Evolutionary developmental systems as "self-made puzzles" that can be programmed:

Lessons from biological morphogenesis

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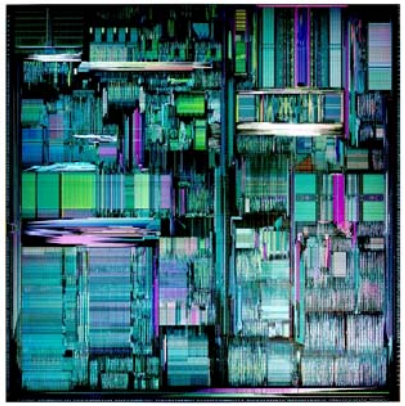
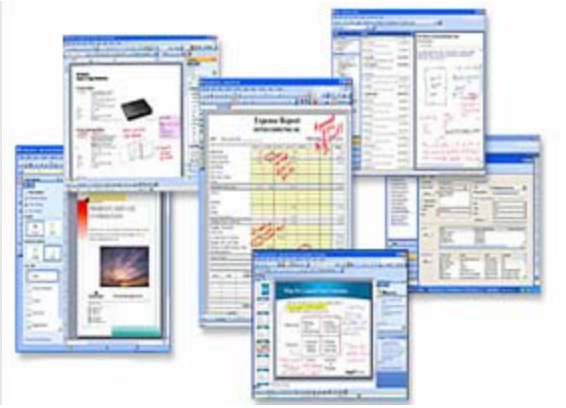
INSTITUT DES SYSTEMES COMPLEXES

De facto complexity of engineering (ICT) systems

- Ineluctable breakup into myriads of modules/components,
  Desirable

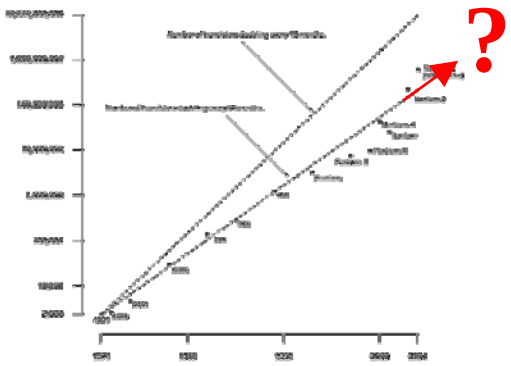


in hardware,

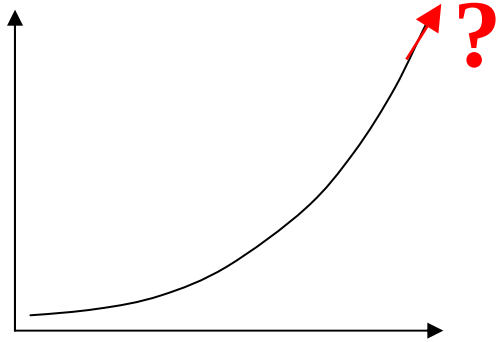


software,

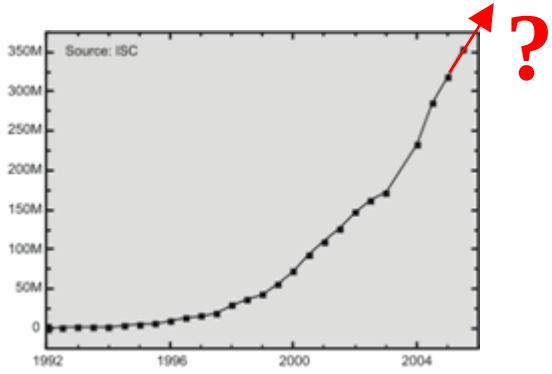
or networks, ...



number of transistors/year



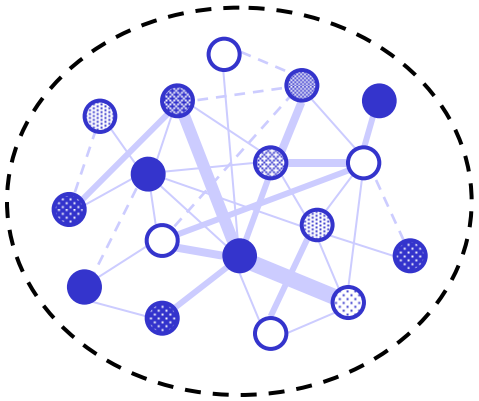
number of O/S lines of code/year



number of network hosts/year

Embracing complexity in design & design in complexity

➢ We are faced with complex systems in many domains

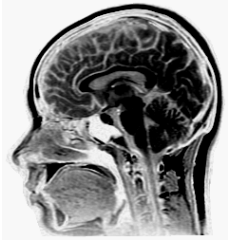


- large number of elementary **agents** interacting **locally**
- simple individual behaviors creating a complex **emergent** collective behavior
- ***decentralized*** *dynamics: no master blueprint or grand architect*

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

pattern formation
○ = matter

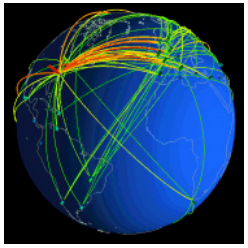
biological development
○ = cell



the brain & cognition
○ = neuron

insect colonies
○ = ant

Internet & Web
○ = host/page



social networks
○ = person

From natural CS to designed CS and back

- The challenges of complex systems (CS) research

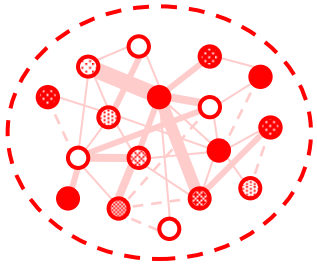
Transfers
- among systems

CS science: understanding "natural" CS

(spontaneously emergent, including human activity)

Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

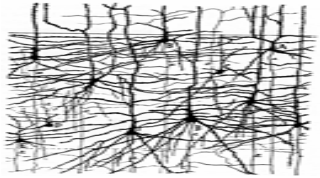
Imports
- observe, model
- control, harness
- design, use



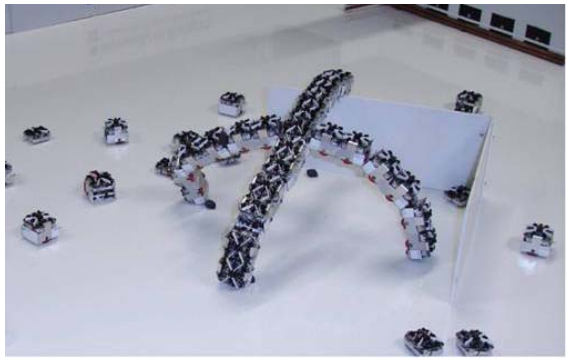
CS engineering: designing a new generation of "artificial" CS (harnessed & tamed, including nature)

