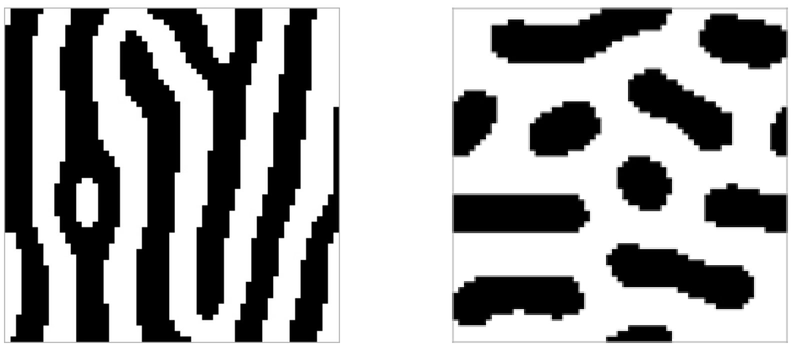


“The stripes are easy, it’s the horse part that troubles me”

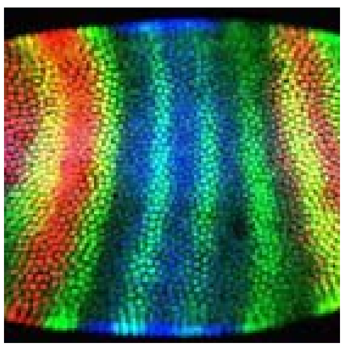
—attributed to A. Turing, after his 1952 paper on morphogenesis

From “statistical” to “morphological” CS

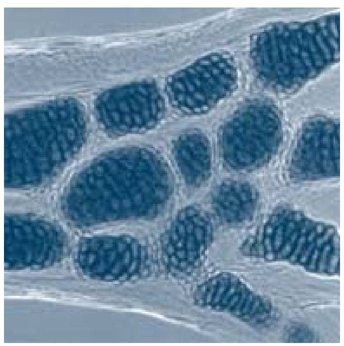
- Physical pattern formation is “free” –
  Biological (multicellular) pattern formation is “guided”



reaction-diffusion
with NetLogo



fruit fly embryo
Sean Caroll, U of Wisconsin



larval axolotl limb condensations
Gerd B. Müller

≠

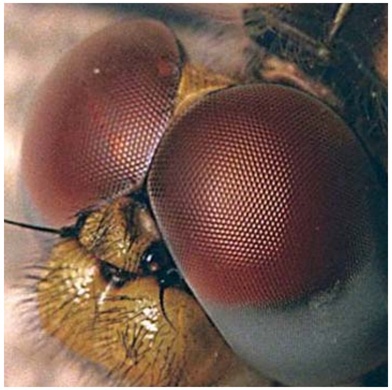
From “statistical” to “morphological” CS

➢ 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

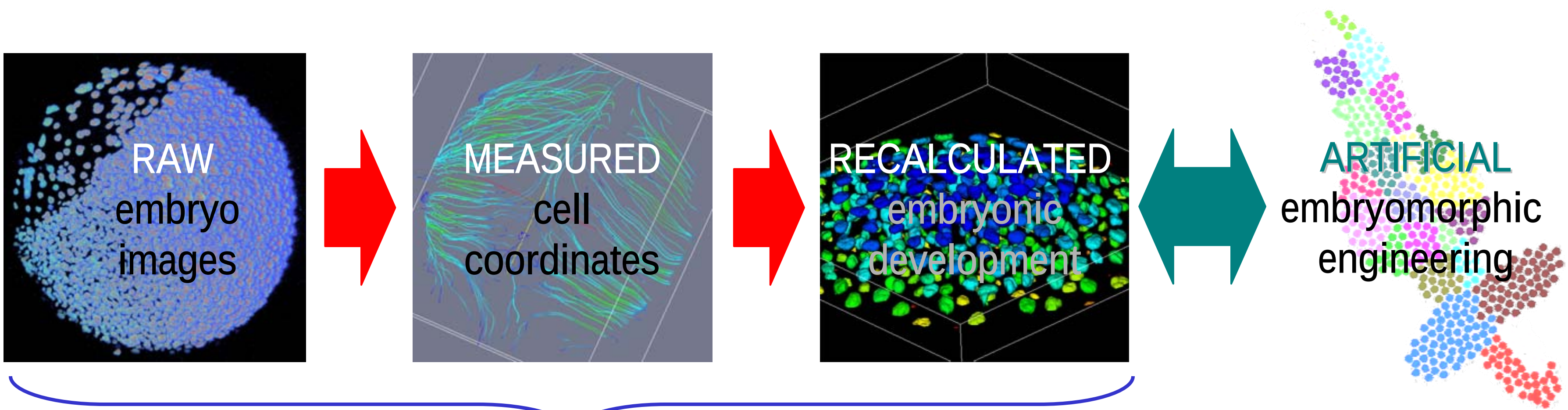
entire structures (flowers, segments) can become modules showing up in random positions and/or numbers

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

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

Evo-devo engineering

- Model embryogenesis ↔ import/export to engineering
  - ✓ automated **observation** and reconstruction of developing organisms by image processing and learning/optimization methods
  - ✓ mathematical and computational (agent-based) **modeling**
  - ✓ **simulation** of recalculated embryos, real and fictitious



FP6 Projects *Embryomics*, *BioEmergences*
Submitted ANR Projects *MEC@GEN*, *SYNBIOTIC*

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

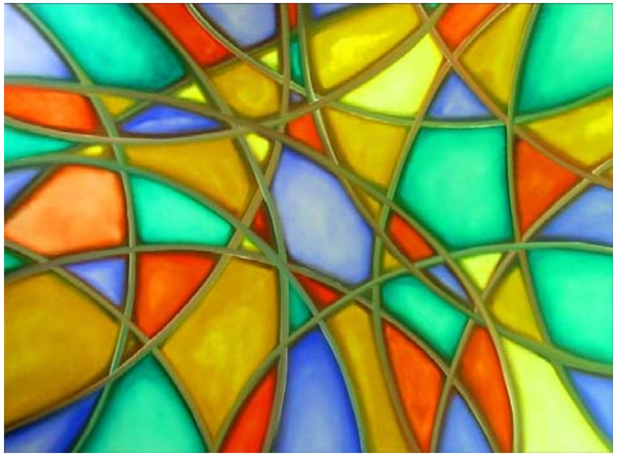
Ádám Szabó, *The chicken or the egg* (2005)
http://www.szaboadam.hu

"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

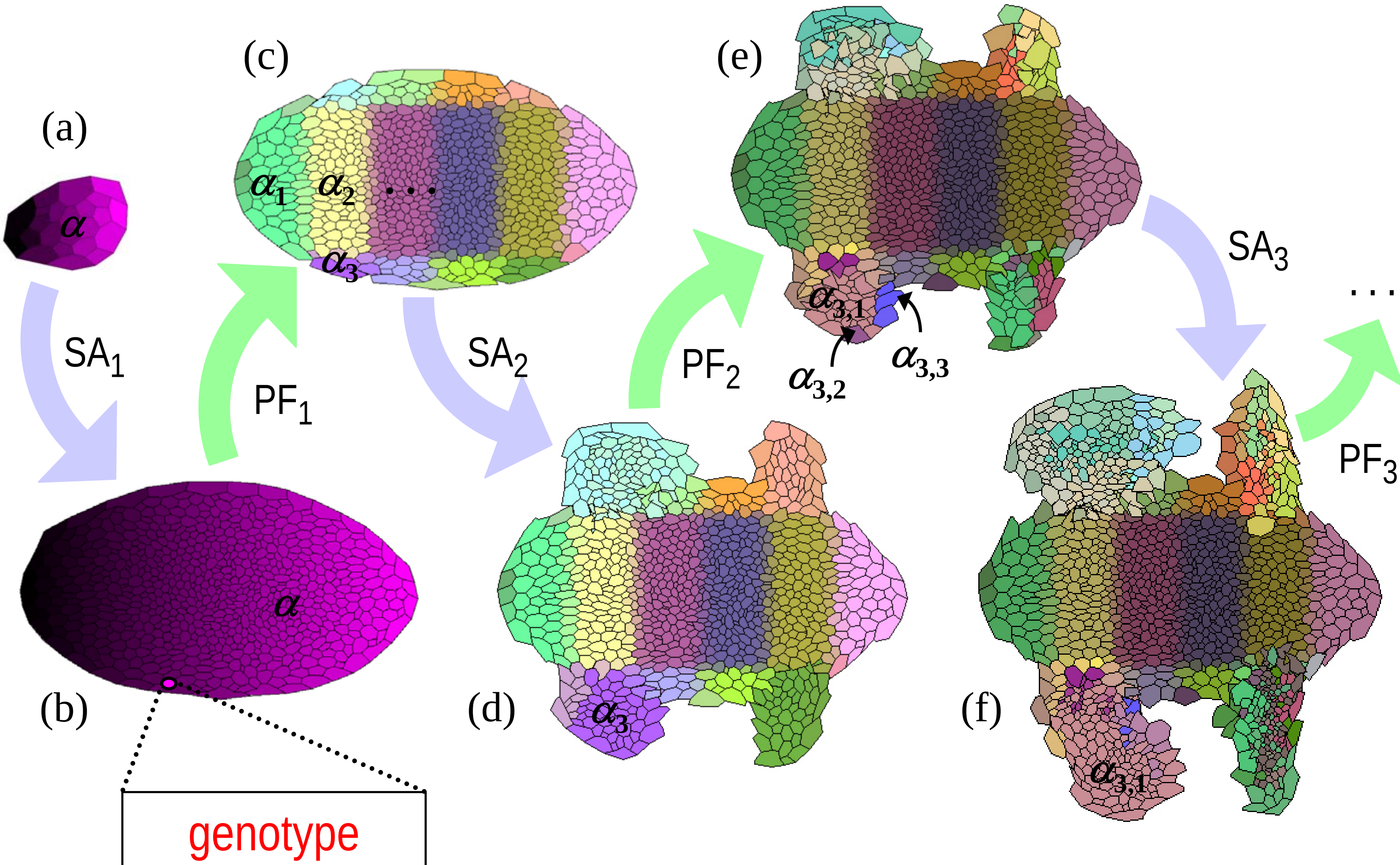


"patterns from shaping"

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

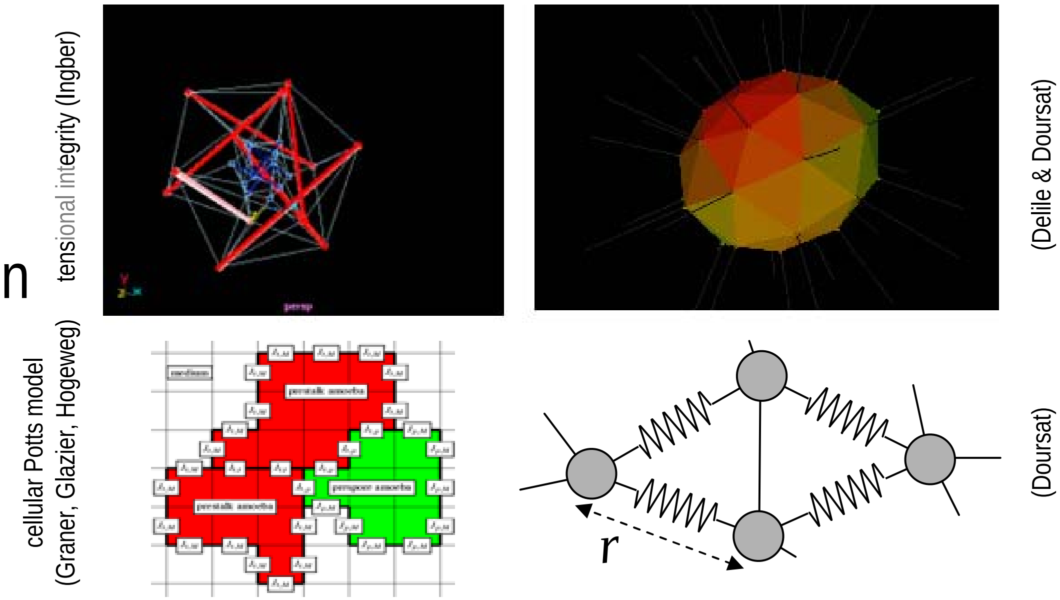
Morphogenesis couples assembly and patterning

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

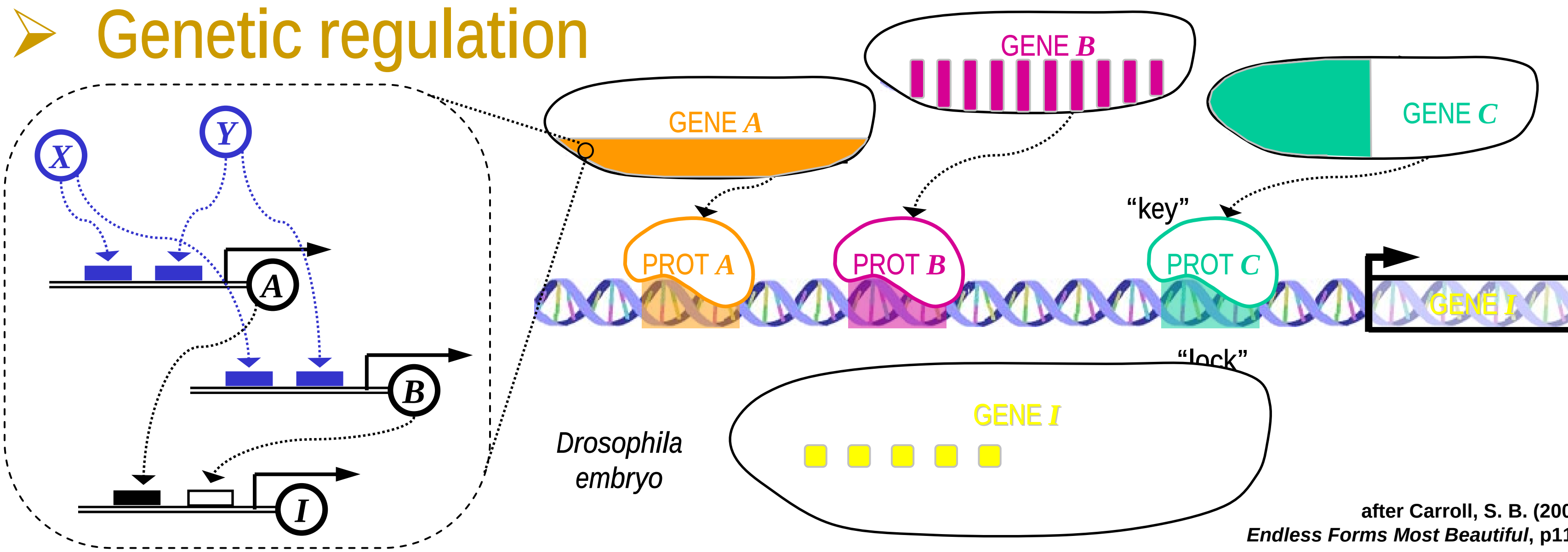


Morphogenesis couples mechanics and regulation

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



- **Genetic regulation**

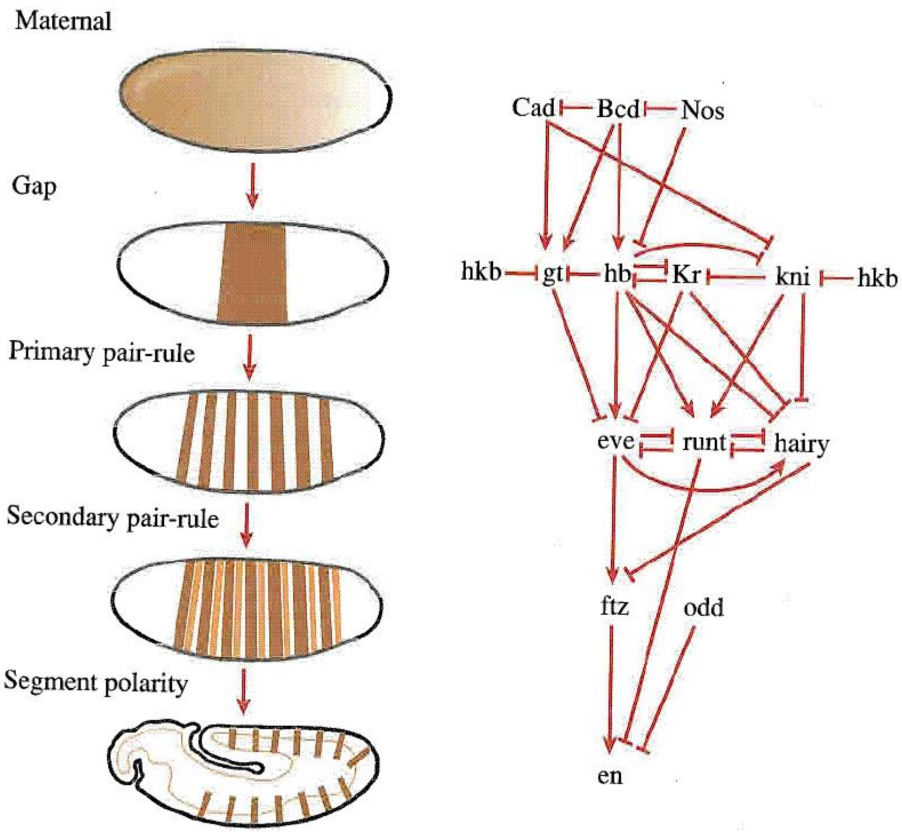


after Carroll, S. B. (2005)
Endless Forms Most Beautiful, p117

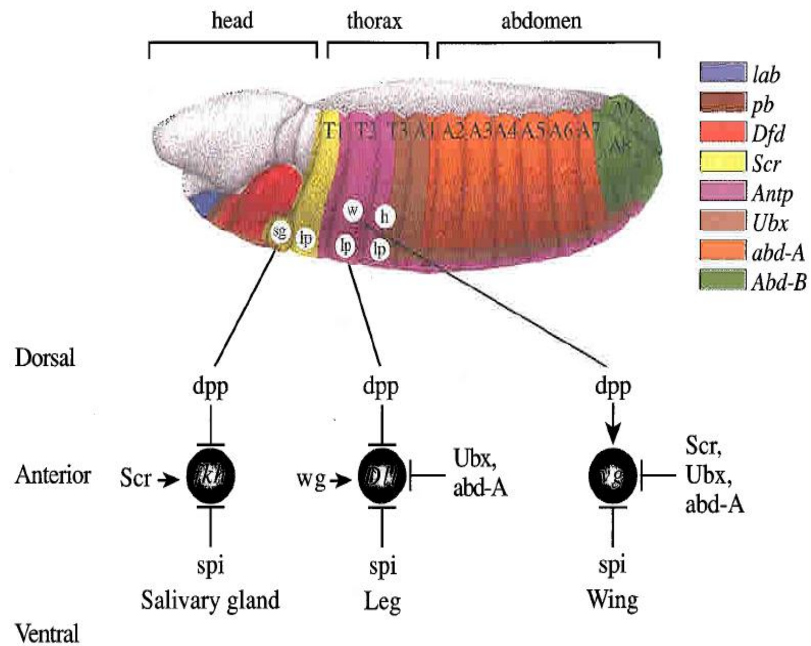
Gene regulatory pattern formation

➢ 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.)