The need for morphogenetic abilities: self-architecturing

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

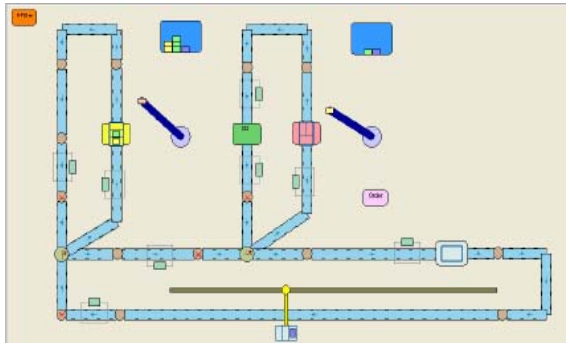


  - ✓ need for morphogenetic abilities in computer science & AI
    - self-forming robot swarm
    - self-architecturing software
    - self-connecting micro-components



http://www.symbrion.eu

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



MAST agents, Rockwell Automation Research Center
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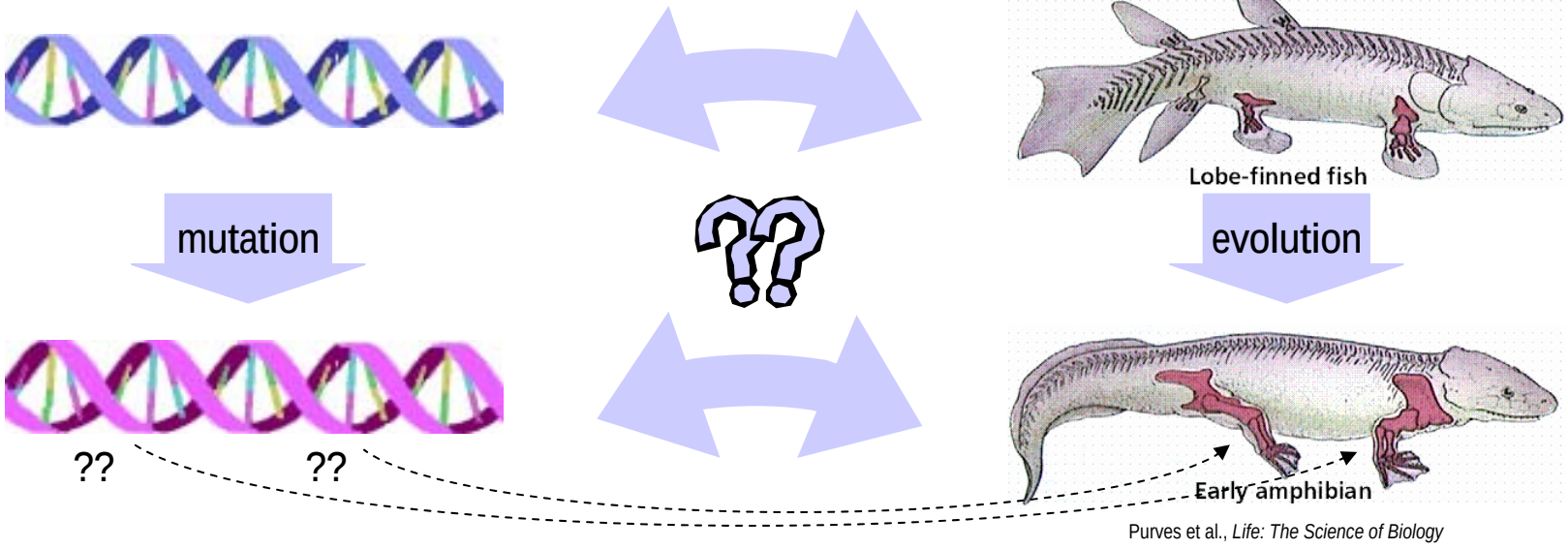
Toward “evo-devo” engineering

- **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**



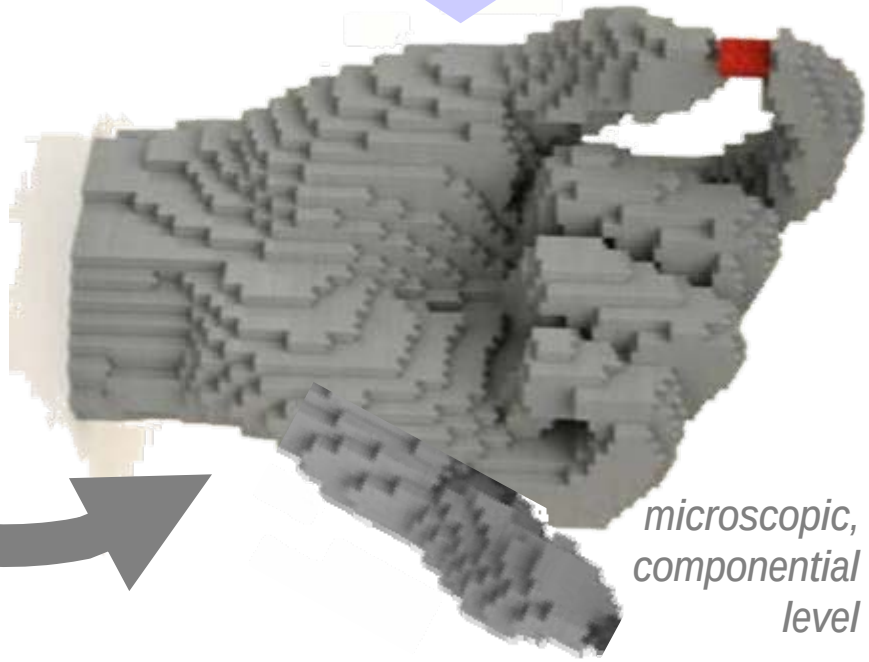
Purves et al., *Life: The Science of Biology*

Toward “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.”