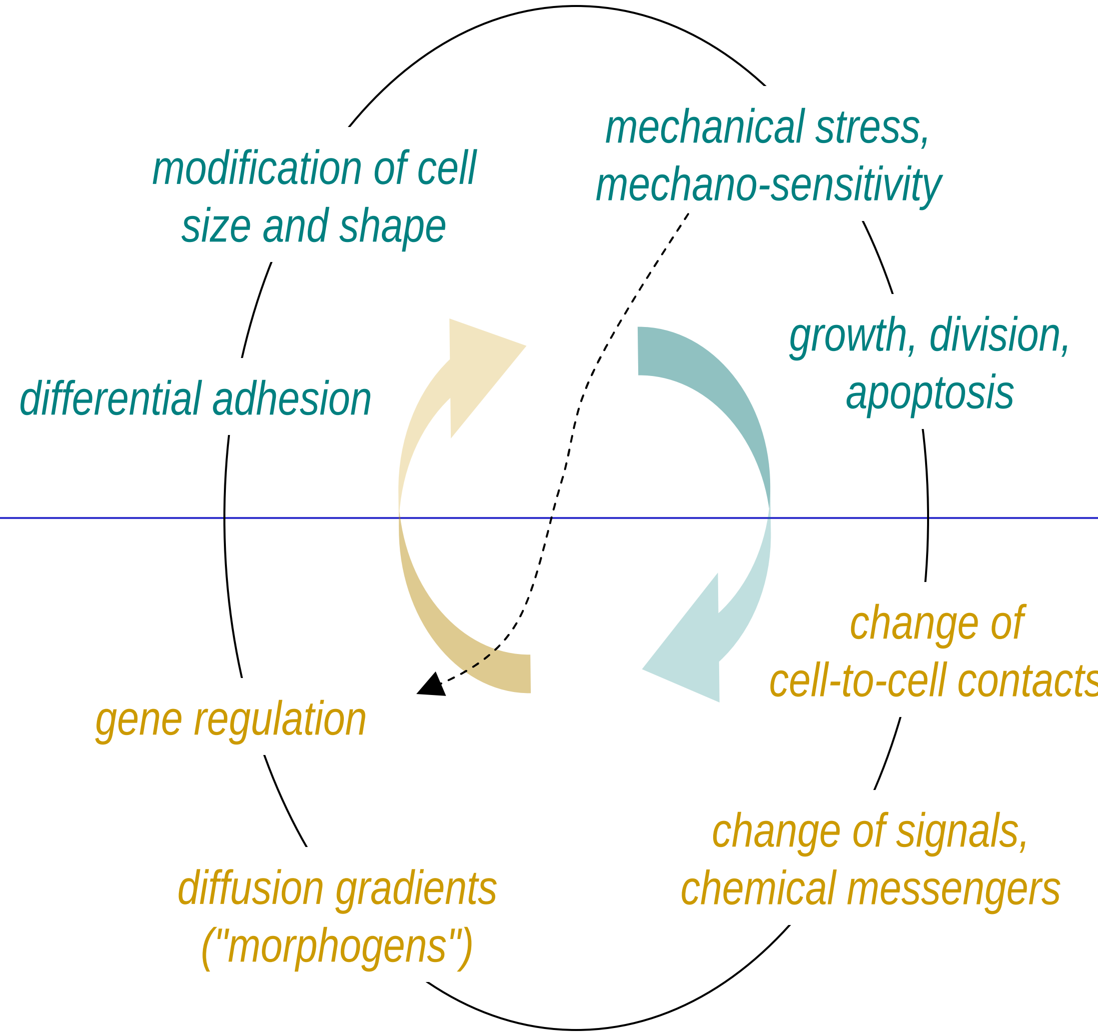


from Carroll, S. B., et al. (2001)
From DNA to Diversity, p63

Morphogenesis couples mechanics and regulation

➢ Cellular mechanics

➢ Genetic regulation

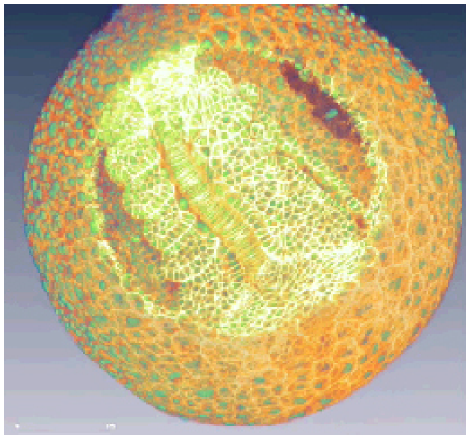


Morphogenesis couples motion and patterns

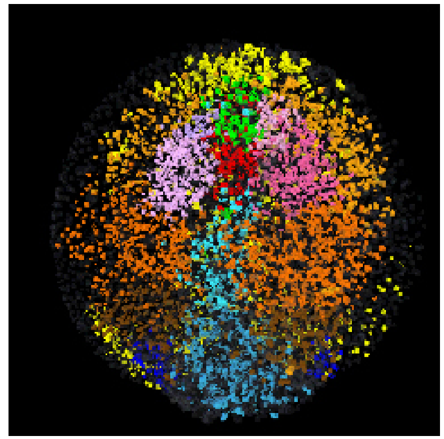
➢ Collective motion regionalized into patterns

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

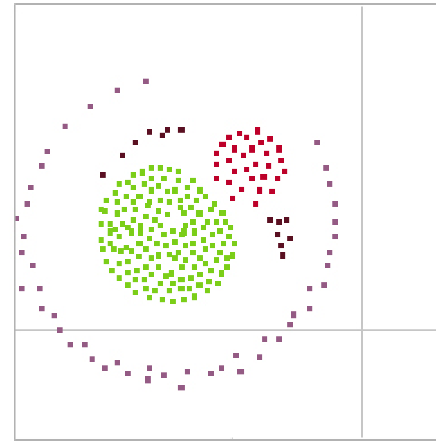
Embryomics & BioEmergences



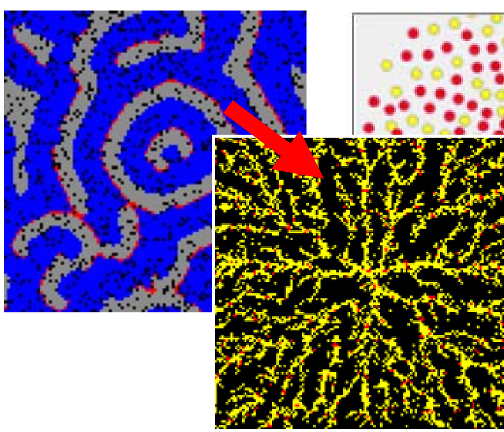
zebrafish



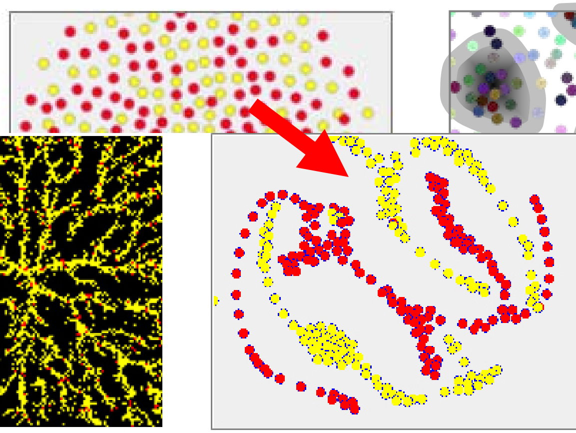
Hiroki Sayama (Swarm Chemistry) http://bingweb.binghamton.edu/~sayama/SwarmChemistry/

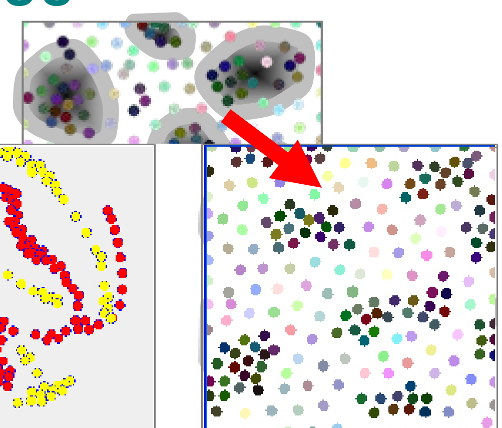


➢ Pattern formation that triggers motion

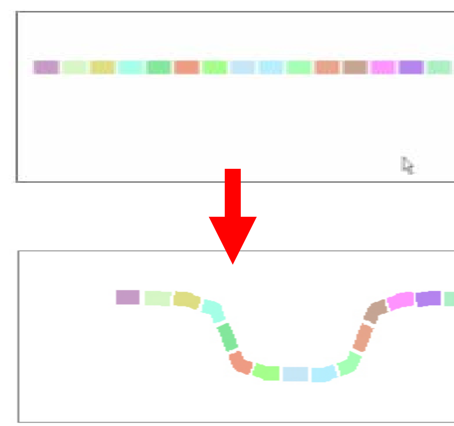


http://zool33.uni-graz.at/schmickl





Doursat



Embryomorphic Engineering

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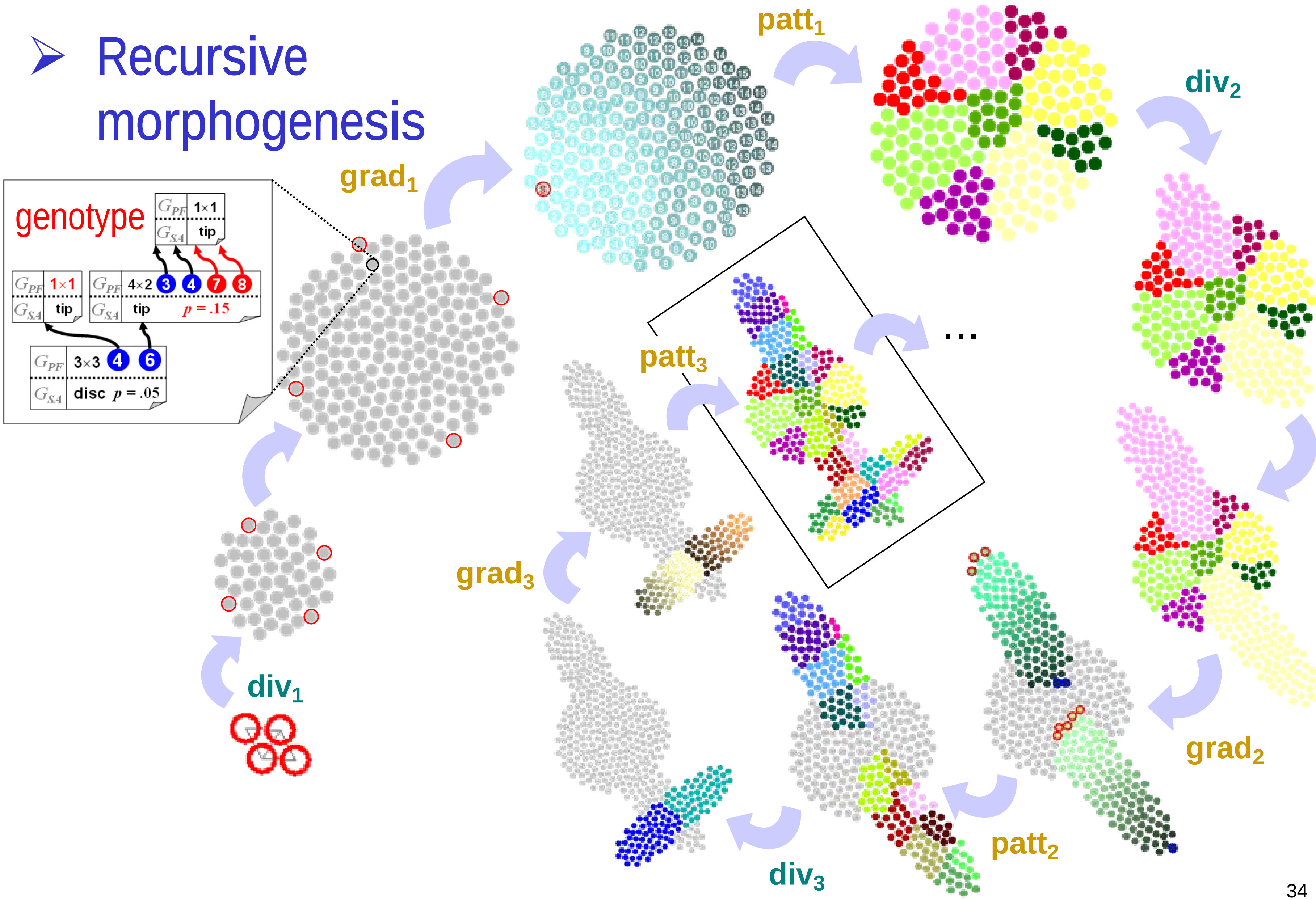
Overview of an embryomorphic system

- Recursive morphogenesis



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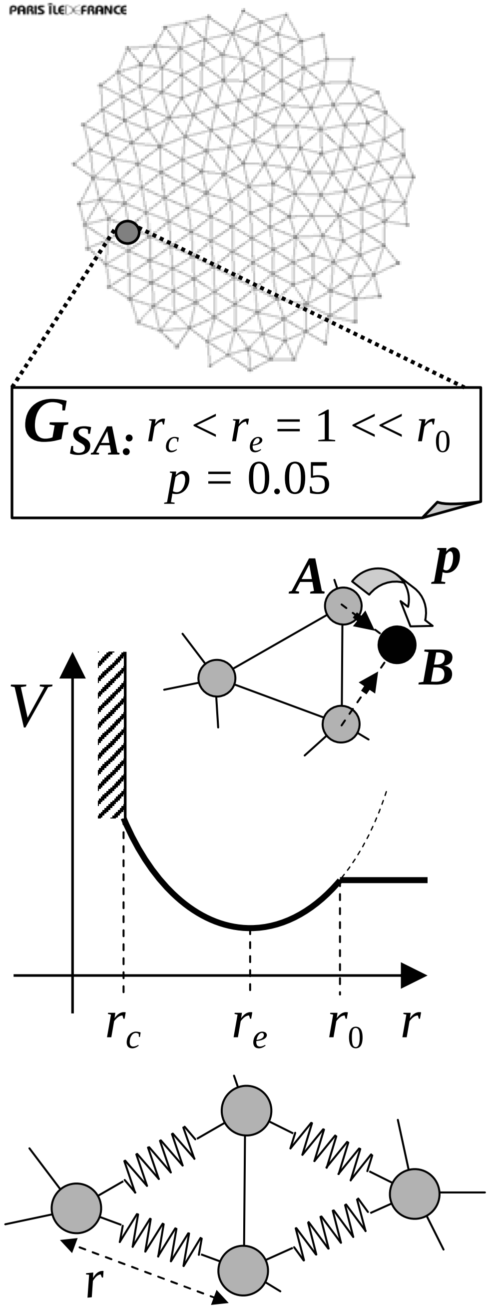

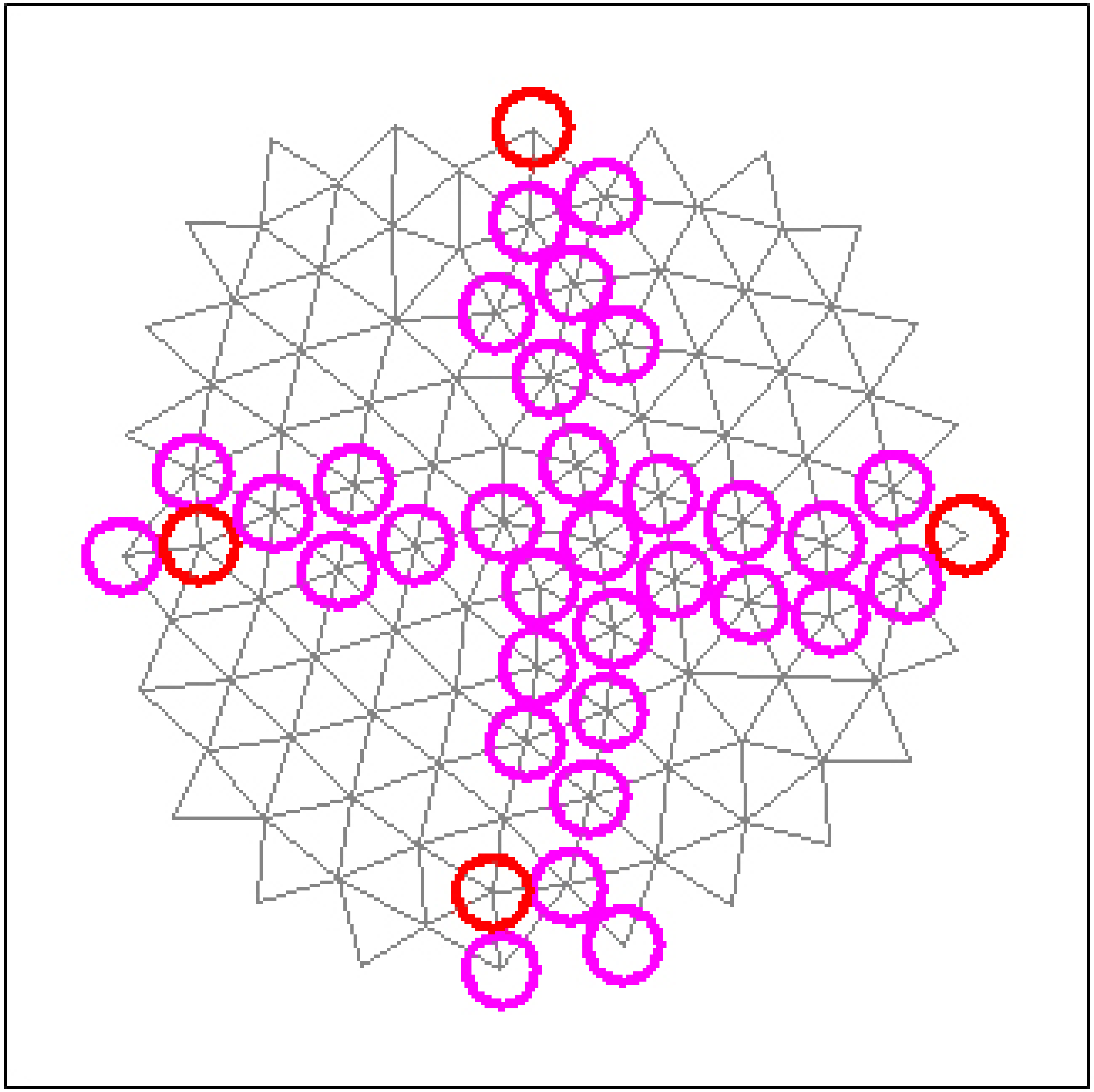

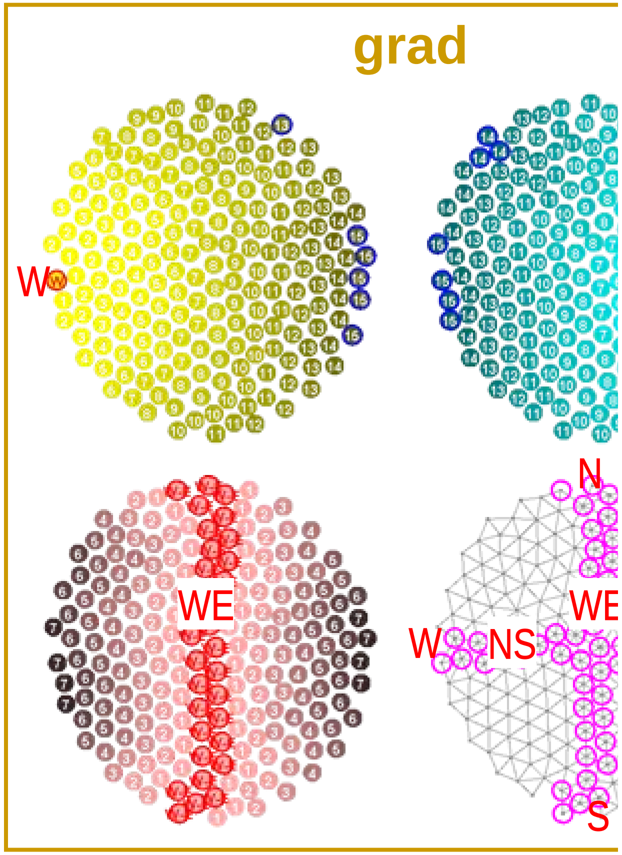
grad
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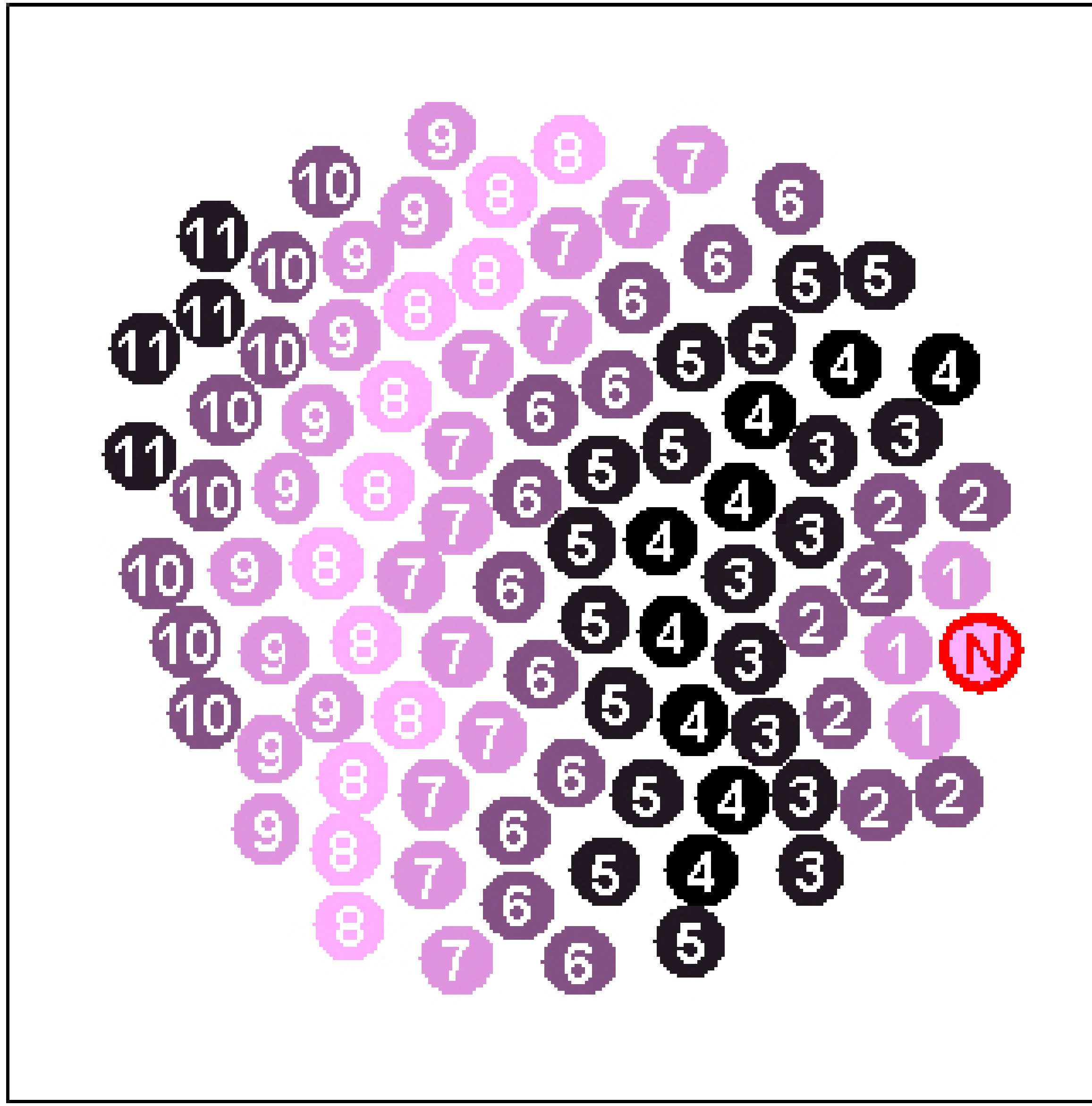
S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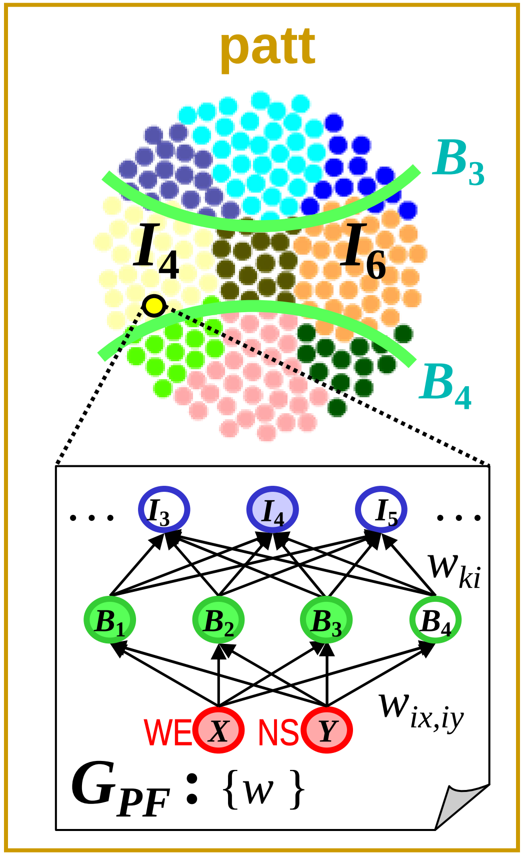
patt
B_3
I_4
I_6
B_4
I_3
I_4
I_5
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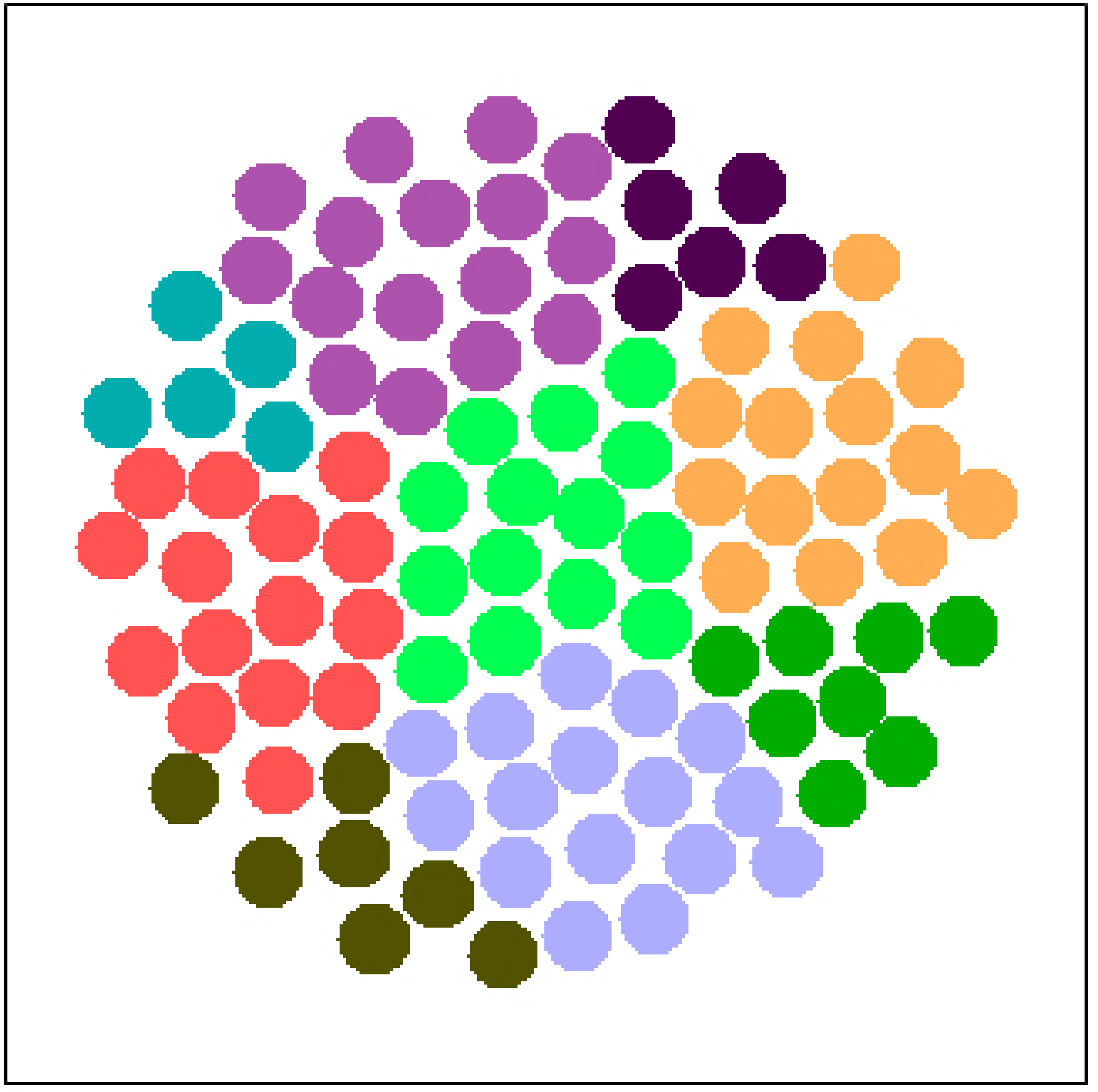
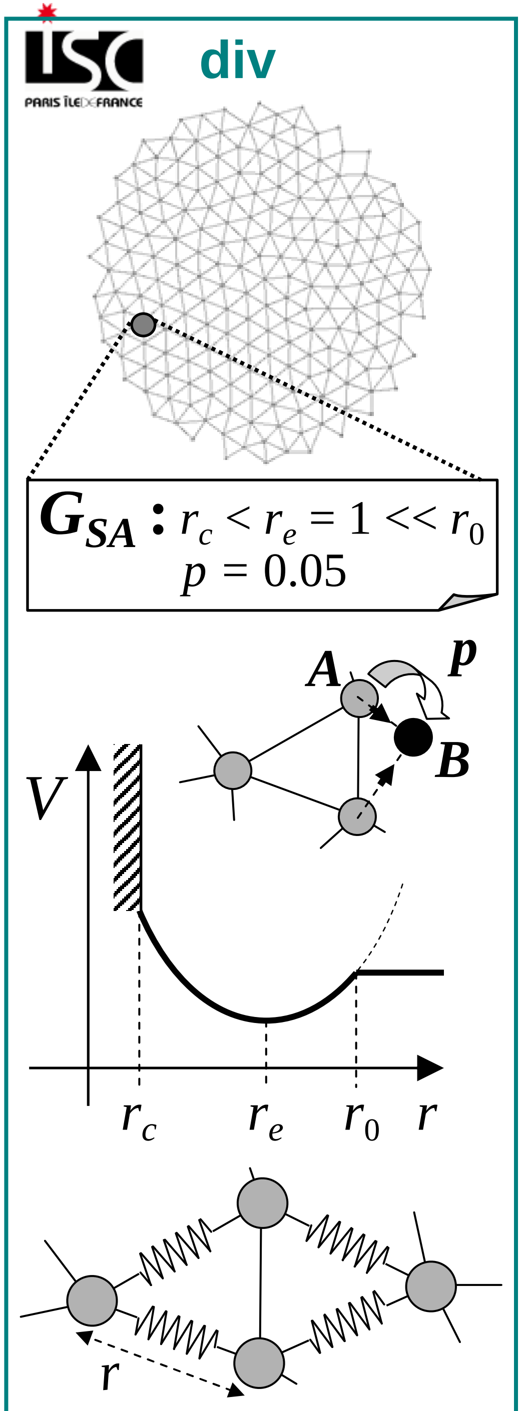
Y
G_{PF} : {w }




div
PARIS ÎLE-DE-FRANCE
G_{SA} : $r_c < r_e = 1 << r_0$
$p = 0.05$
A
p
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V
r_c
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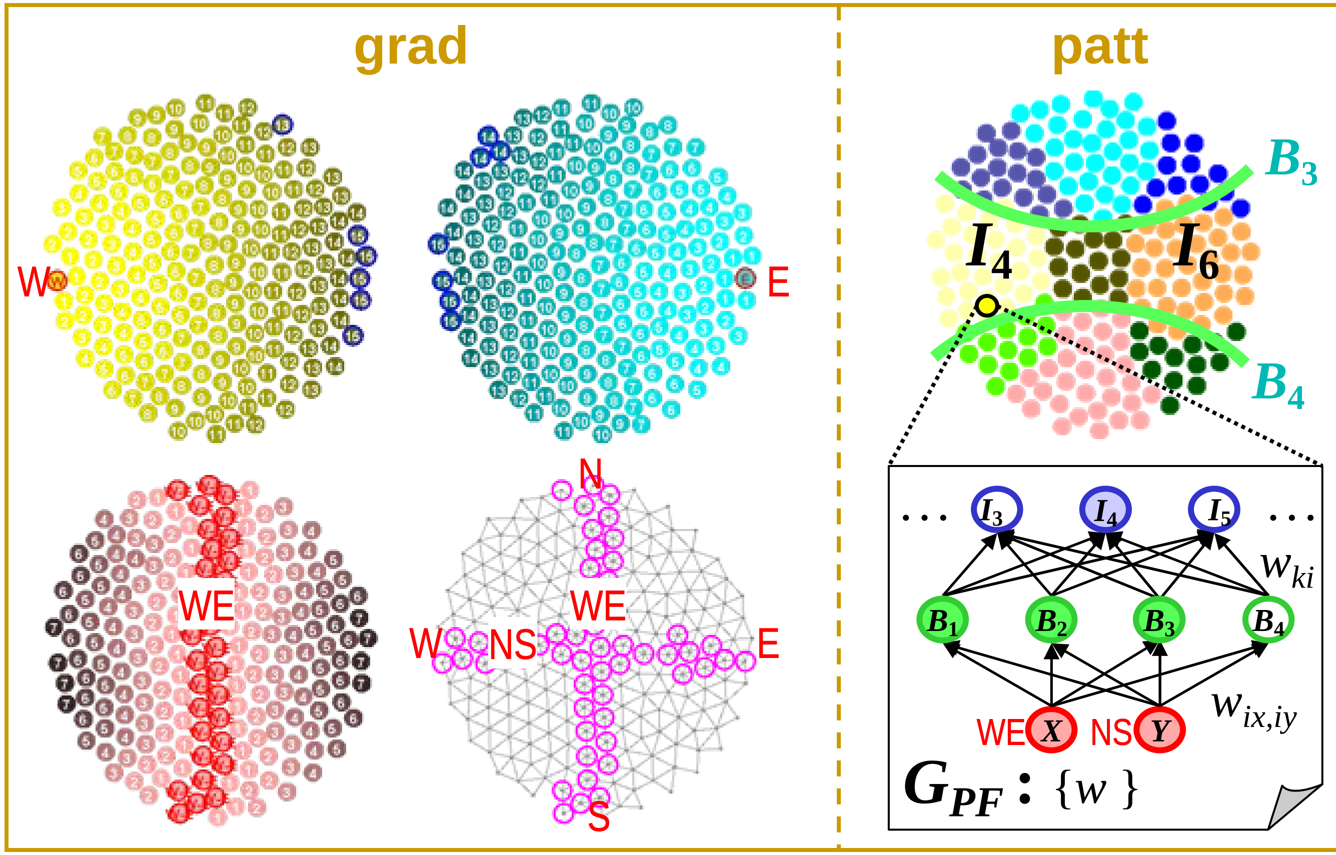
grad
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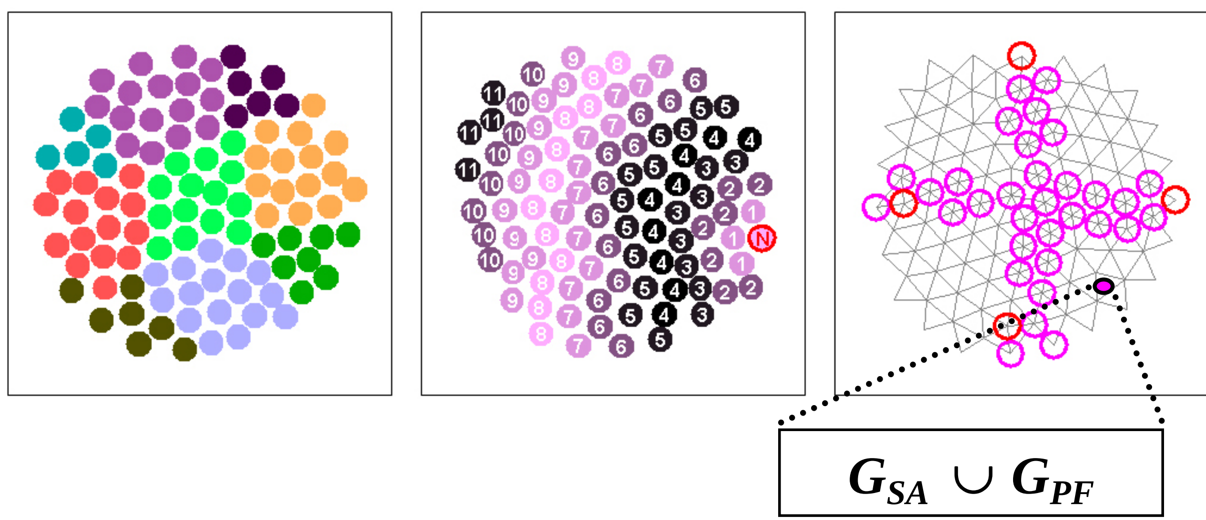
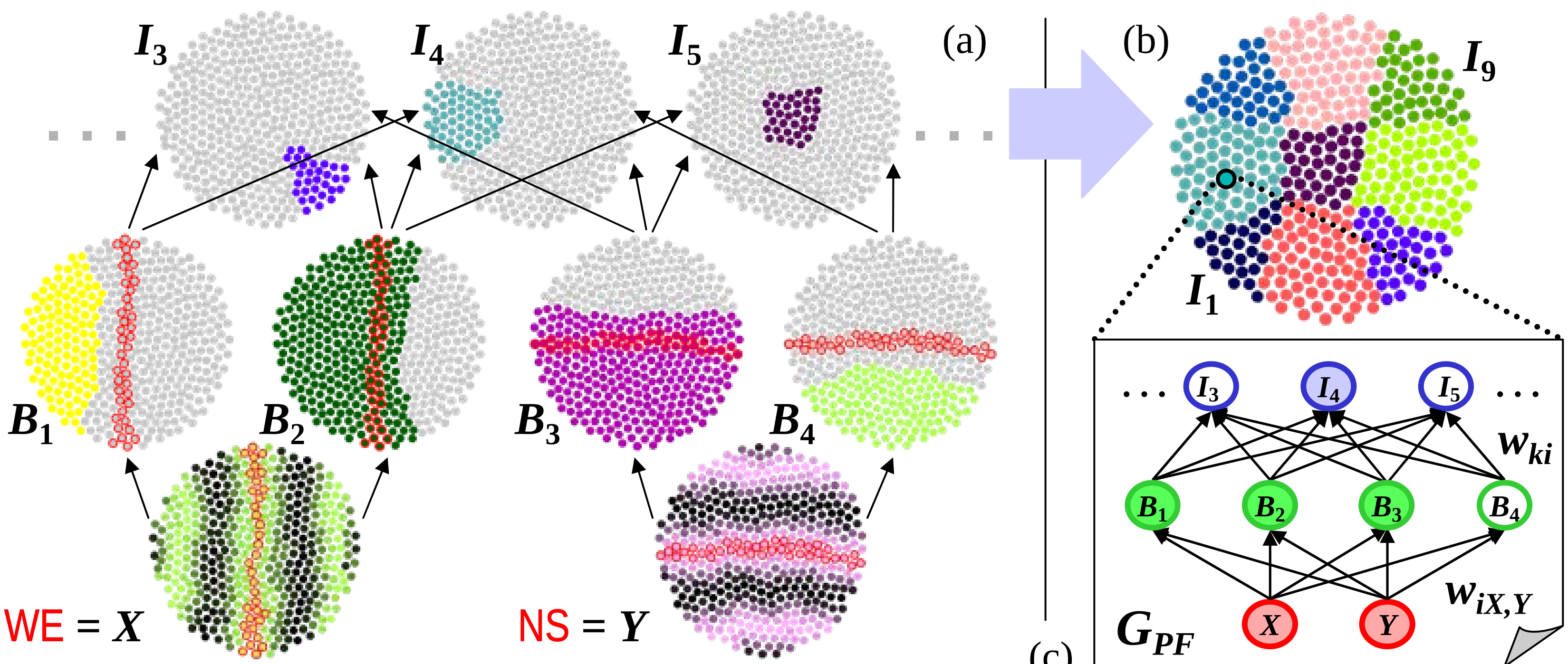
NS
Y
G_{PF} : {w}


N
$G_{SA} \cup G_{PF}$

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.

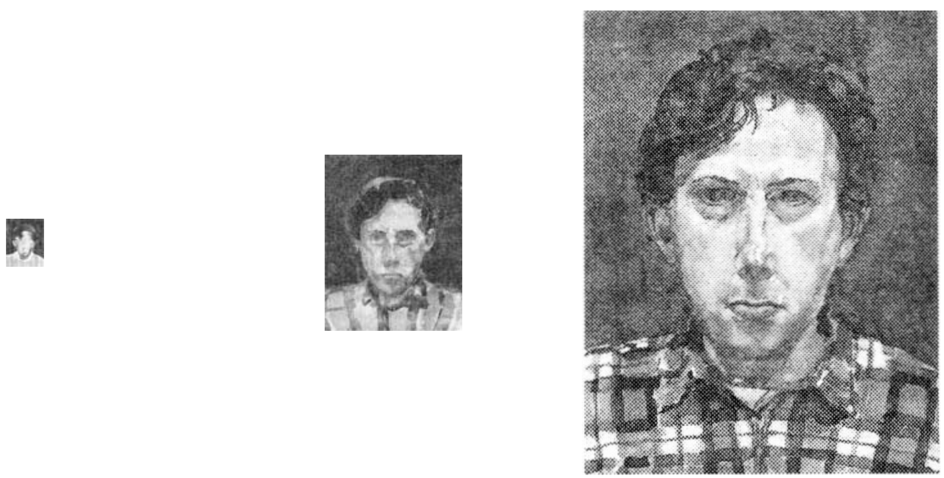


Hierarchical morphogenesis

➢ Morphological refinement by iterative growth

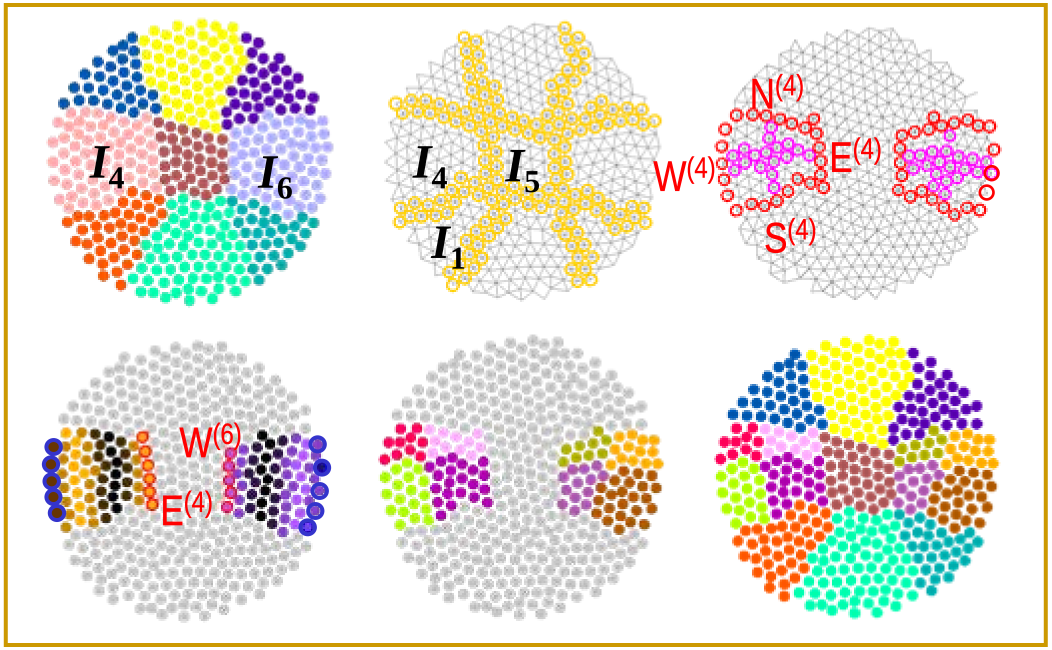
- ✓ details are not created in one shot, but gradually added. . .