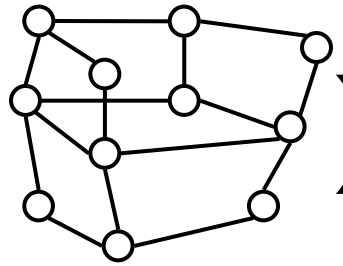


microscopic, componential level

Toward “evo-devo” engineering

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

more or less direct representation

≈ () ≈

Amy L. Rawson
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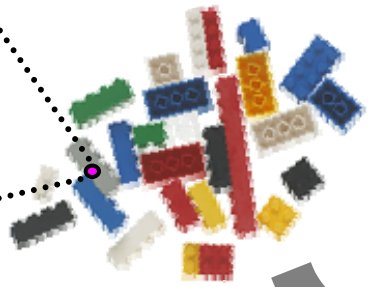
macroscopic, emergent level

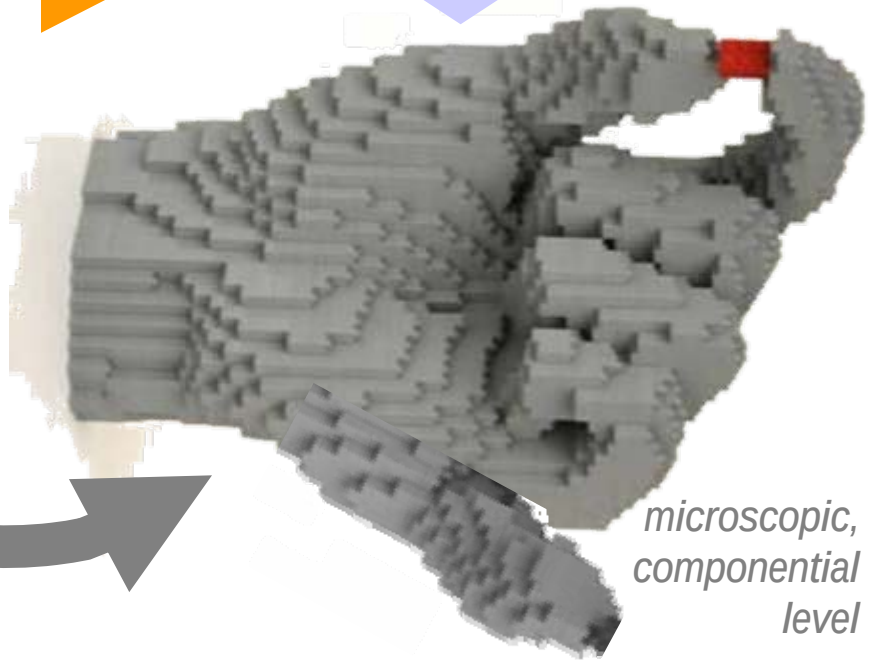
Genotype

“Transformation”?

Phenotype

generic elementary rules of self-assembly



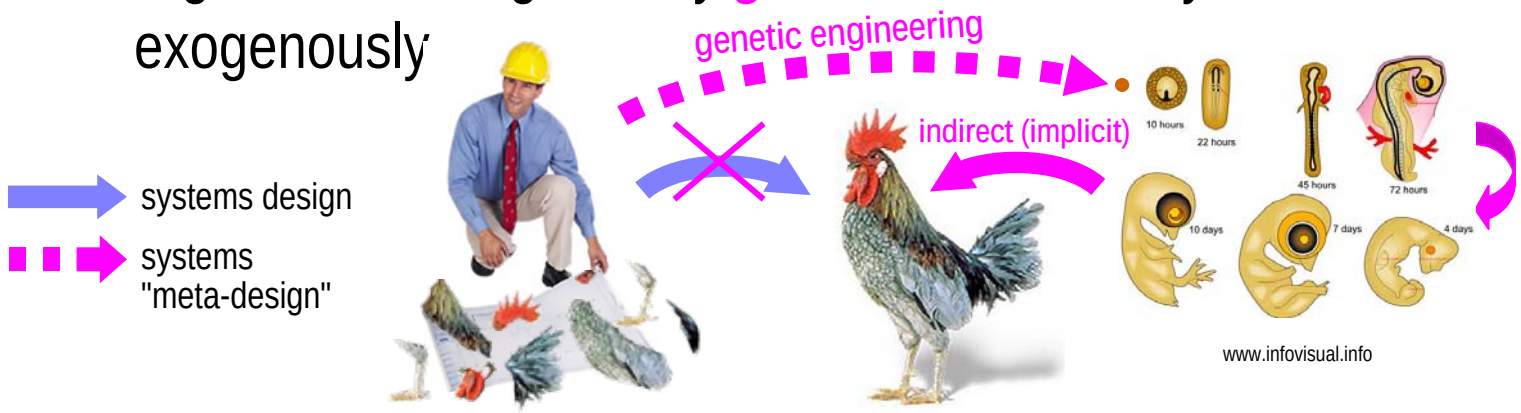


Nathan Sawaya
www.brickartist.com

microscopic, componential level

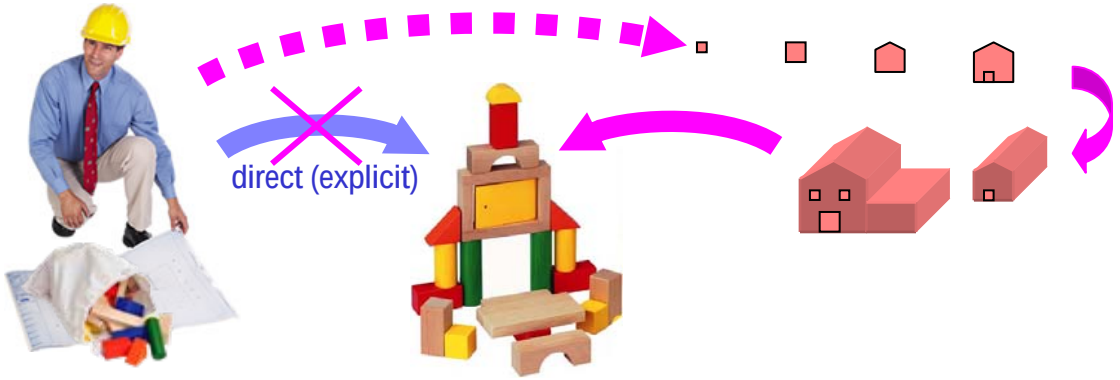
Toward “evo-devo” engineering

- ... and of Evolutionary Computation: toward “meta-design”
  - ✓ organisms endogenously *grow* but artificial systems *are built* exogenously

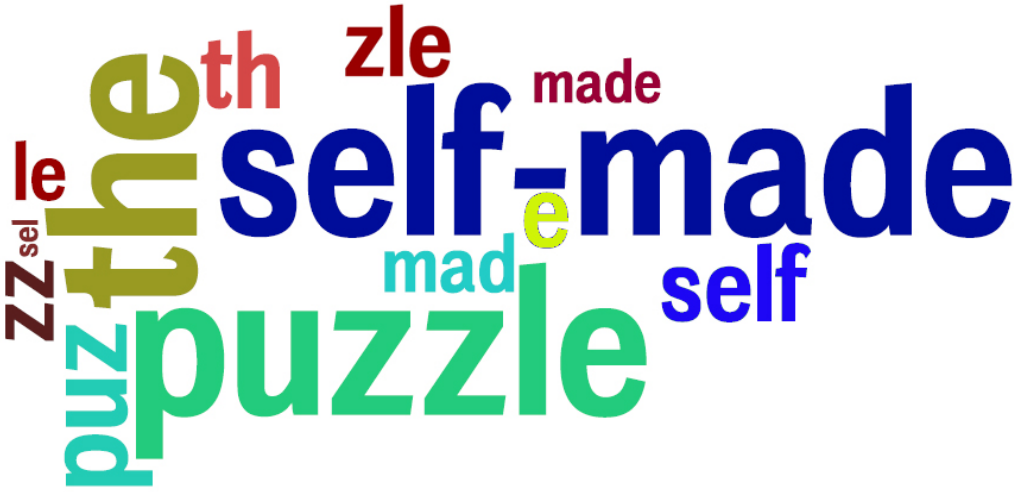


  - ✓ could engineers “step back” from their creation and only set *generic* conditions for systems to self-assemble?

instead of building the system from the top (phenotype), program the components from the bottom (genotype)



The evolutionary “self-made puzzle” paradigm



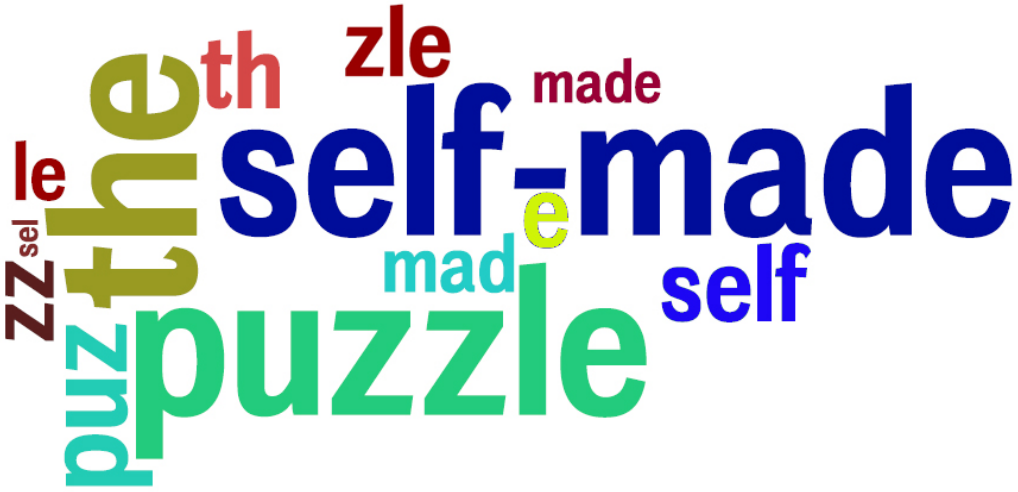
a. Construe systems as *self-assembling (developing) puzzles*

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



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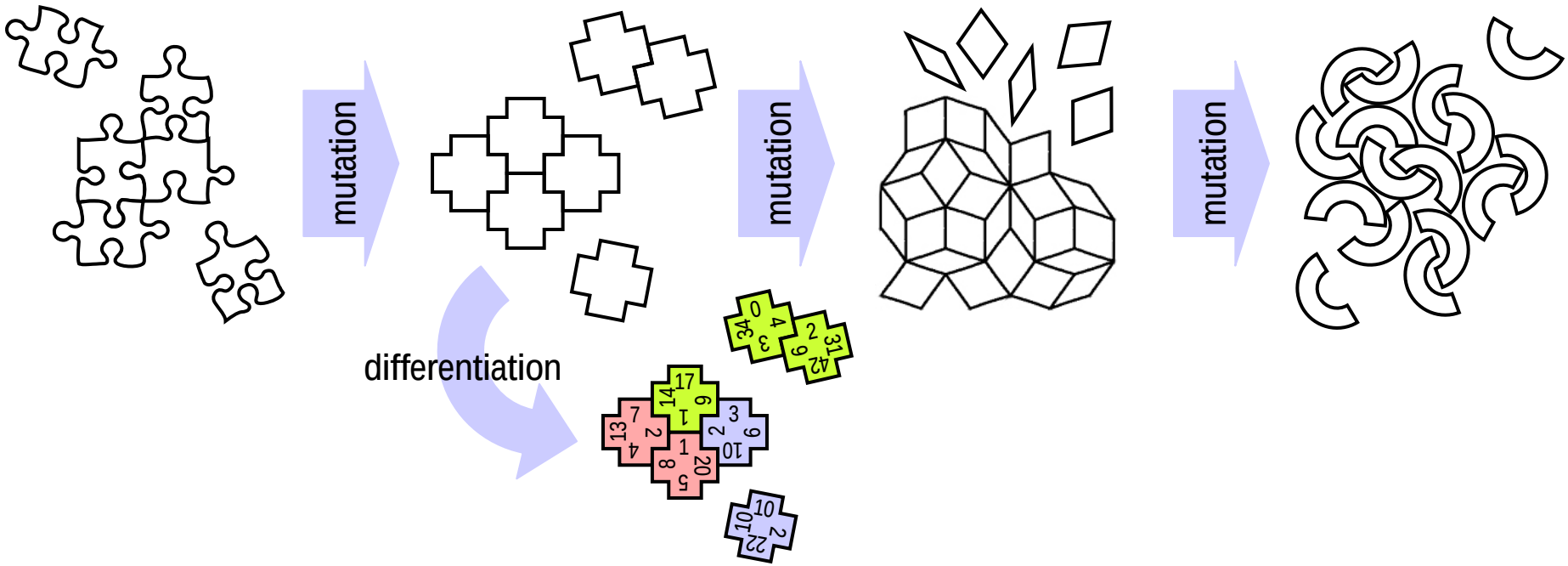


Systems that are self-organized and architectured

the challenge for complex systems: integrate a true ***architecture***

Peugeot Picasso

the challenge for complicated systems: integrate ***self-organization***

free self-organization

deliberate design

evolve the birds!