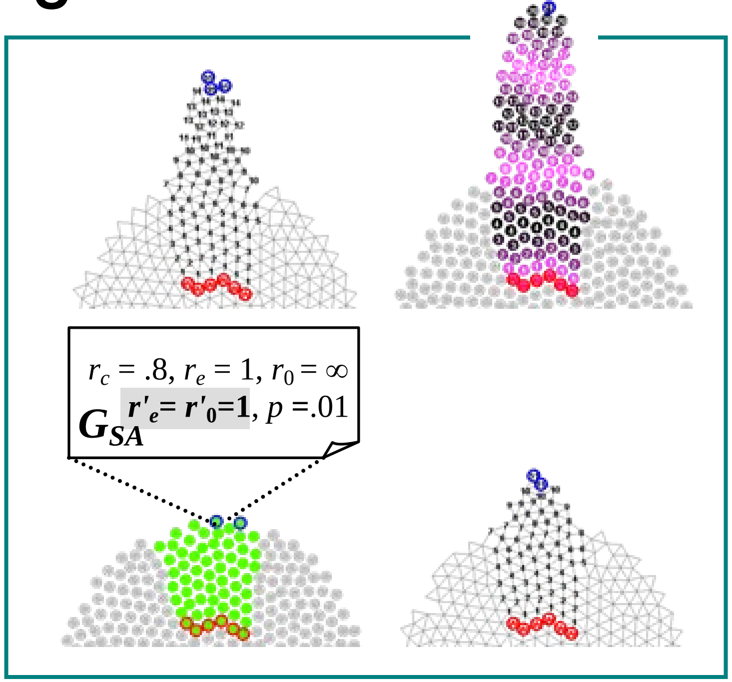
- ✓ . . . while, at the same time, the canvas grows

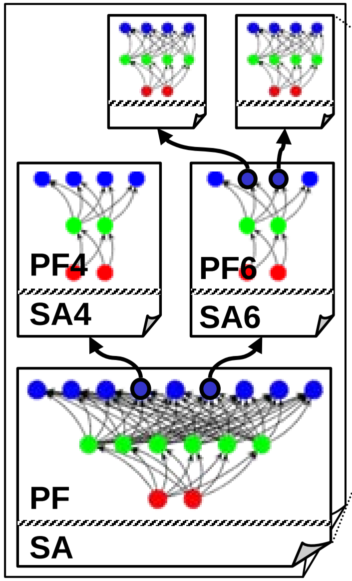


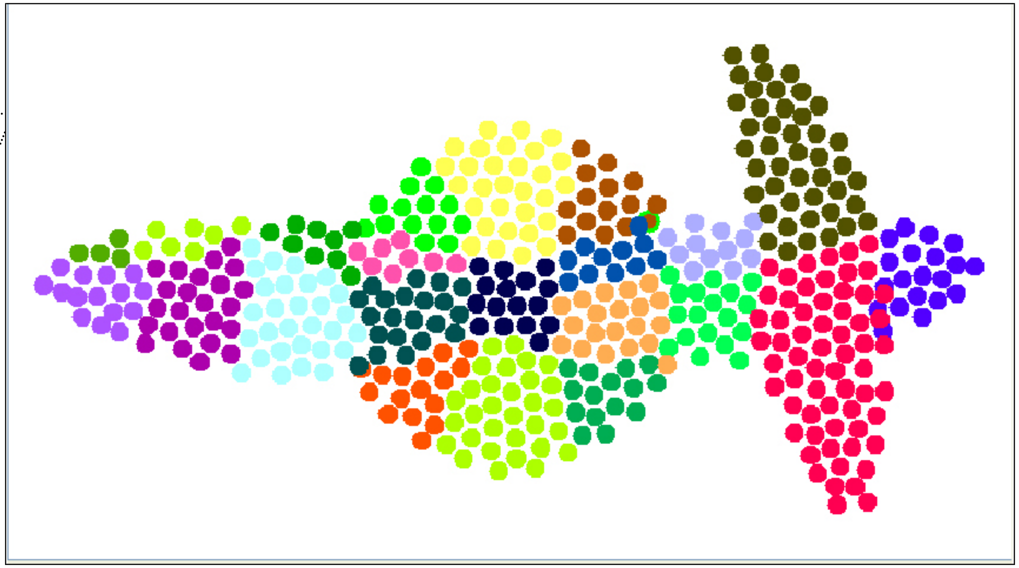
from Coen, E. (2000)
The Art of Genes, pp131-135

Hierarchical embryogenesis

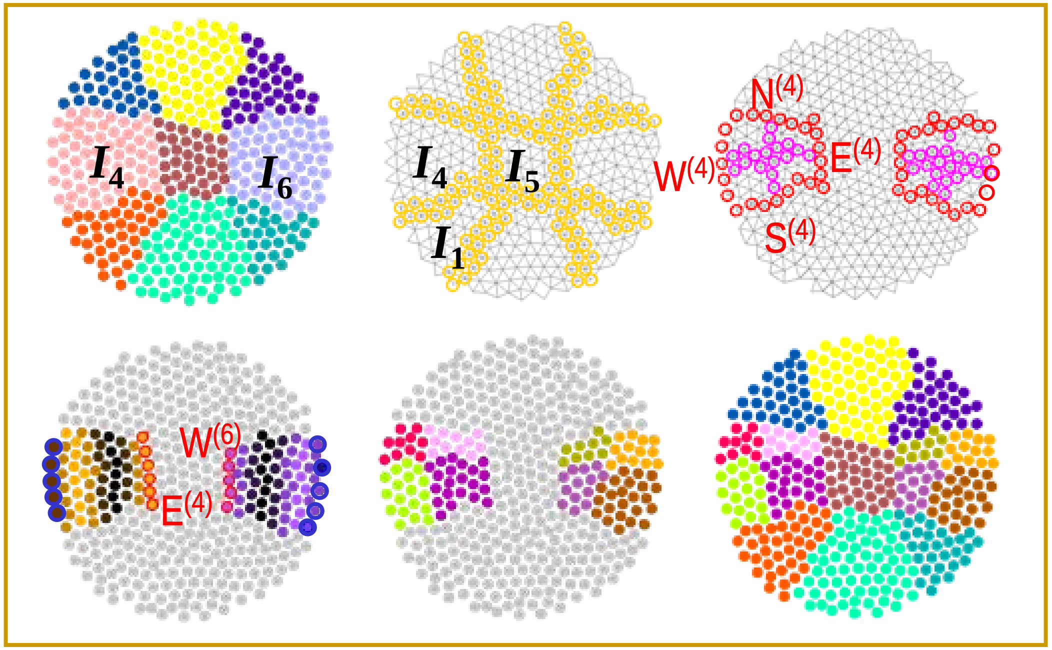


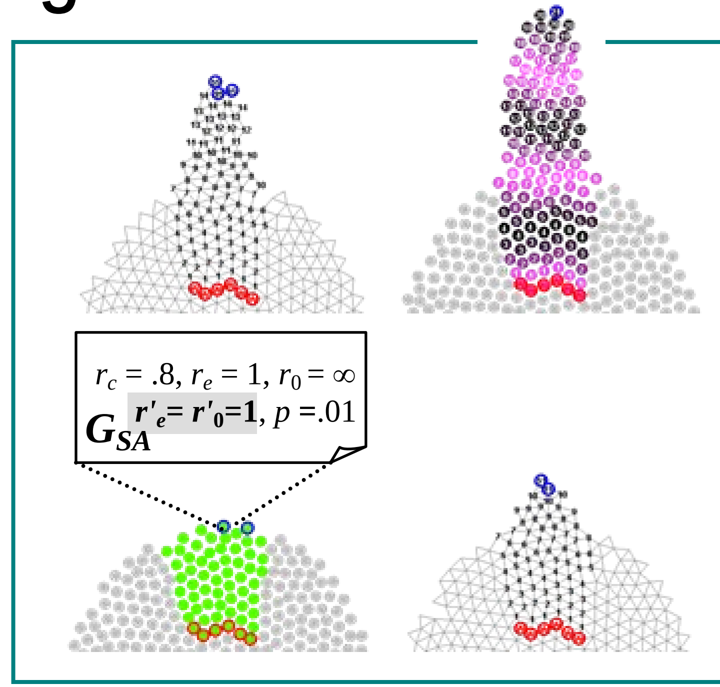


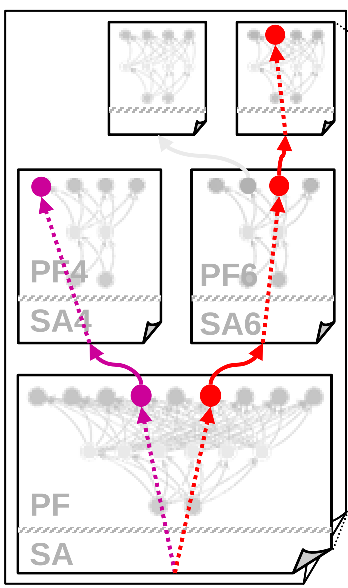




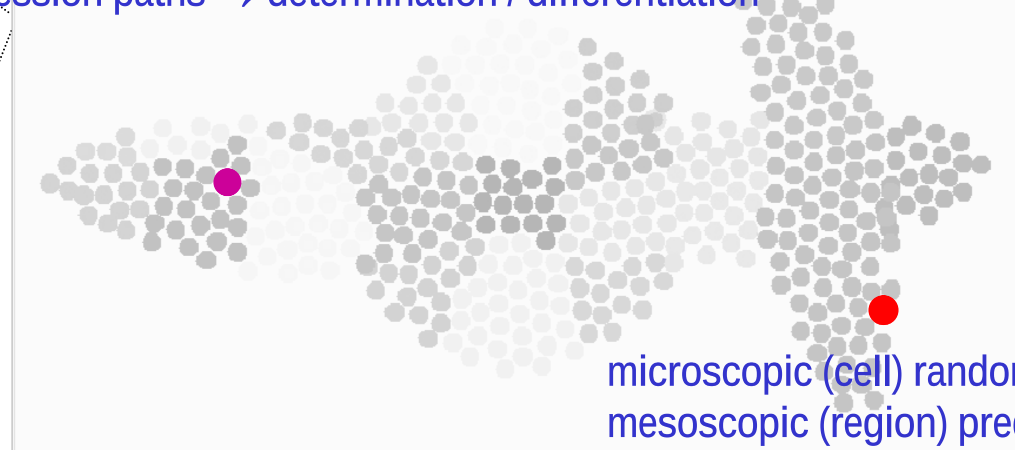
Hierarchical embryogenesis







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



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

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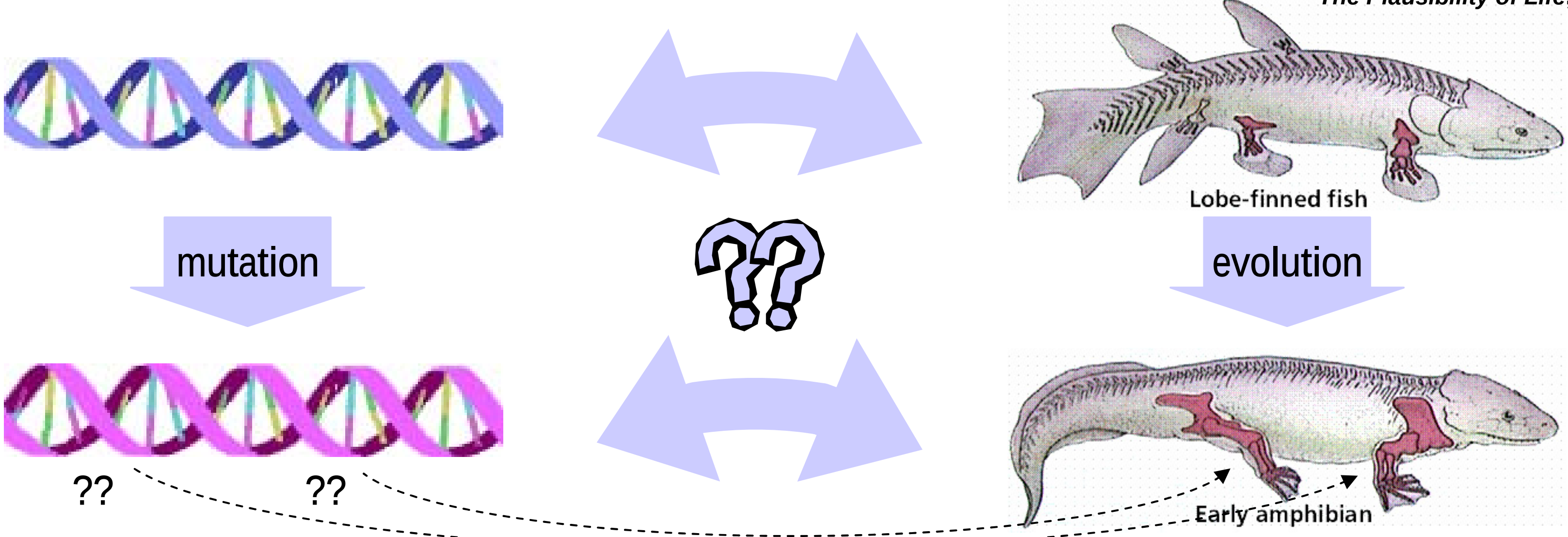
Evolutionary innovation by development

➢ 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**



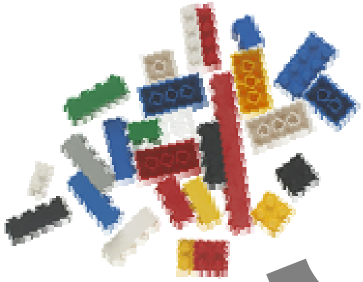
Purves et al., *Life: The Science of Biology*

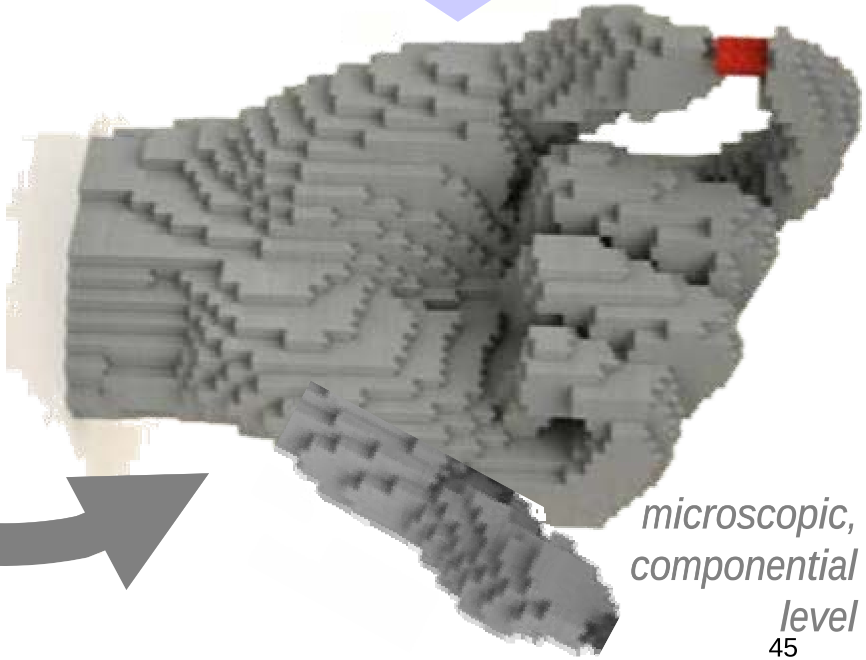
The self-made puzzle of “evo-devo” engineering

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

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.”





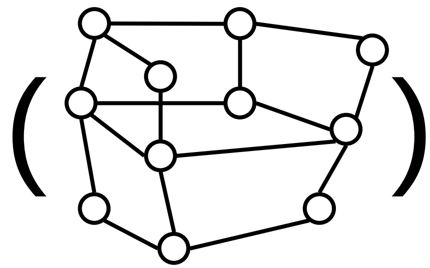
microscopic, componential level

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

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

more or less direct representation

≈



≈

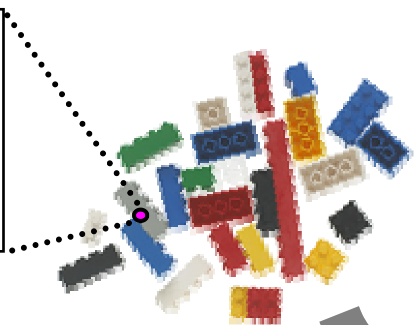
macroscopic, emergent level

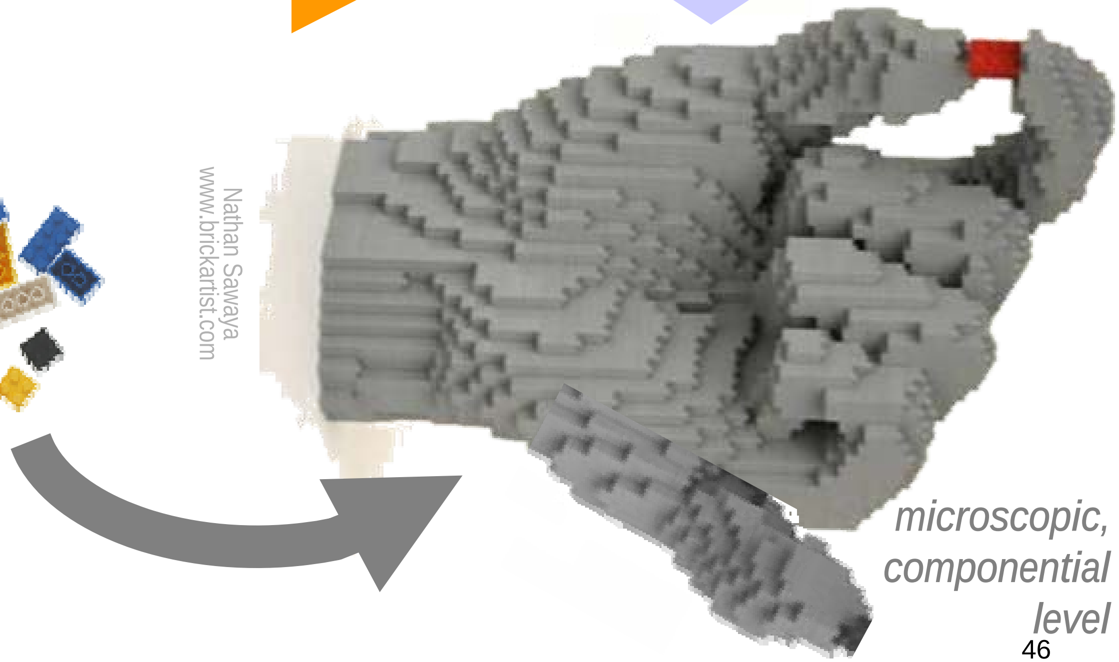
Genotype

“Transformation”