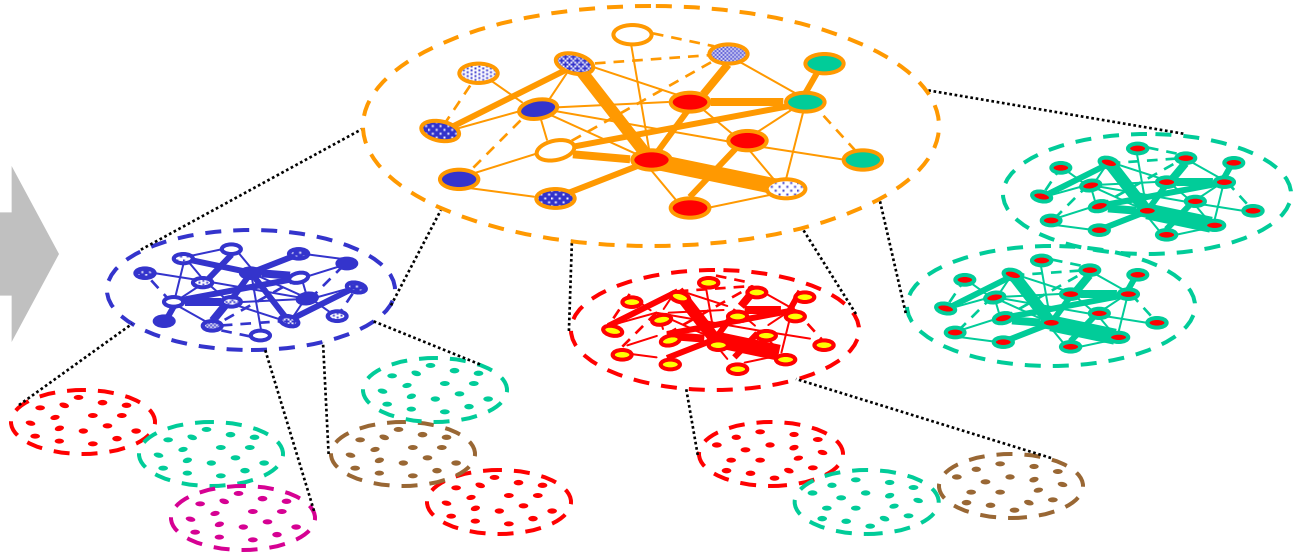
Peugeot Picasso

decompose the system!

designed self-organization / self-organized design

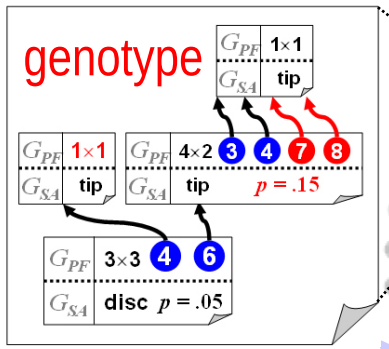
The challenges of developmental systems

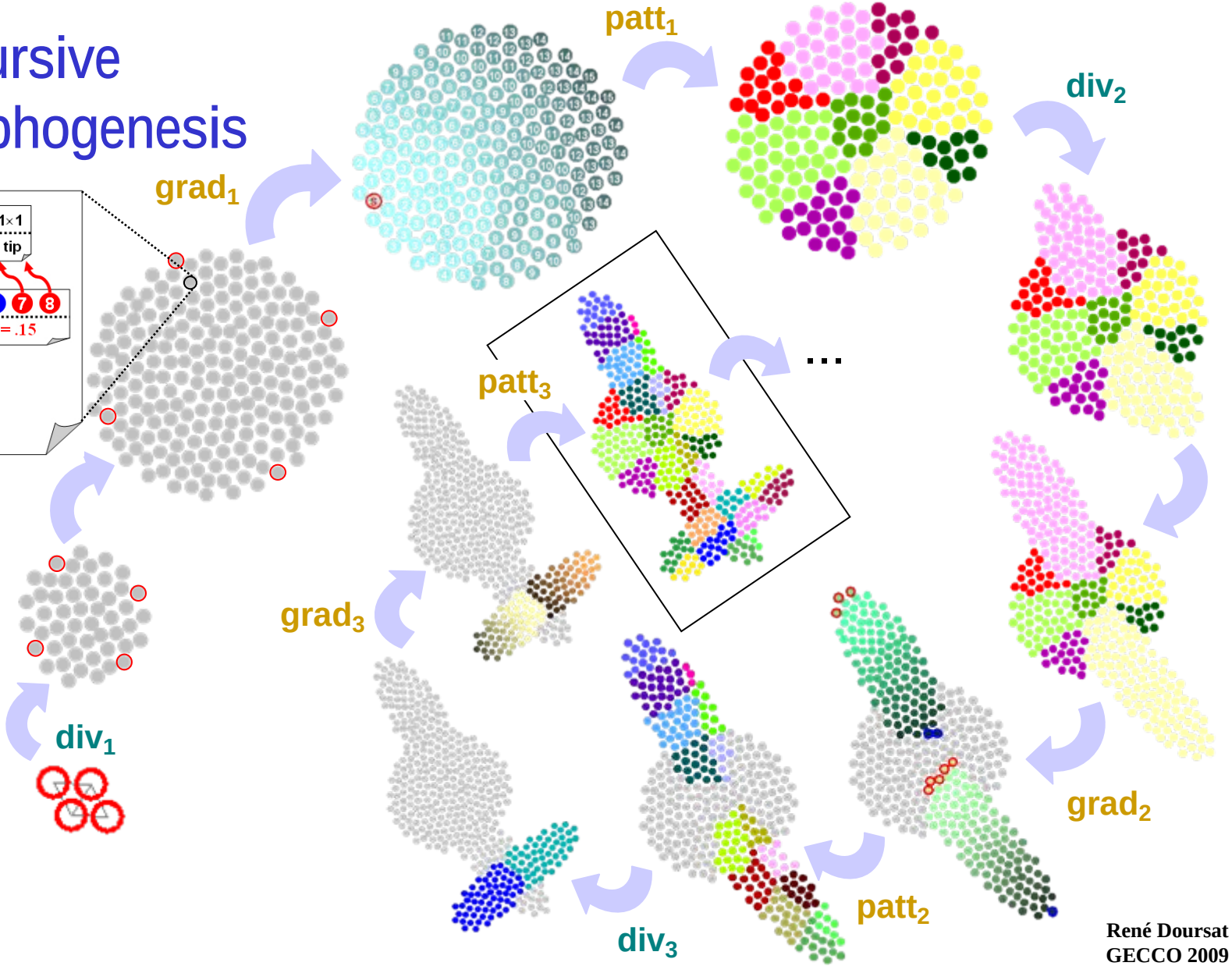
- Going beyond the “soup” of complexity
  - ✓ “complex” doesn’t necessarily imply “homogeneous”...
    → *heterogeneous agents and diverse patterns, via positions*
  - ✓ “complex” doesn’t necessarily imply “flat” (or “scale-free”)...
    → *modular, hierarchical, detailed architecture (at specific scales)*
  - ✓ “complex” doesn’t necessarily imply “random”...
    → *reproducible patterns relying on programmable agents*



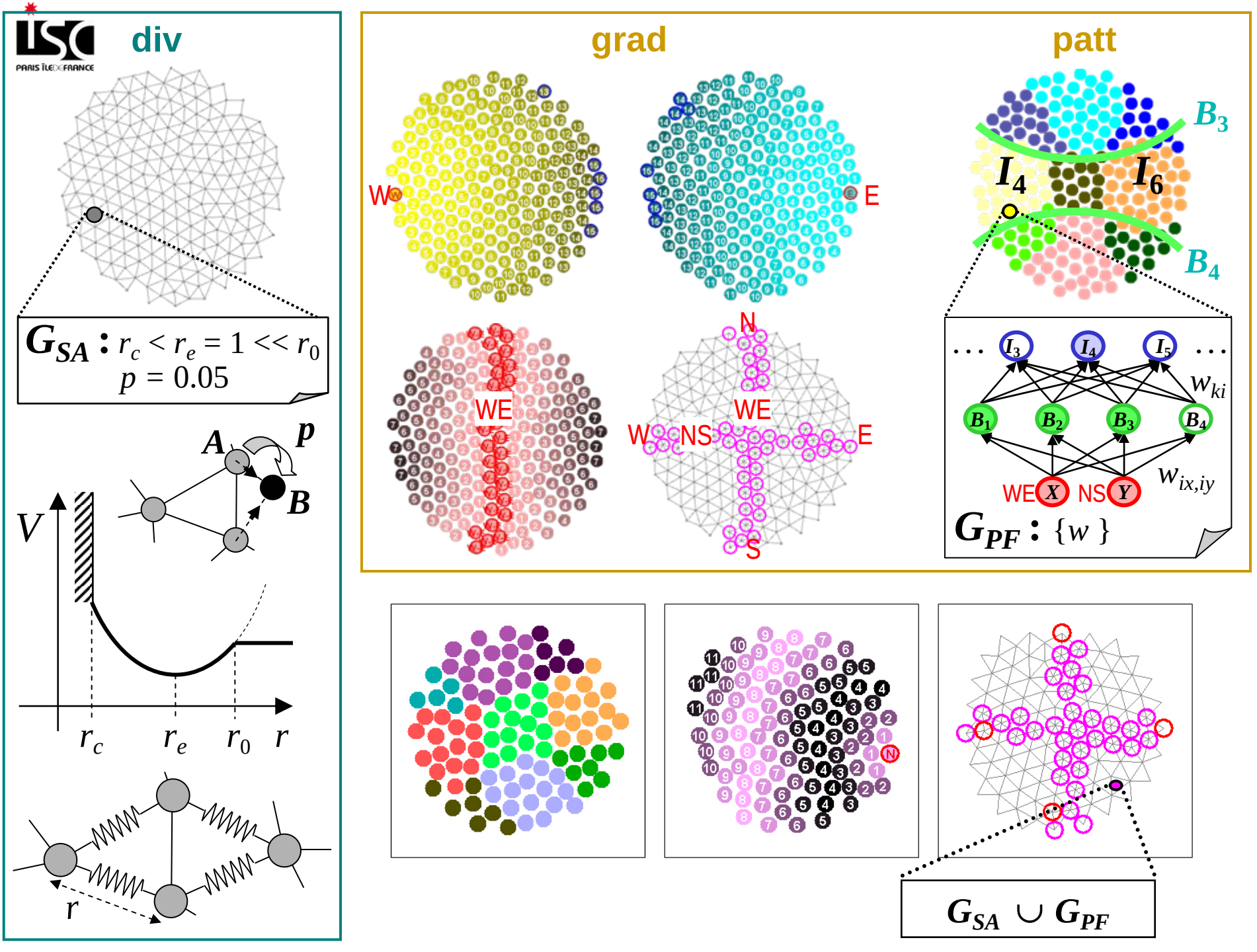
An example of developmental “meta-design”...