Phenotype

generic elementary rules of **self-assembly**

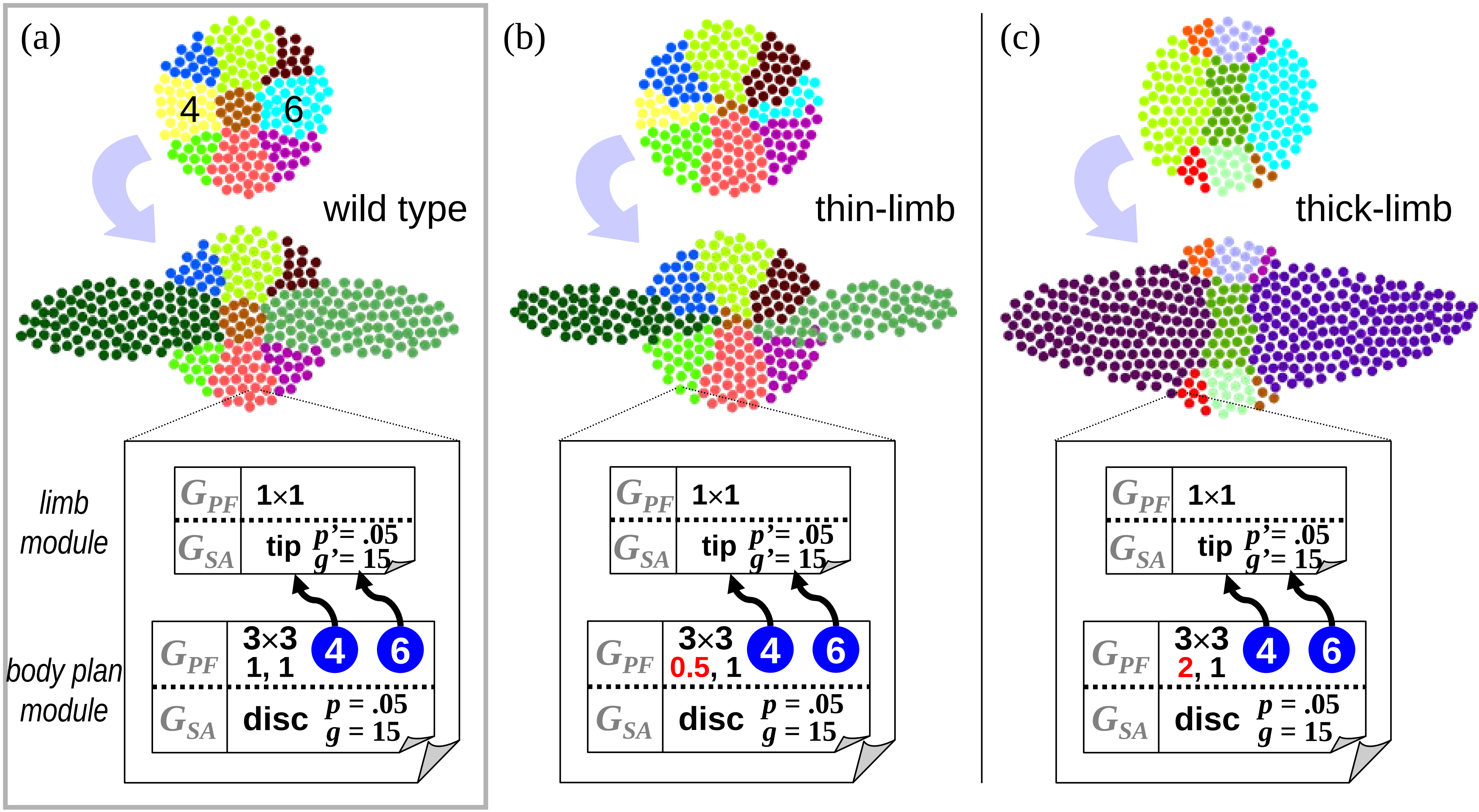




microscopic, componential level

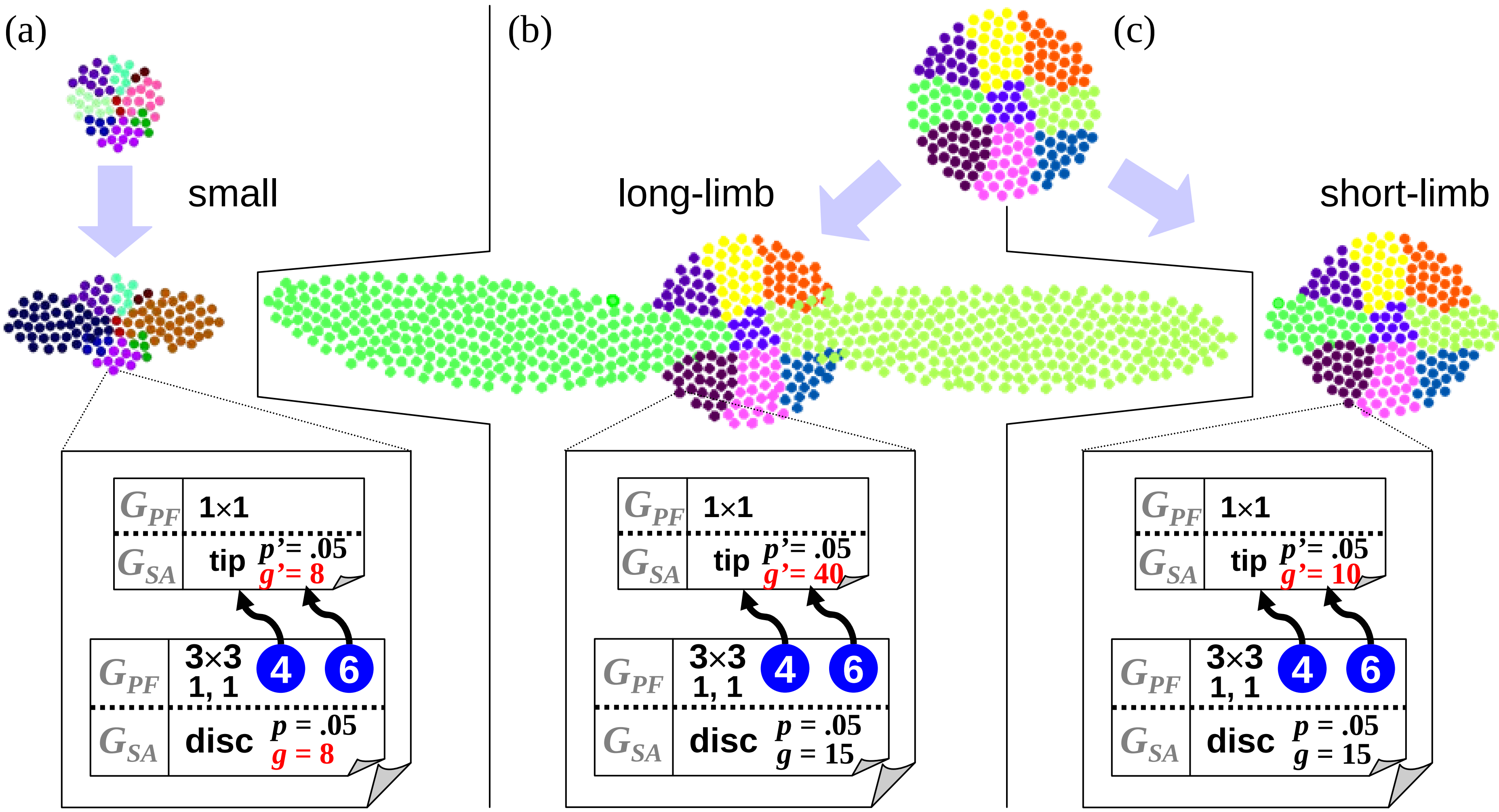
Multi-agent evolutionary development (evo-devo)

➤ Quantitative mutations: limb thickness



Multi-agent evolutionary development (evo-devo)

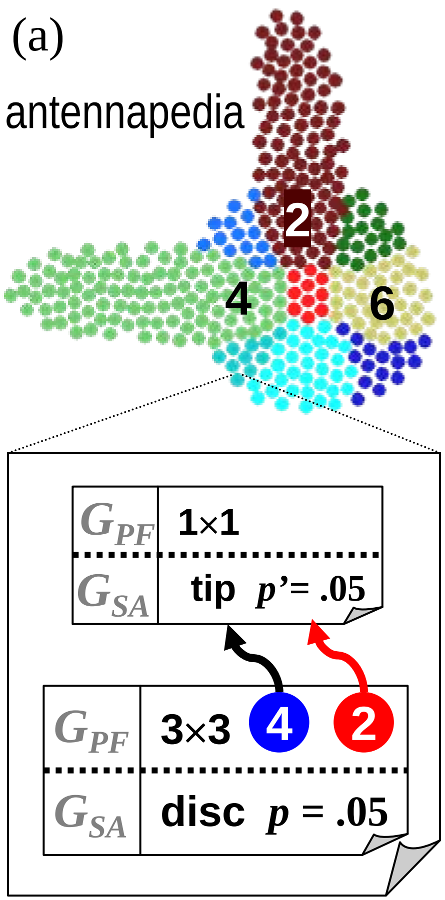
- Quantitative mutations: body size and limb length

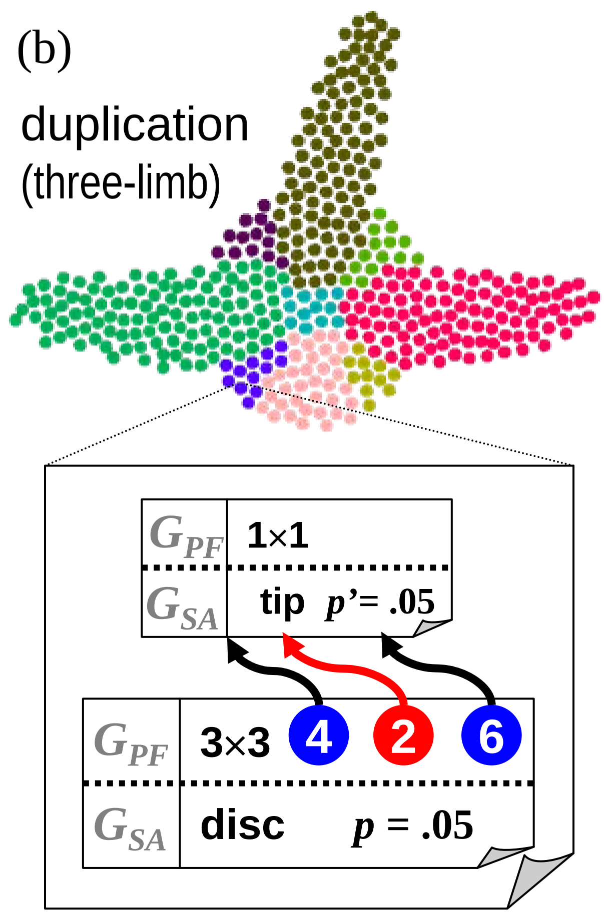


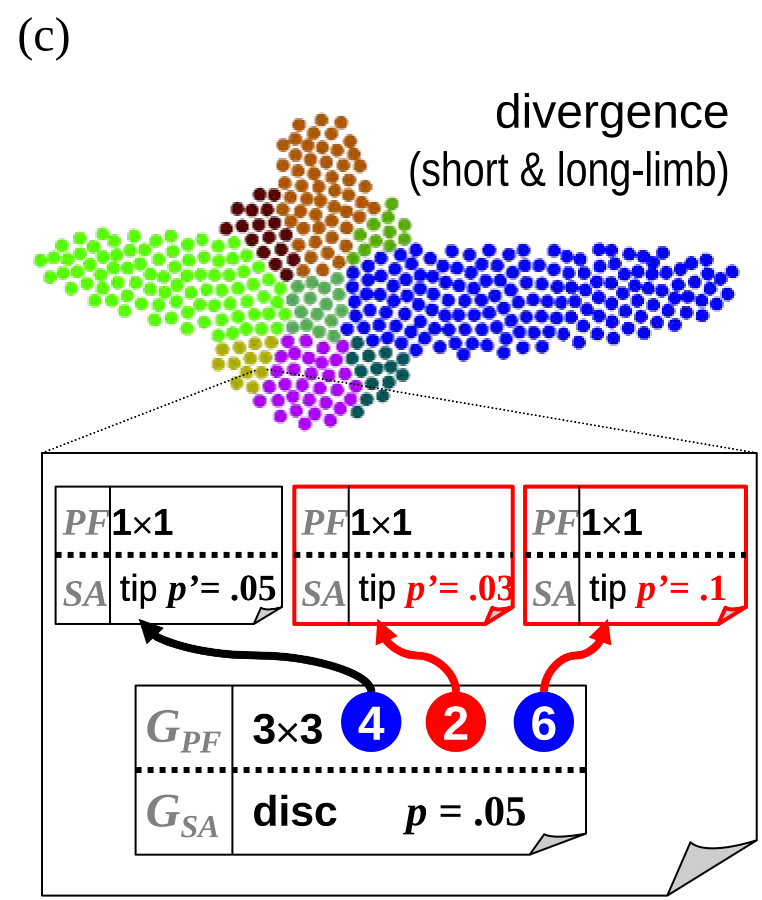
Multi-agent evolutionary development (evo-devo)

➢ Qualitative mutations: limb position and differentiation

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

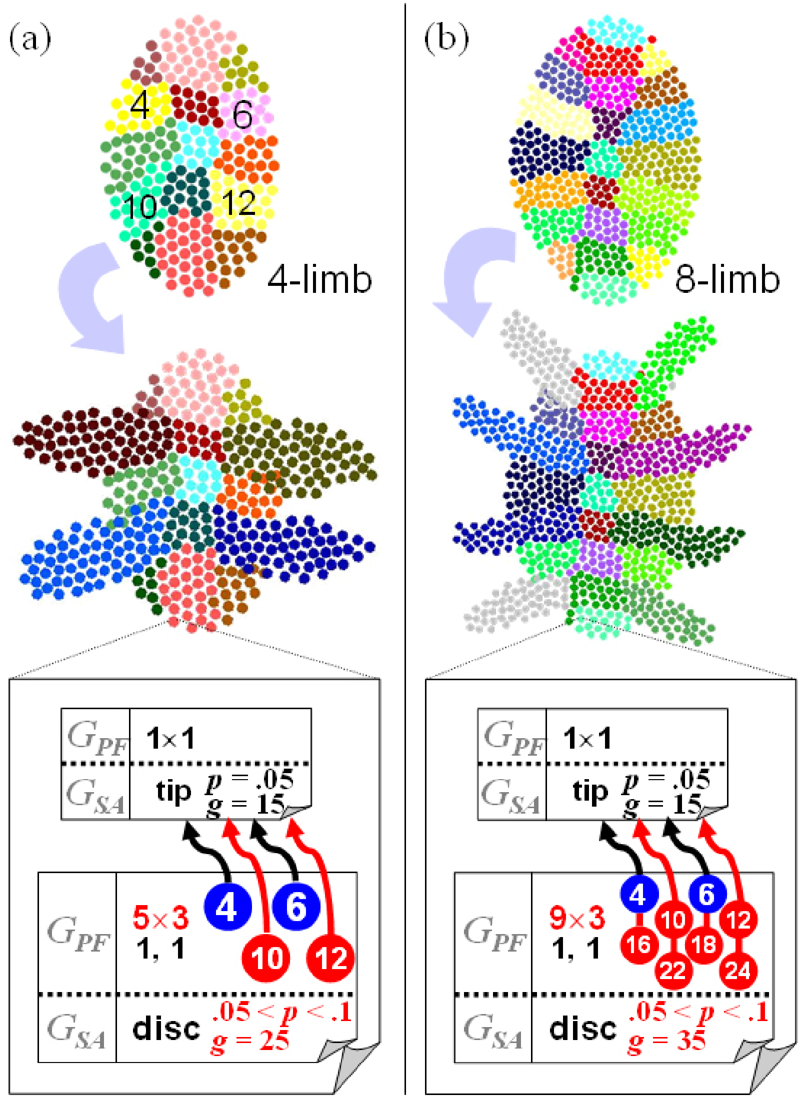






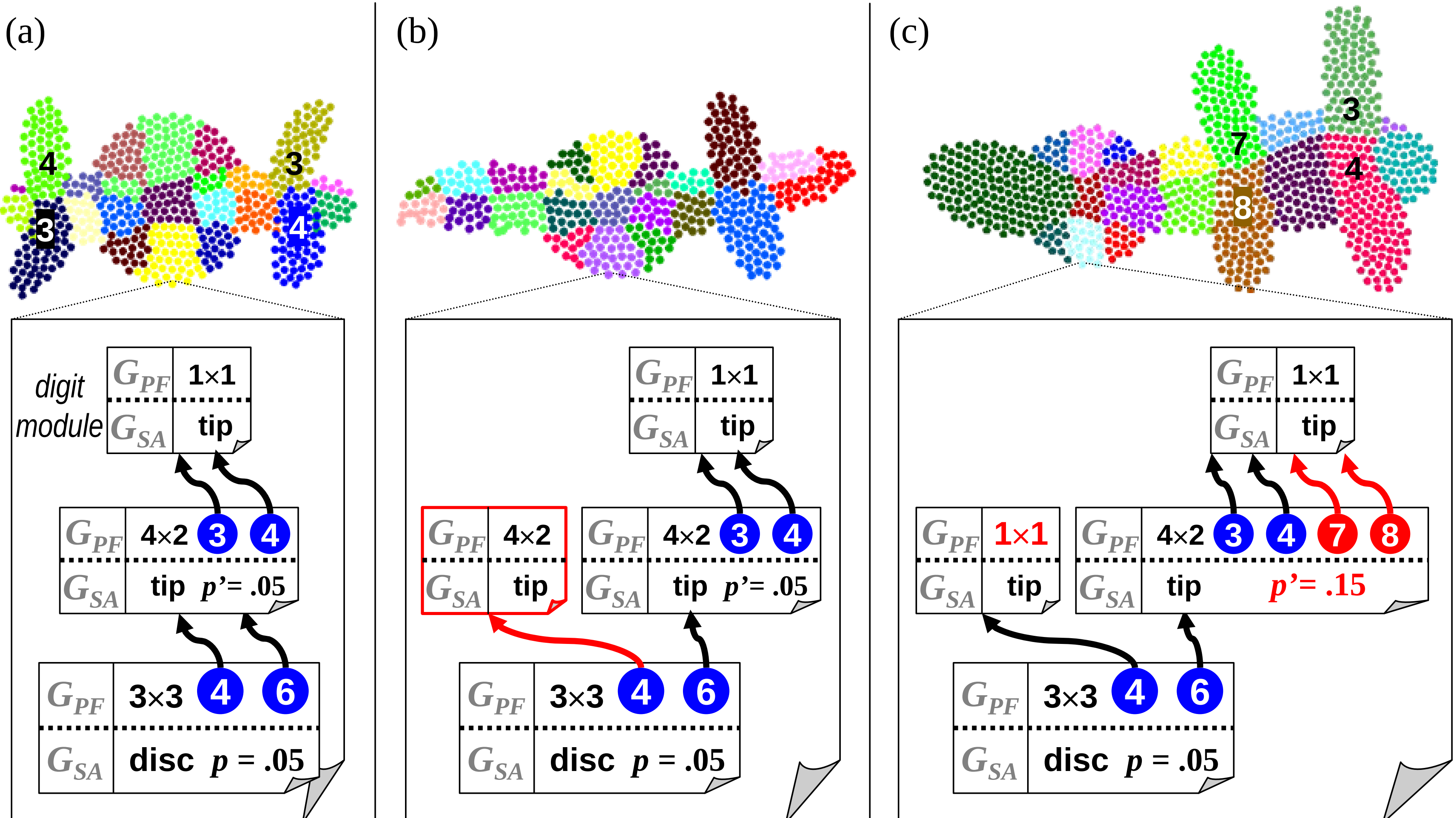
Multi-agent evolutionary development (evo-devo)

- Qualitative mutations: number of limbs



Multi-agent evolutionary development (evo-devo)

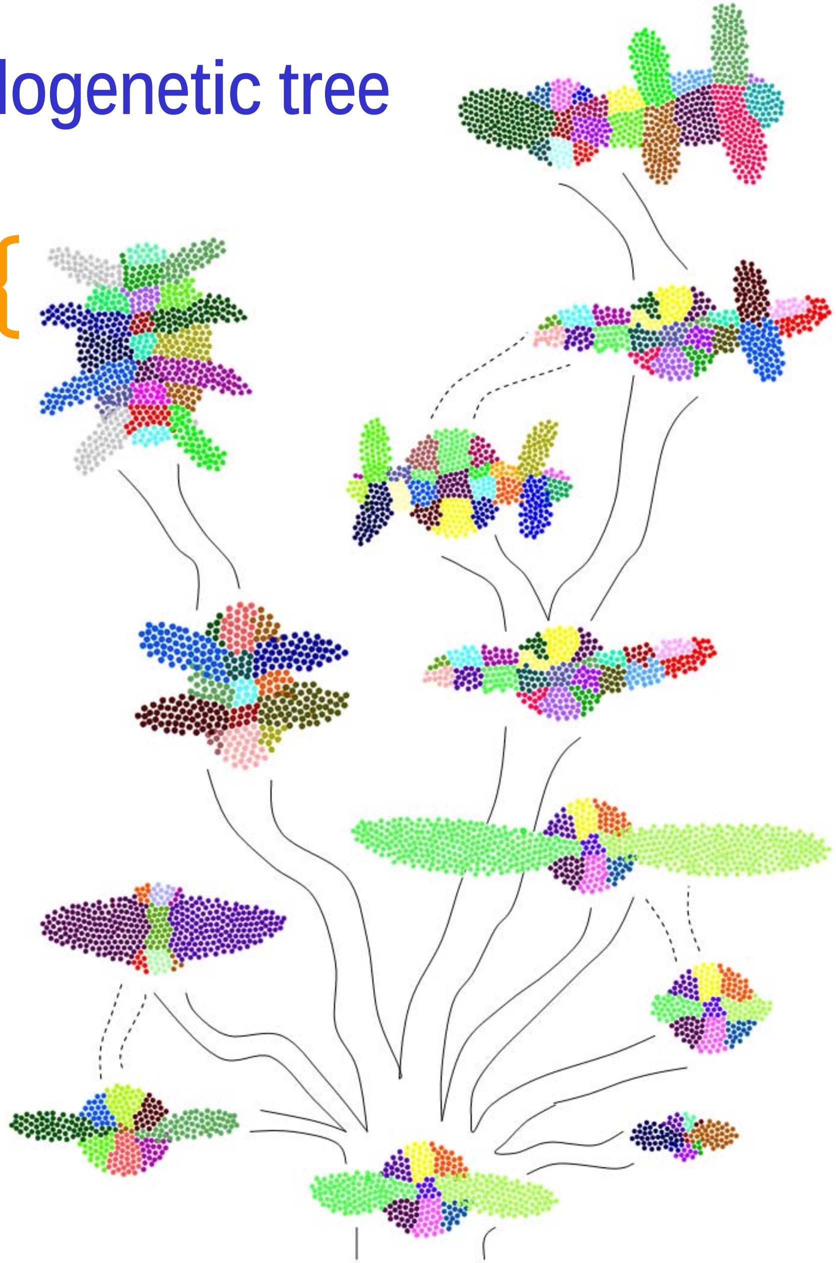
- Qualitative mutations: 3rd-level digits



Multi-agent evolutionary development (evo-devo)