- Recursive morphogenesis





René Doursat
GECCO 2009


div
G_{SA} : $r_c < r_e = 1 << r_0$
$p = 0.05$
A
p
B
V
r_c
r_e
r_0
r
r
grad
W
E
WE
N
WE
W
NS
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S
patt
B_3
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I_6
B_4
I_3
I_4
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w_{ki}
B_1
B_2
B_3
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WE
X
NS
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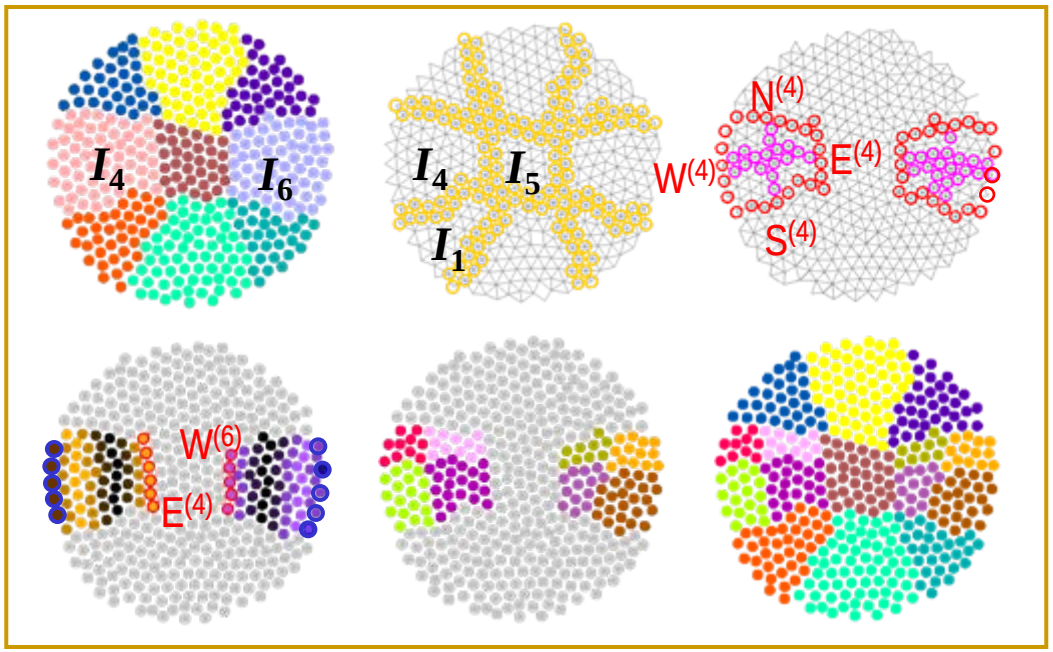
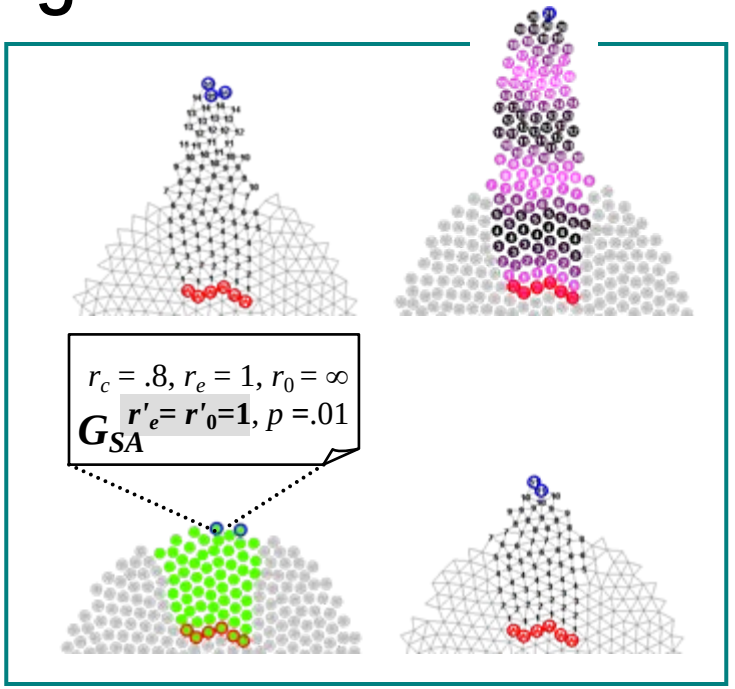
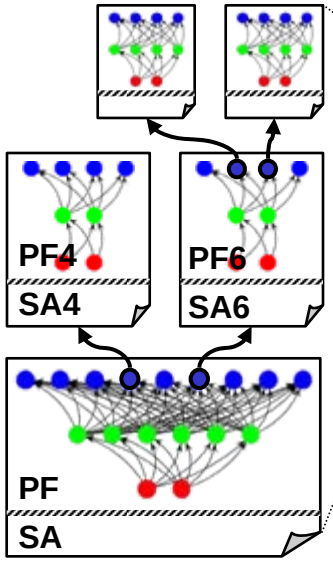
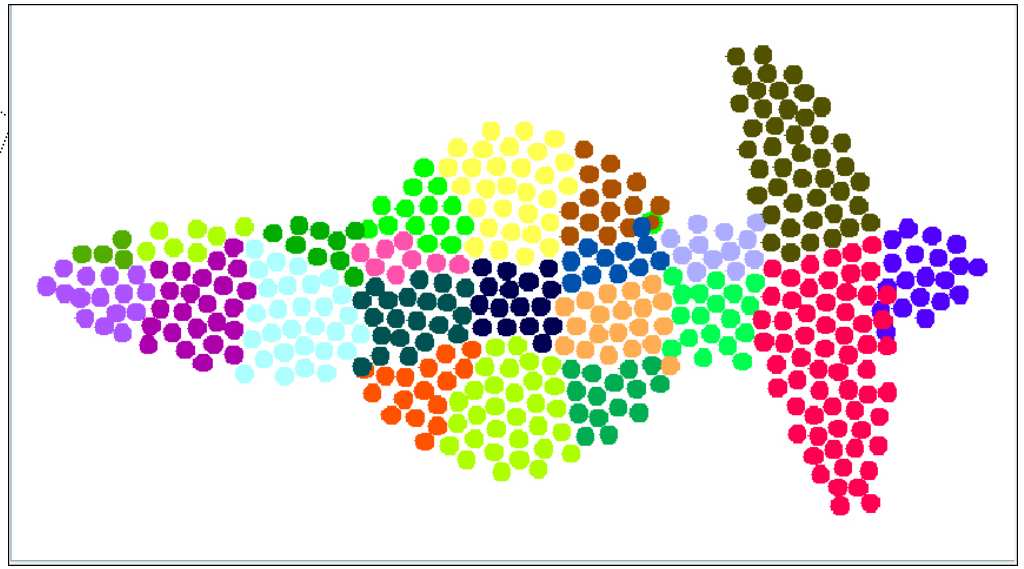
$w_{ix,iy}$
G_{PF} : {w }
$G_{SA} \cup G_{PF}$

Hierarchical morphogenesis





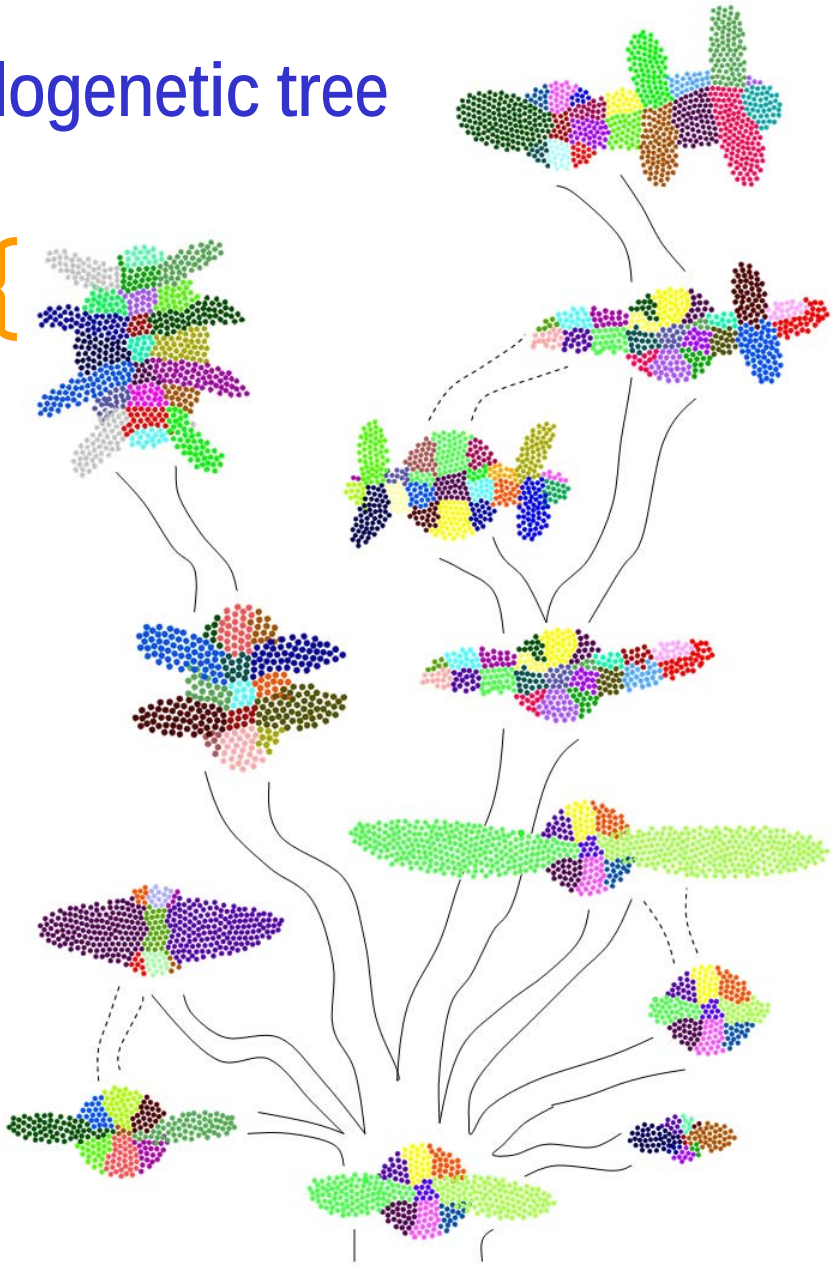




... supporting fine-grained evolutionary innovation

- Artificial phylogenetic tree

production of structural innovation



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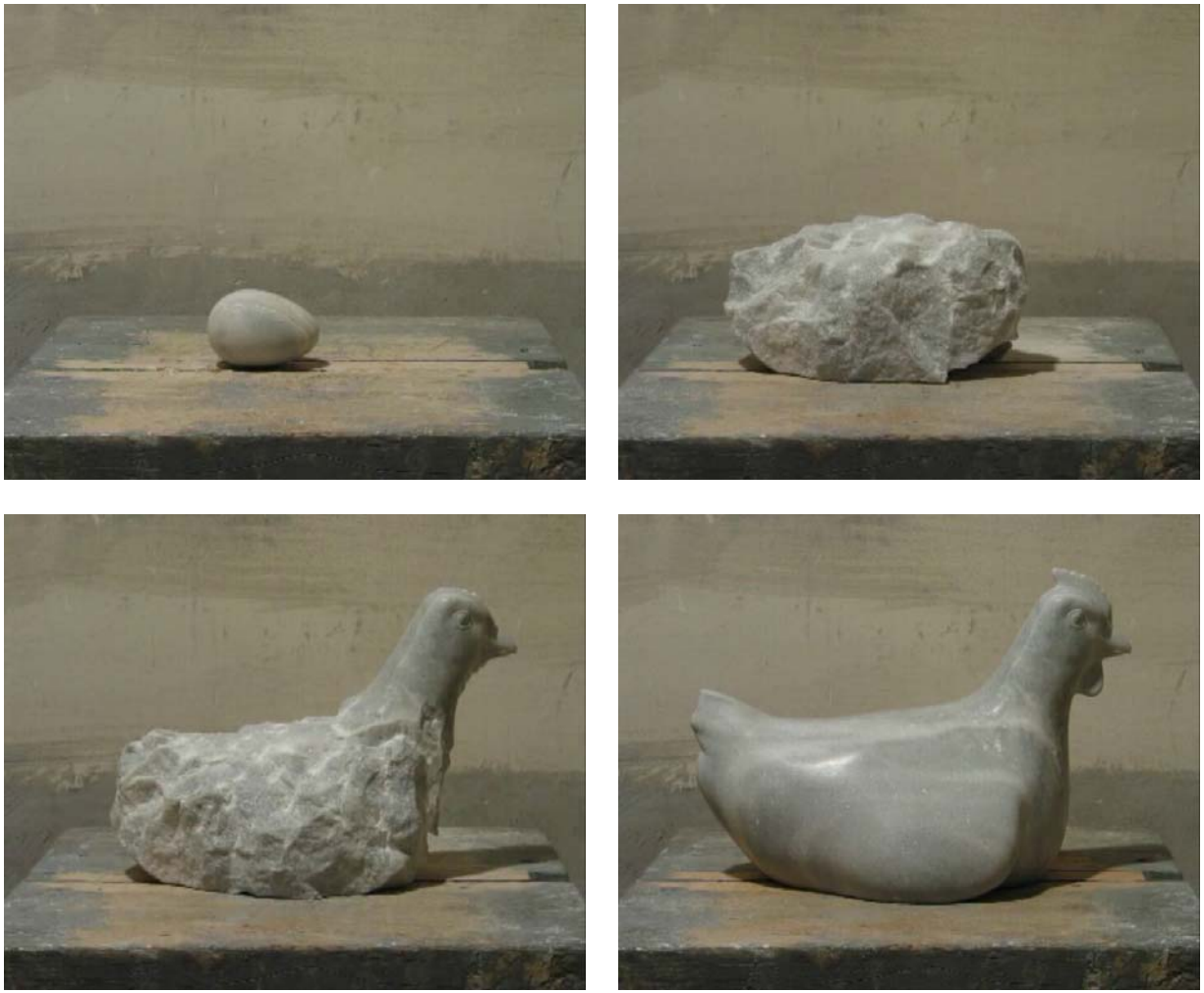
The Self-Made Puzzle



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