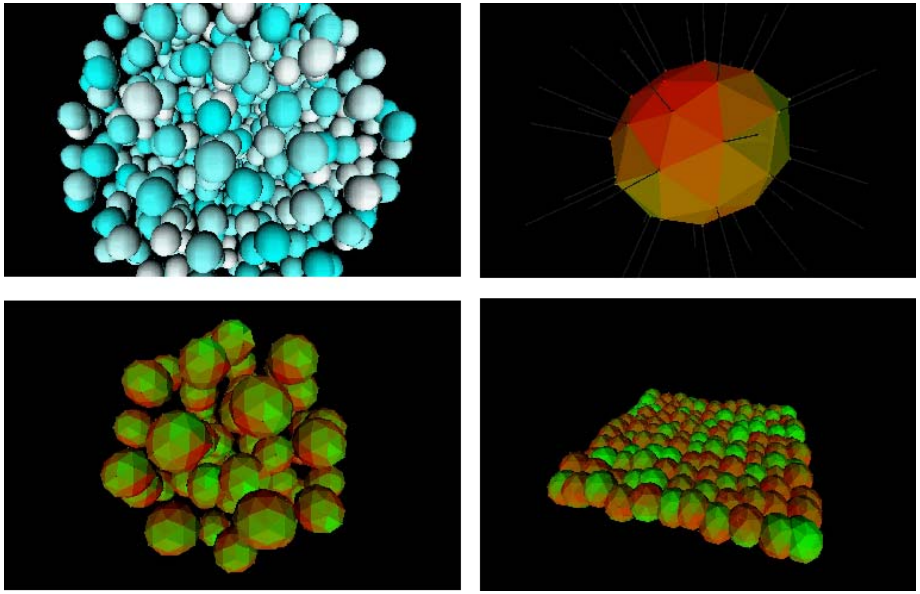
- Artificial phylogenetic tree

production of structural innovation



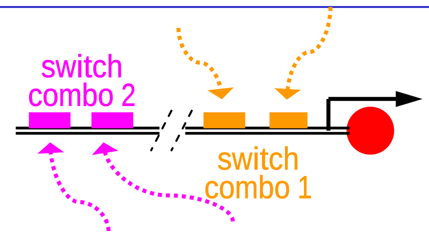
Work toward more accurate biological modeling

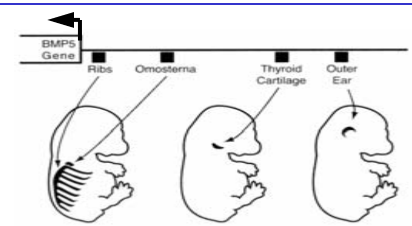
- ➢ **More accurate mechanics**
  - ✓ 3-D
  - ✓ individual cell shapes
  - ✓ collective motion, migration
  - ✓ adhesion



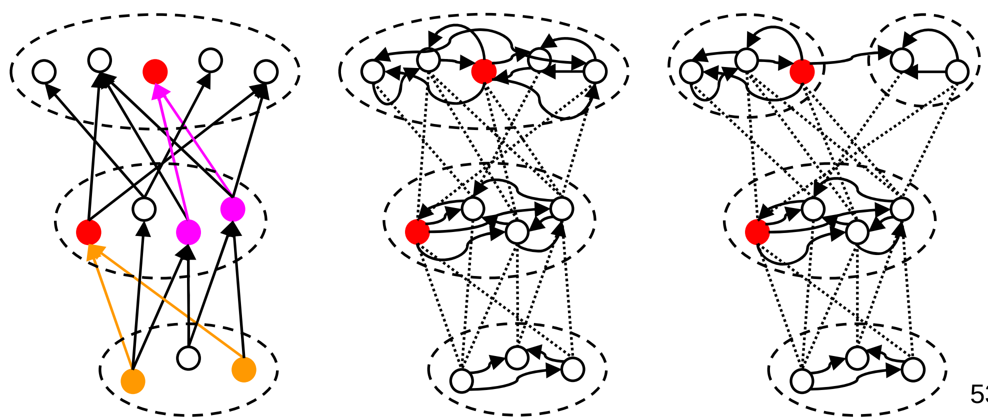
(Delille, Doursat, Peyrieras)

- ➢ **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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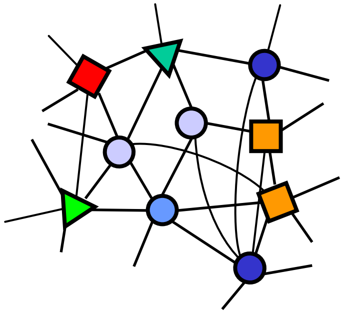
Programmable techno-social networks

➢ Harnessing complex networks

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

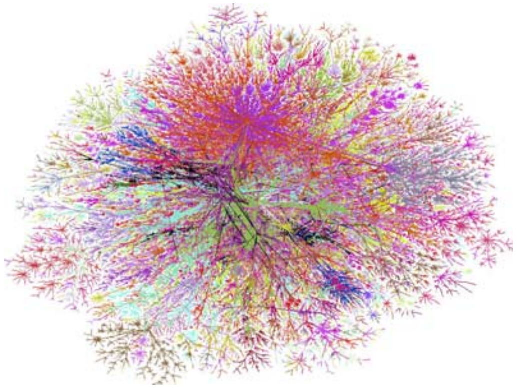


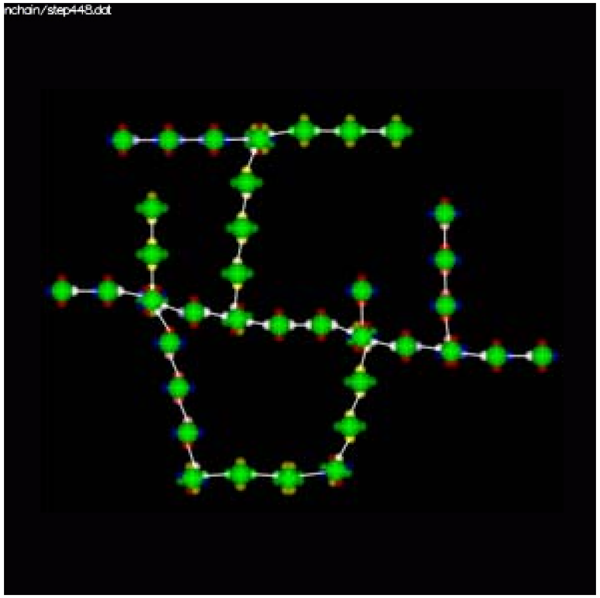
explosion in size and complexity of techno-social networks in all domains: energy, education, healthcare, business, defense

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

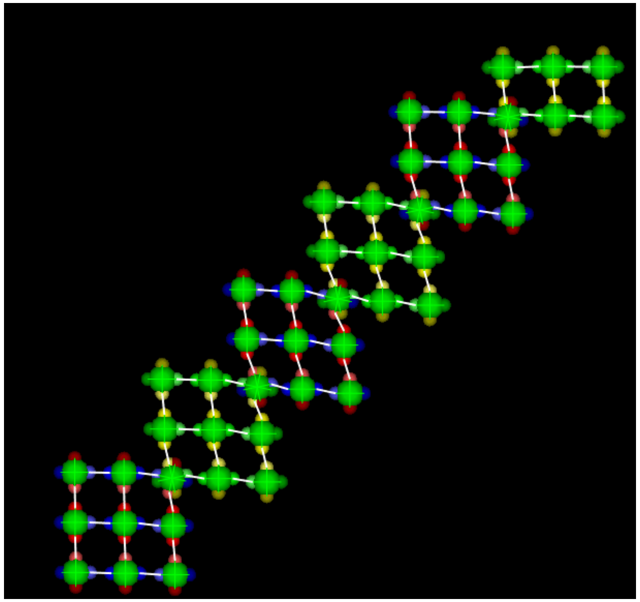
time to design new collaborative technologies to harness this decentralisation and emergence

From "scale-free" to architectured networks

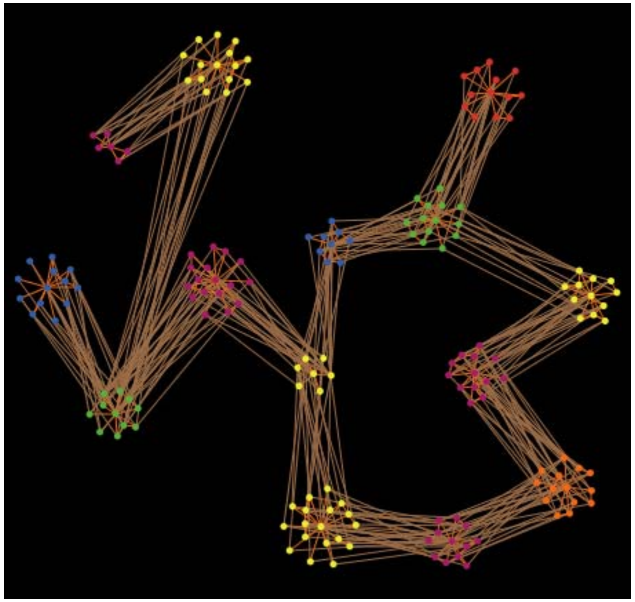




single-node
composite branching



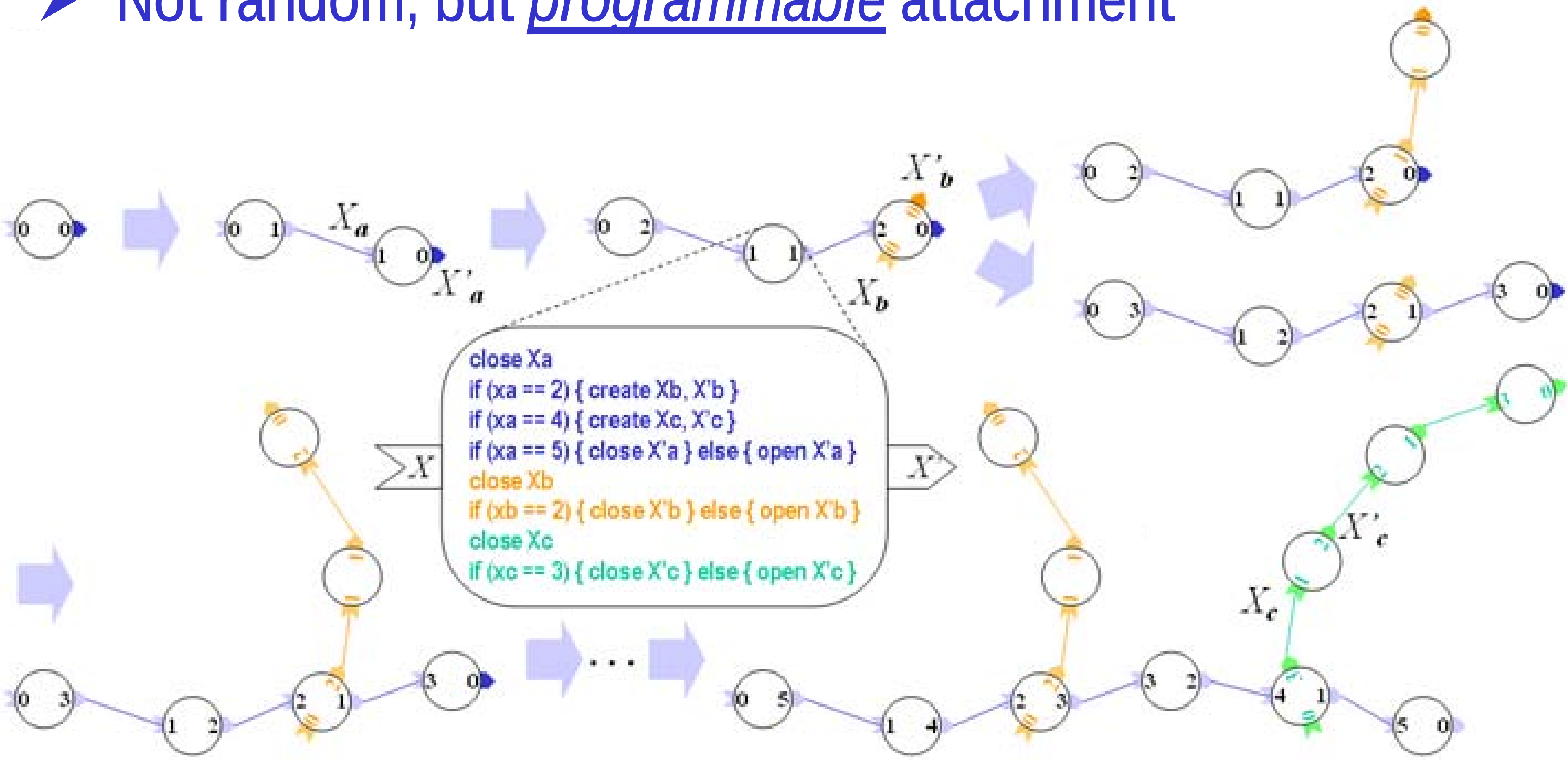
iterative lattice pile-up



clustered
composite branching

Self-knitting networks

- Not random, but *programmable* attachment



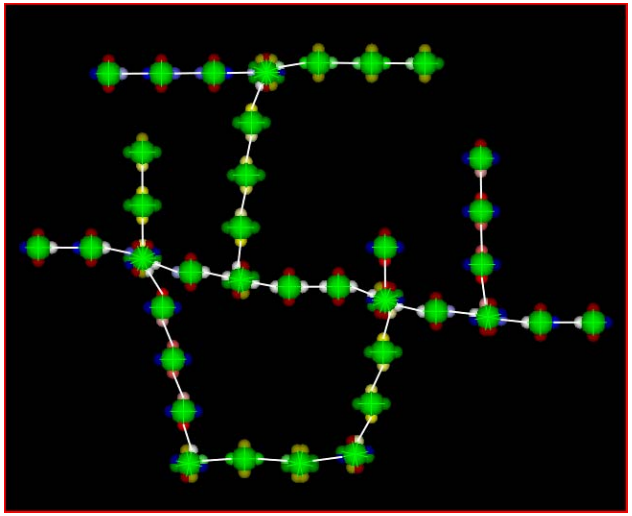
✓ a generalisation of morphogenesis in *n* dimensions

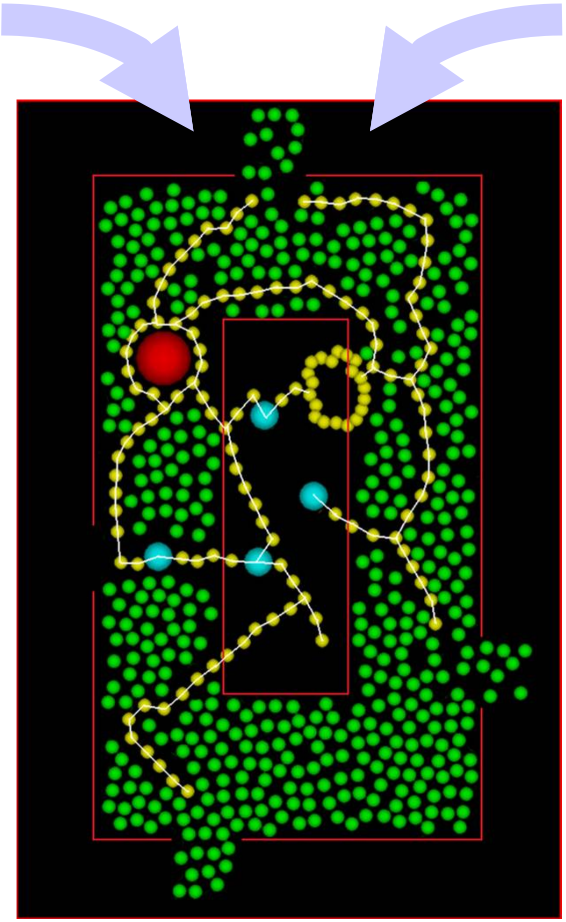
✓ the node routines are the *"genotype"* of the network

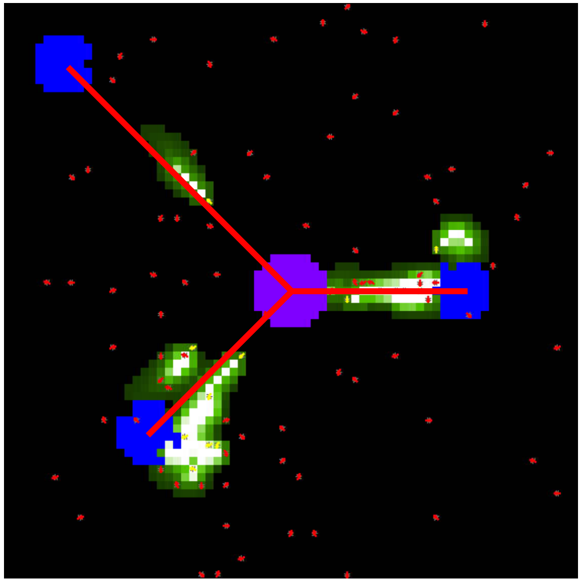
Self-organized programmable networks

➢ strong intrinsic morphology – no influence from the environment

➢ no intrinsic morphology – complete adaptation to the environment

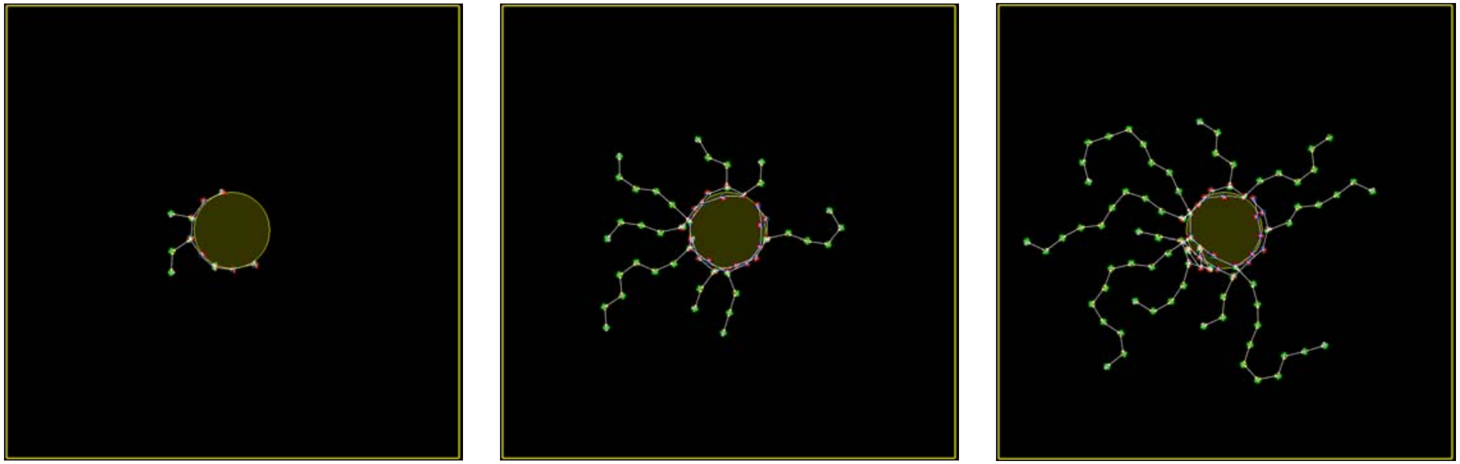


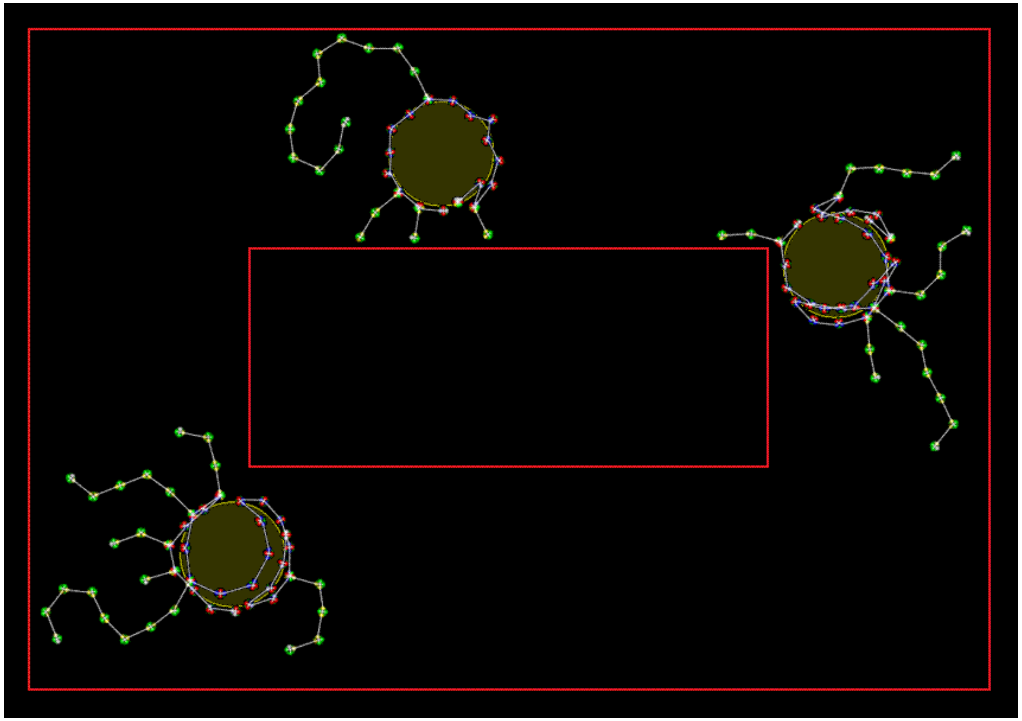




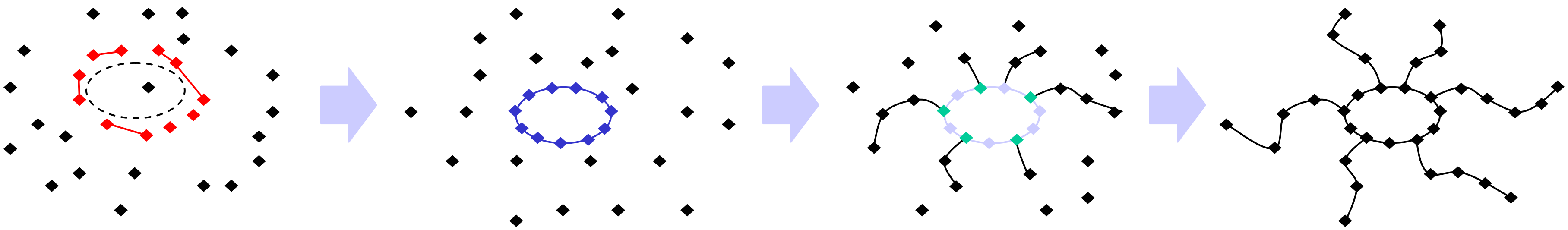
➢ intrinsic morphologies that are non-trivial *and* adapt dynamically to their environment

Order influenced (not imposed) by the environment

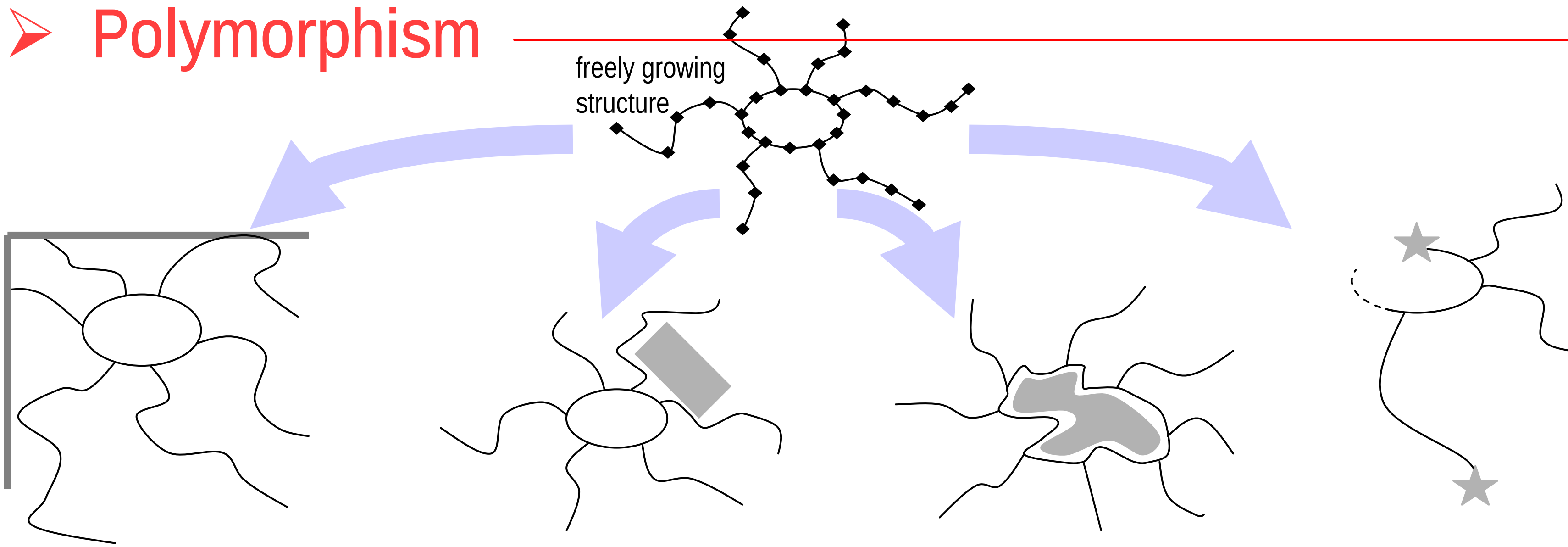




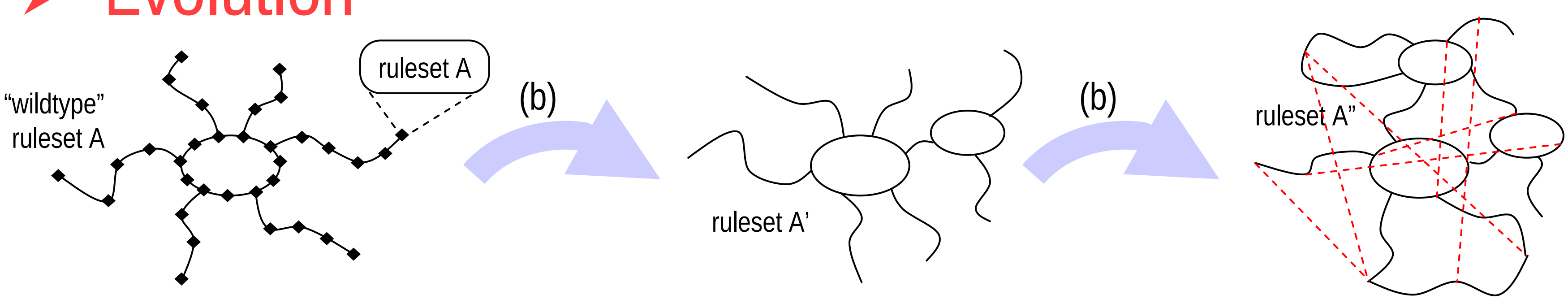
Development



Polymorphism



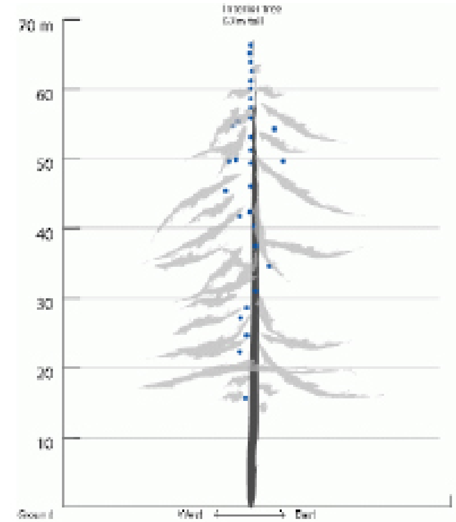
Evolution



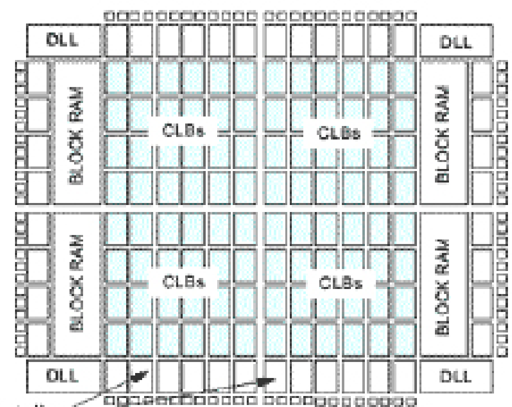
Spatial Computers

Robot Swarms

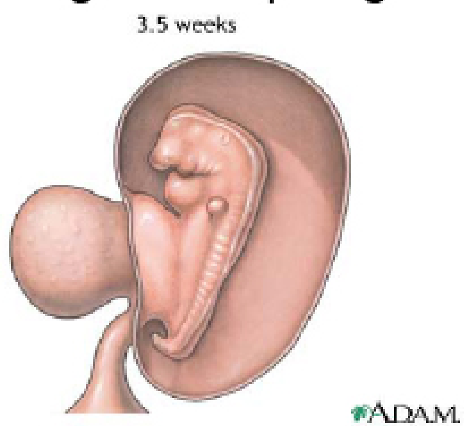
Biological Computing



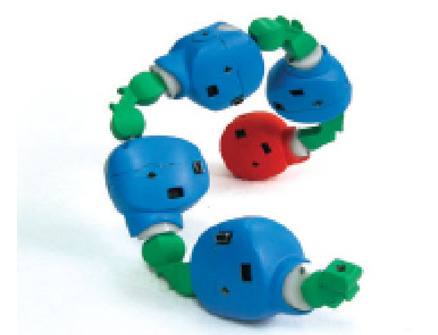
Sensor Networks



Reconfigurable Computing



Cells during Morphogenesis



Modular Robotics

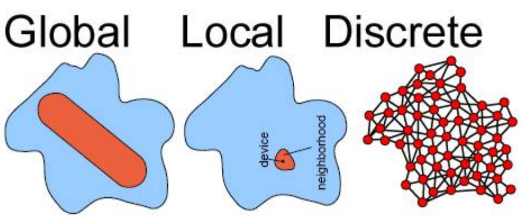
Slide from Jake Beal's course on Spatial Computing, 2009 (CSAIL, MIT)

Decentralized Network Engineering

➢ Methodologies and tools

✓ an original, young field of investigation without a strong theoretical framework yet – but close links with many established disciplines, which can give it a more formal structure through their own tools

- cellular automata, pattern formation
- collective motion, swarm intelligence (Ant Colony Optim. [Dorigo])
- gene regulatory networks: coupled dynamical systems, attractors
- spatial computing languages:
  PROTO [Beal] and MGS [Giavitto]
  (top-down compilation)



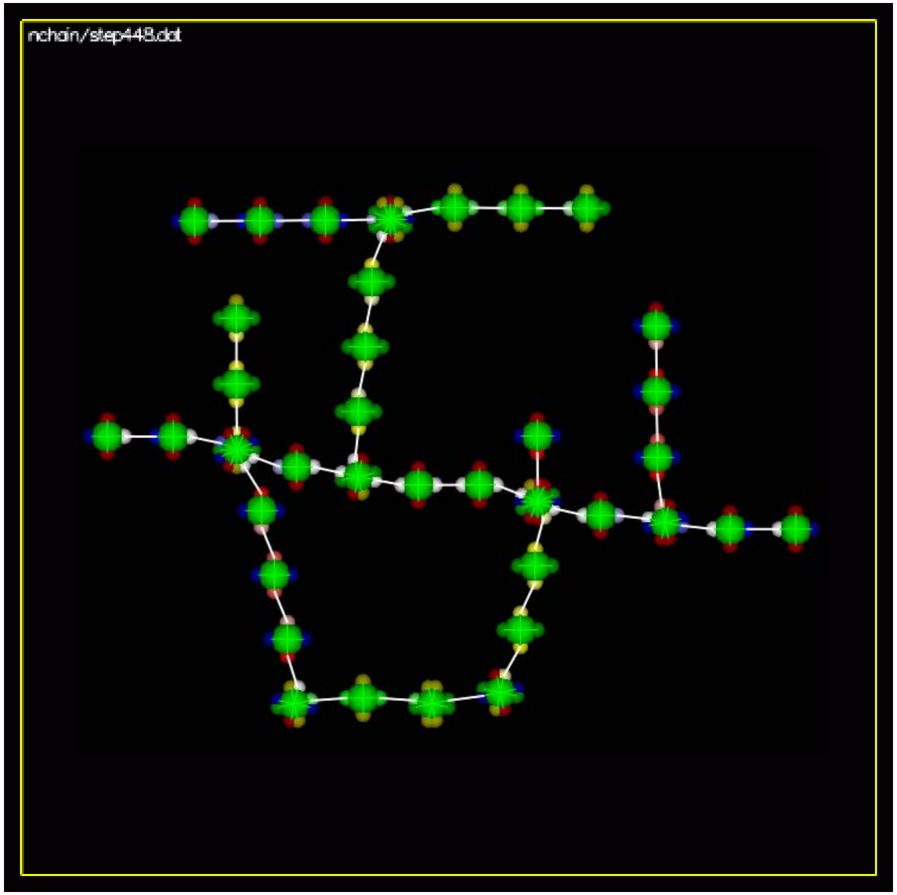
PROTO

- evolution: genetic algorithms, computational evolution [Banzhaf]
- Iterative Function Systems (IFS) [Lutton]

→ *goal: going beyond agent-based experiments and find an abstract description on a macroscopic level, for better control and proof*

Details: an abstract model of self-made network

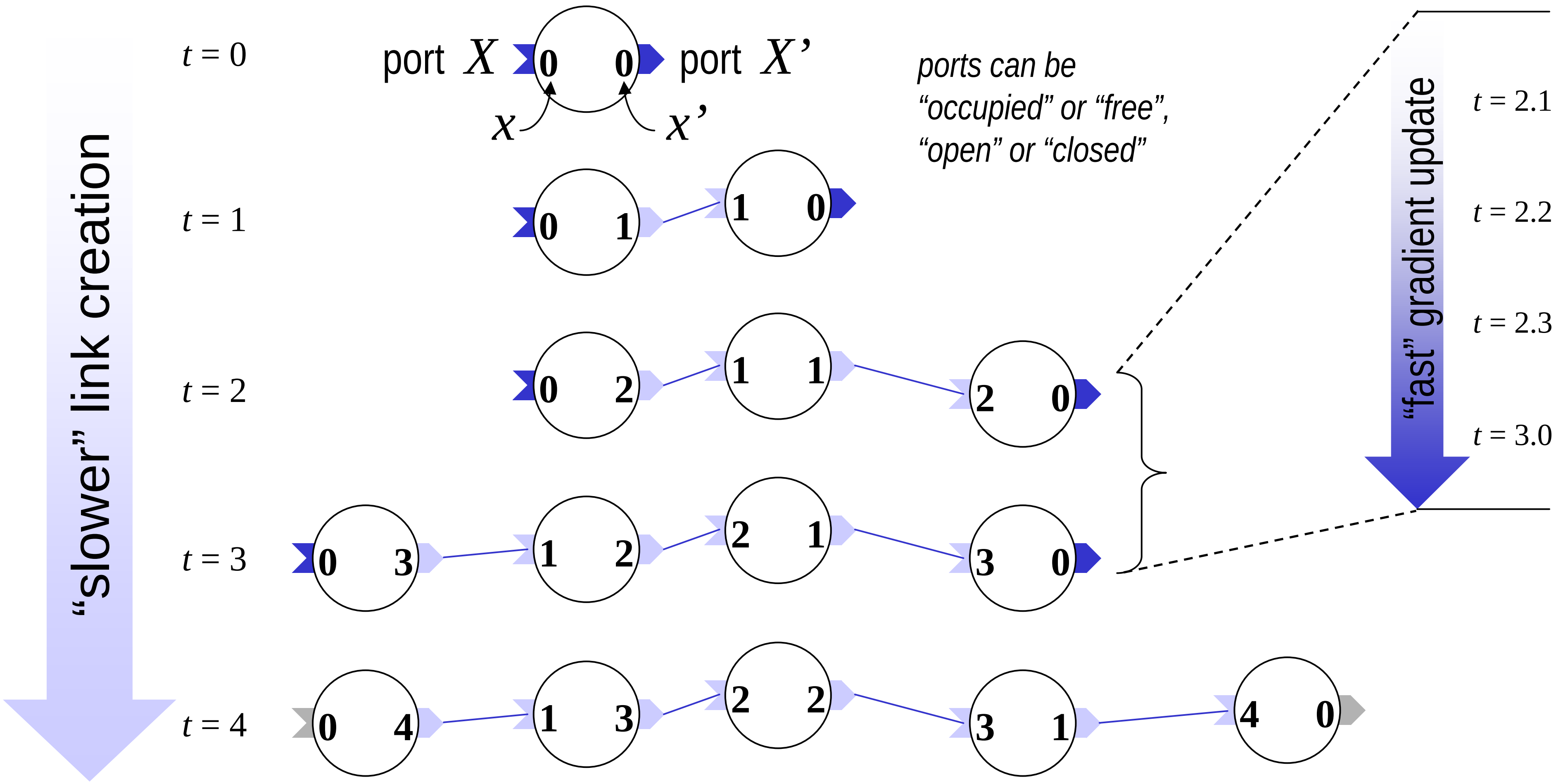
- Formation of a specific, reproducible structure
  - ✓ nodes attach randomly, but only to a few available ports



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

Abstract model of self-made network

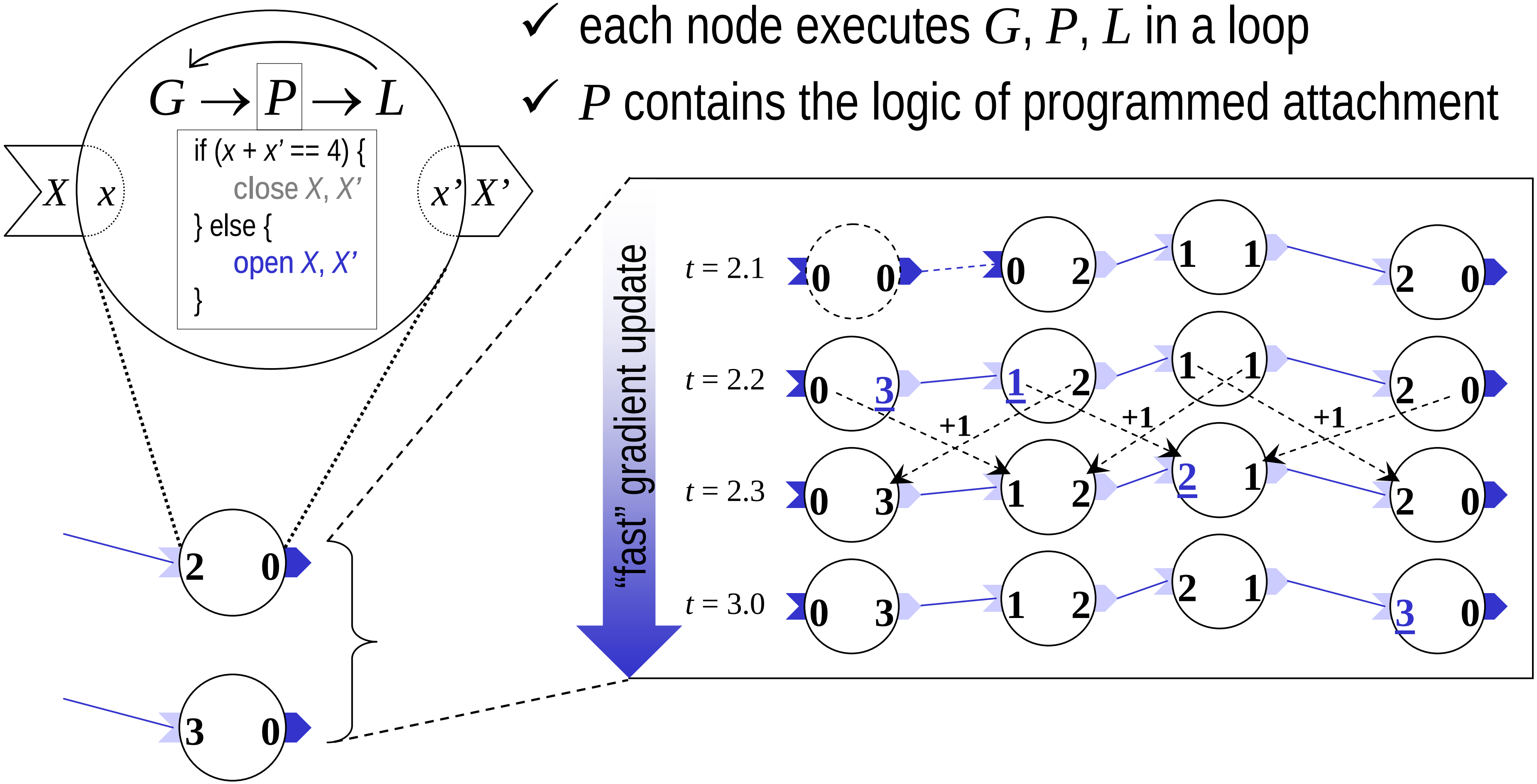
- Simple chaining
  - ✓ link creation (L) by programmed port management (P)



Abstract model of self-made network

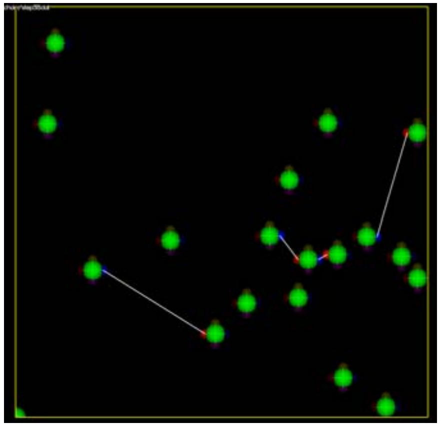
Simple chaining

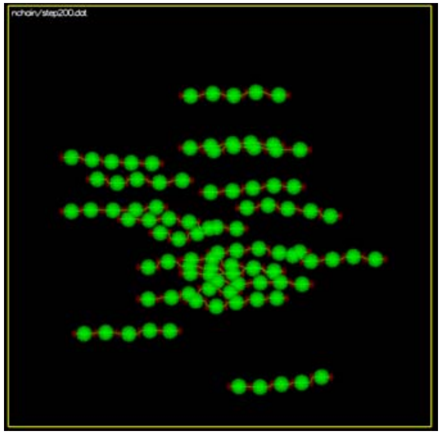
- ✓ port management (P) relies on gradient update (G)
- ✓ each node executes G, P, L in a loop
- ✓ P contains the logic of programmed attachment



Abstract model of self-made network

- Simple chaining

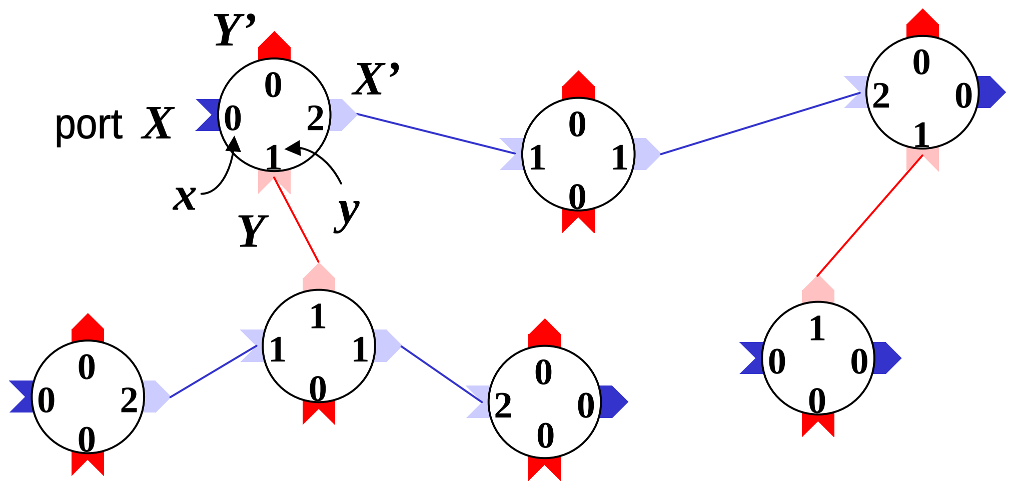




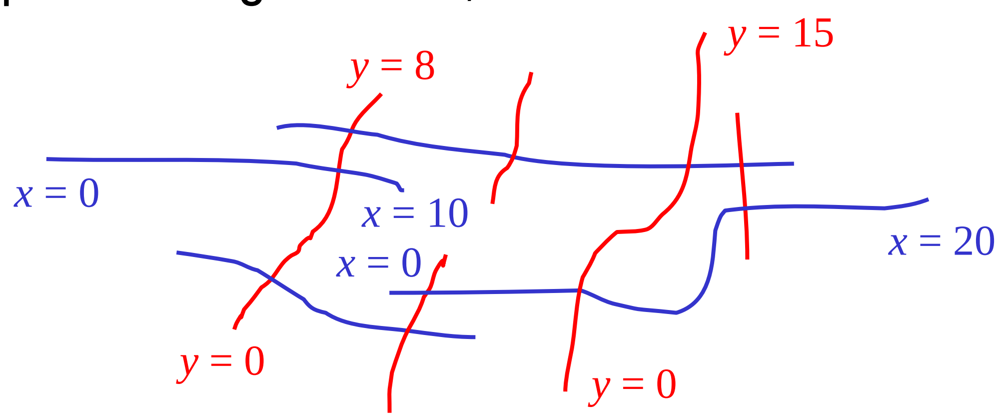
Abstract model of self-made network

➢ Lattice formation by guided attachment

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



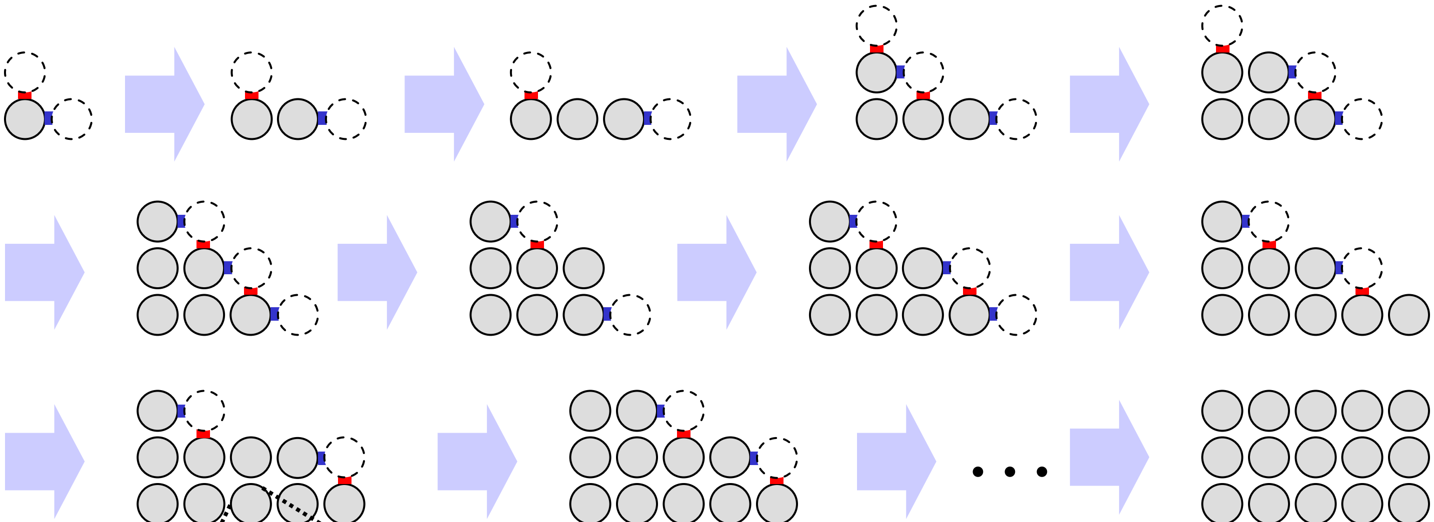
- ✓ without port management *P*, chains form and intersect randomly

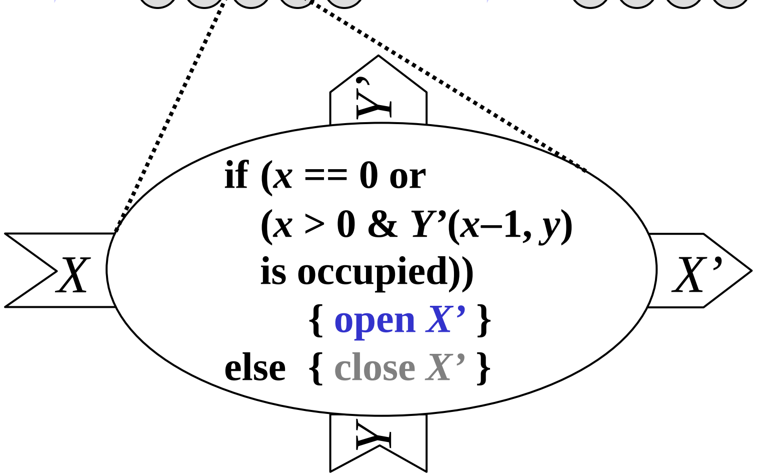


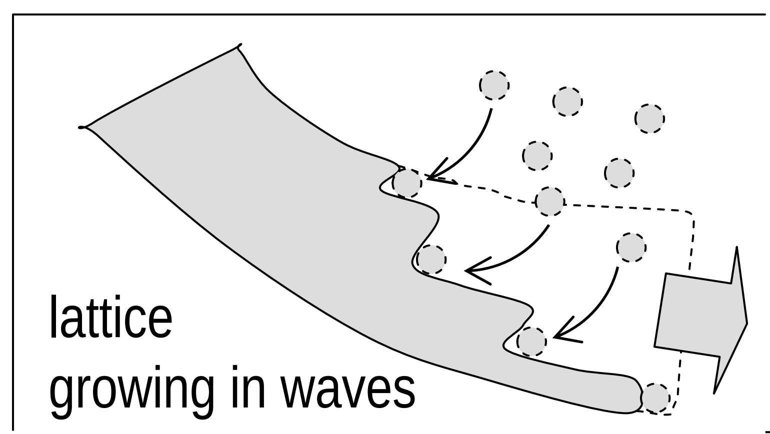
Abstract model of self-made network

➢ Lattice formation by guided attachment

- ✓ only specific spots are open, similar to beacons on a landing runway



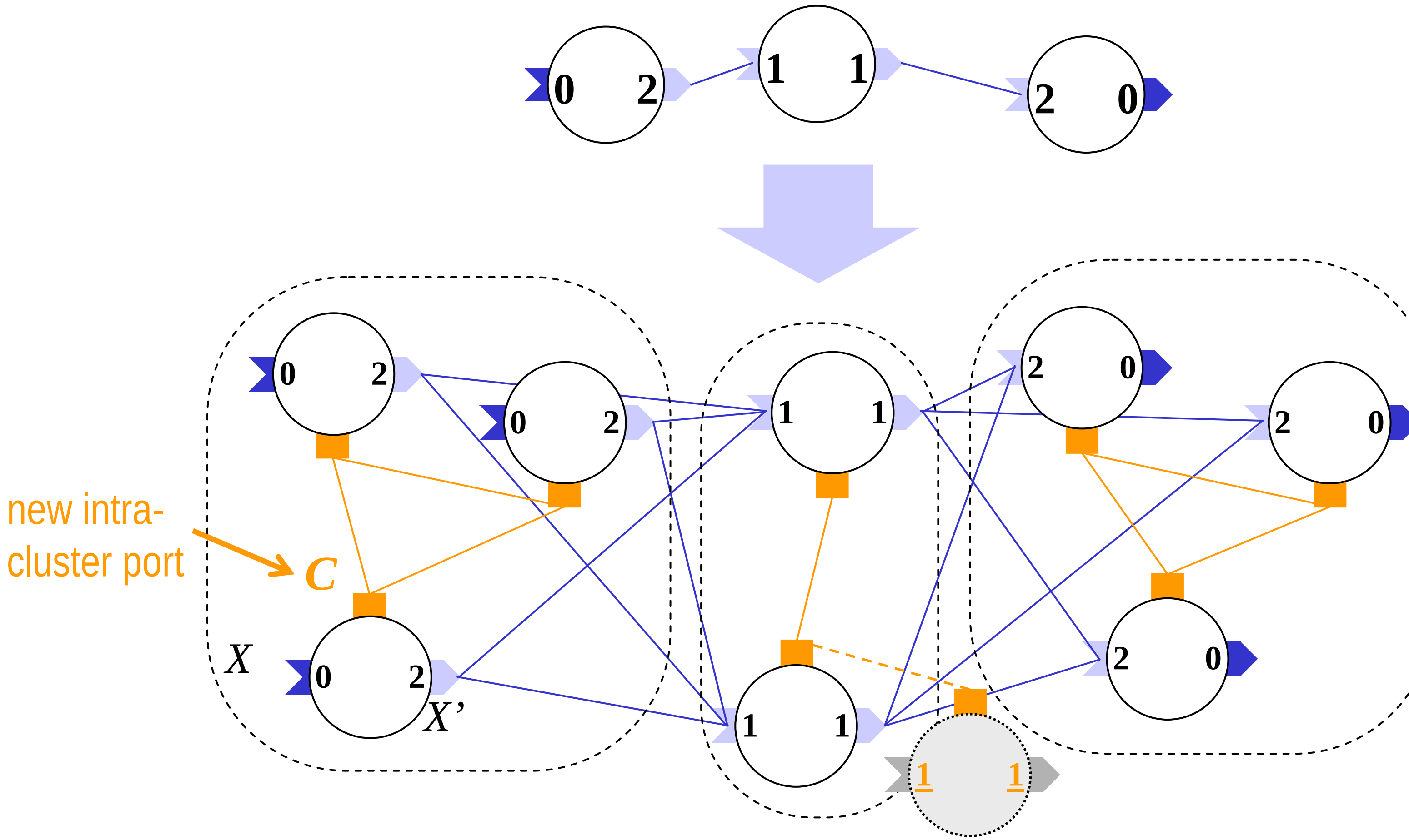




Abstract model of self-made network

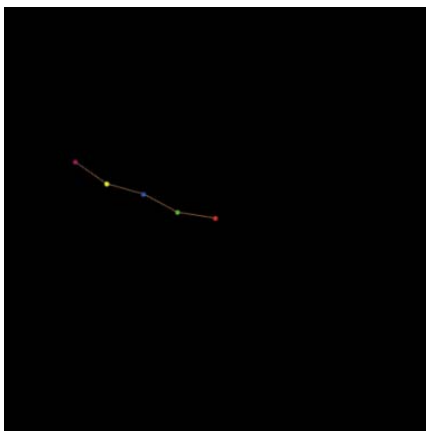
Cluster chains and lattices

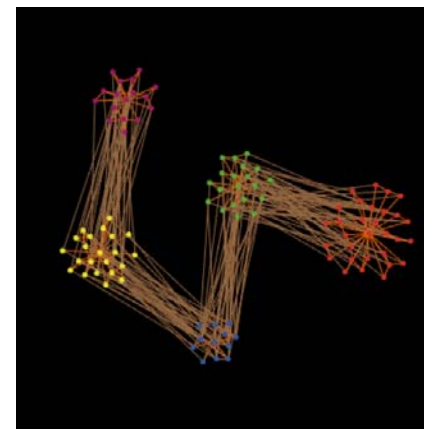
- ✓ several nodes per location: reintroducing randomness but only within the constraints of a specific structure



Abstract model of self-made network

- Cluster chains and lattices

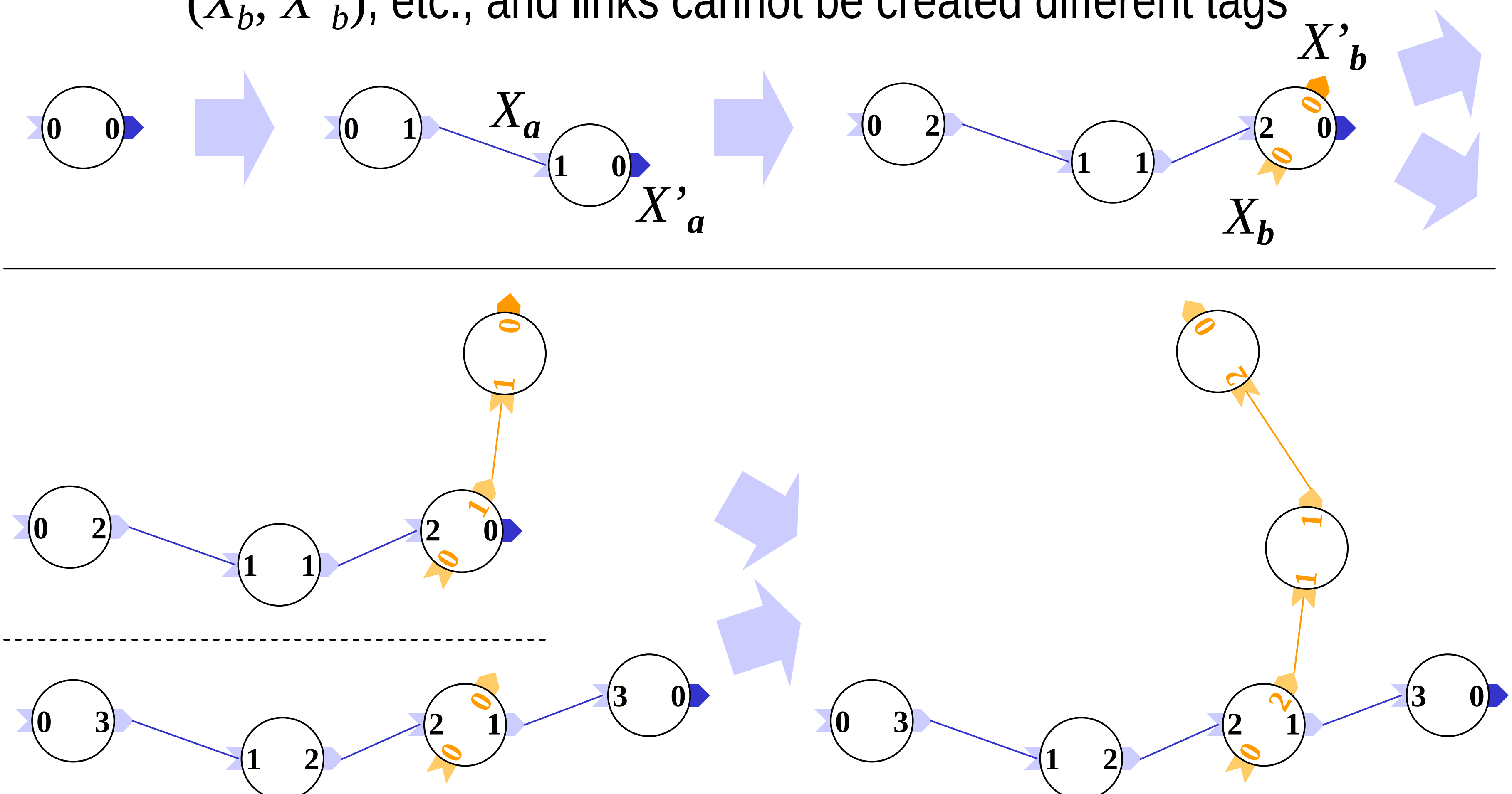




Abstract model of self-made network

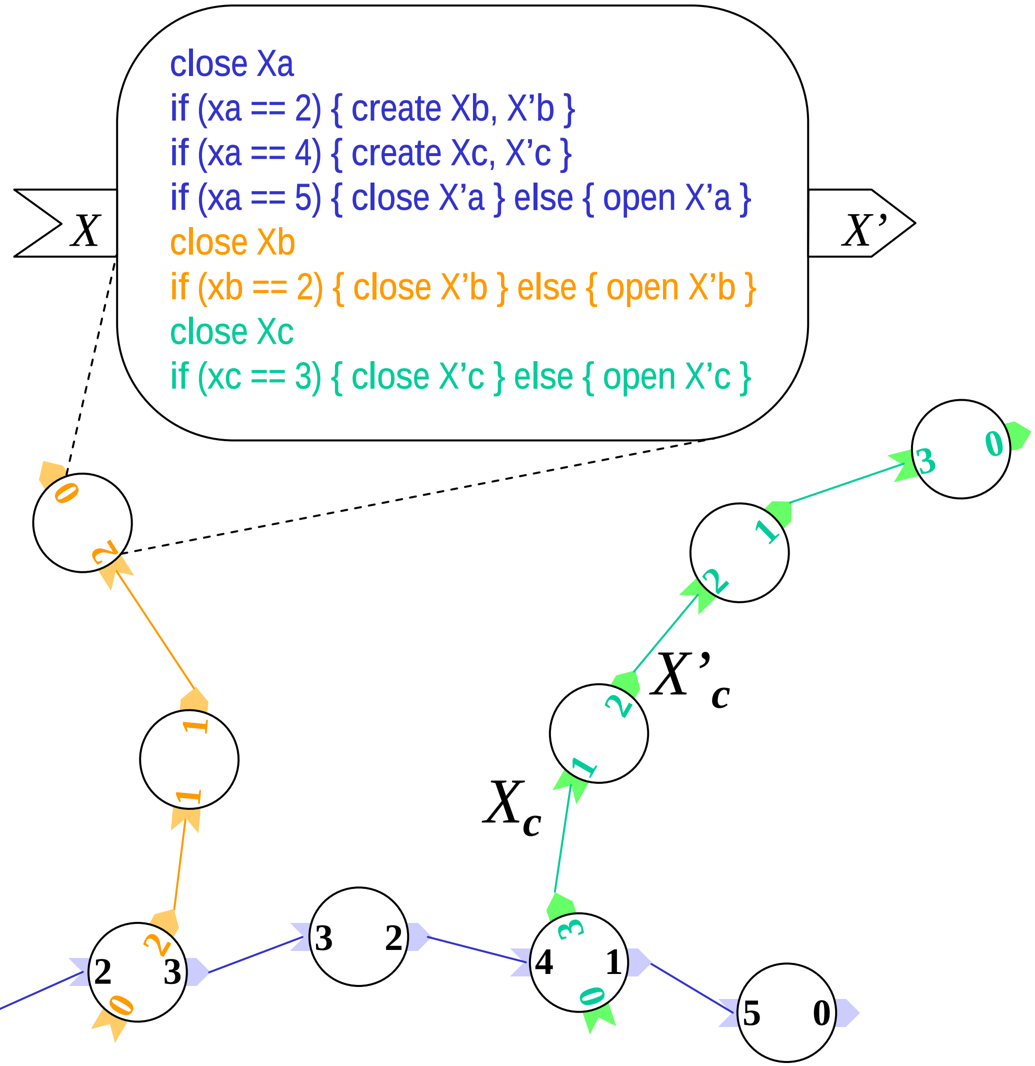
➢ Modular structures by local gradients

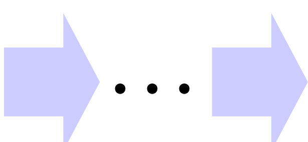
✓ modeled here by different coordinate systems, (X_a, X'_a), (X_b, X'_b), etc., and links cannot be created different tags



Abstract model of self-made network

- Modular structures by local gradients
  - the node routines are the *“genotype”* of the network





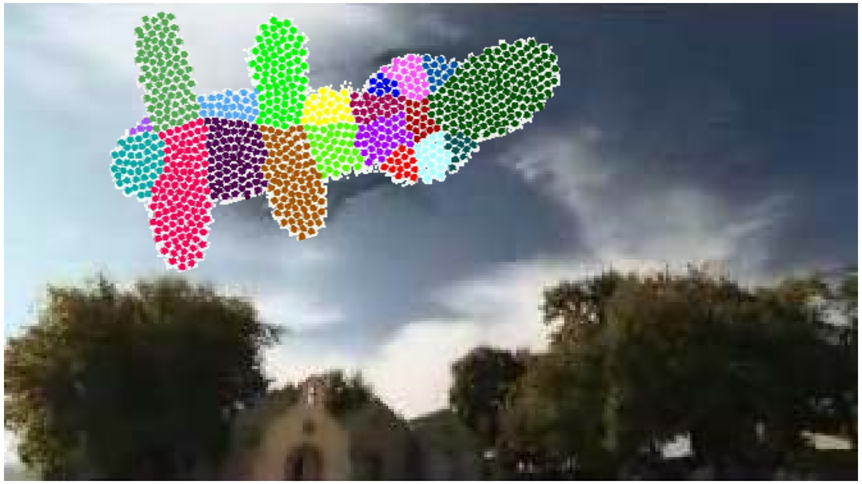
Morphogenetic Engineering, ANTS 2010, Brussels

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

+ Springer book in preparation



Thank you

Embryomorphic Engineering

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