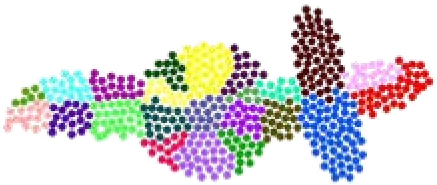
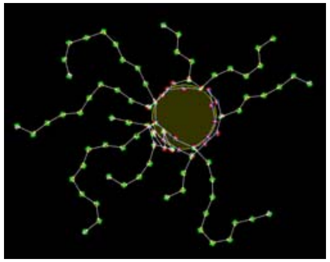


Embryomorphic Engineering:



From biological development to self-organized computational architectures

René Doursat

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

Systems that are self-organized *and* architectured

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

free self-organization

Peugeot Picasso

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

architecture, design

meta-design the agents

decompose the system

Peugeot Picasso

self-organized architecture / architectured self-organization

ARCHITECTURE AND SELF-ORGANIZATION

1. What are Complex Systems?

- Decentralization
- Emergence
- Self-organization

2. Architects Overtaken by their Architecture

Designed systems that became suddenly complex

3. Architecture Without Architects

Self-organized systems that *look* like they were designed

but were not

4. Embryomorphic Engineering

From biological cells to robots and networks

5. The New Challenge of "Meta-Design"

Or how to organize spontaneity

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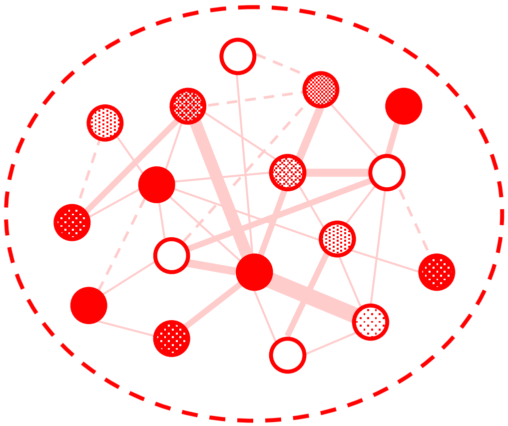
1. What are Complex Systems?

➢ Complex systems can be found everywhere around us



a) **decentralization:** the system is made of myriads of "simple" agents (local information, local rules, local interactions)

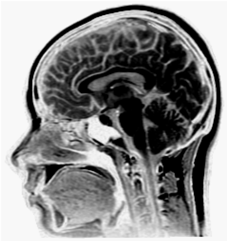
b) **emergence:** function is a bottom-up collective effect of the agents (asynchrony, balance, combinatorial creativity)

c) **self-organization:** the system operates *and changes* on its own (autonomy, robustness, adaptation)

➢ Physical, biological, technological, social complex systems

pattern formation
○ = matter

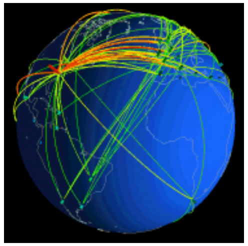
biological development
○ = cell



the brain & cognition
○ = neuron

insect colonies
○ = ant

Internet & Web
○ = host/page

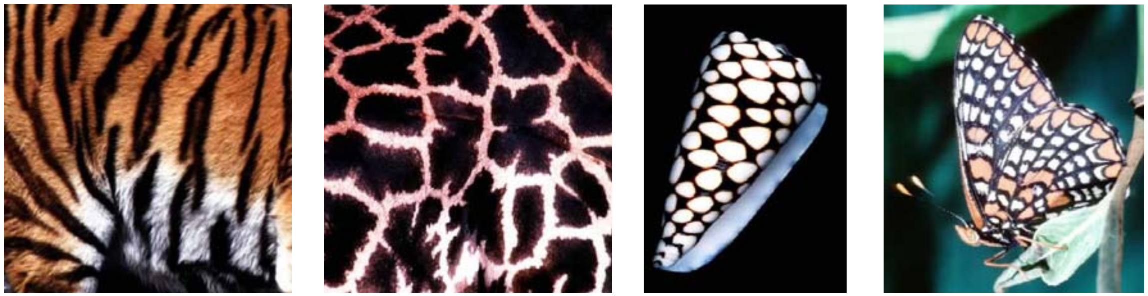


social networks
○ = person

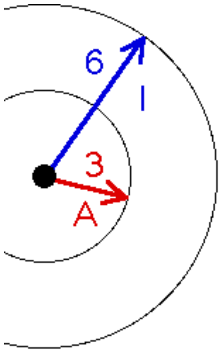
1. What are Complex Systems?

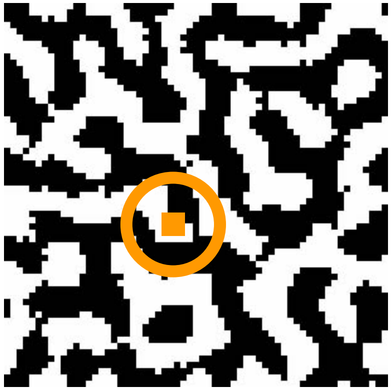
➢ Ex: Pattern formation – Animal colors

- ✓ animal patterns caused by pigment cells that try to copy their nearest neighbors but differentiate from farther cells



Mammal fur, seashells, and insect wings
(Scott Camazine, http://www.scottcamazine.com)





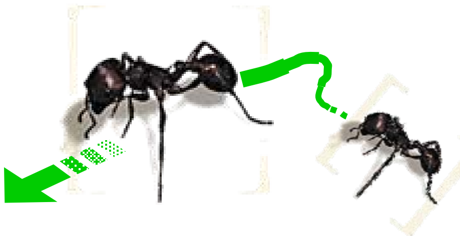
NetLogo Fur simulation

➢ Ex: Swarm intelligence – Insect colonies

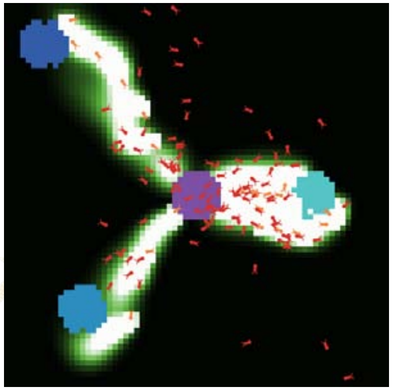
- ✓ trails form by ants that follow and reinforce each other's pheromone path

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

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



Harvester ants
(Deborah Gordon, Stanford University)

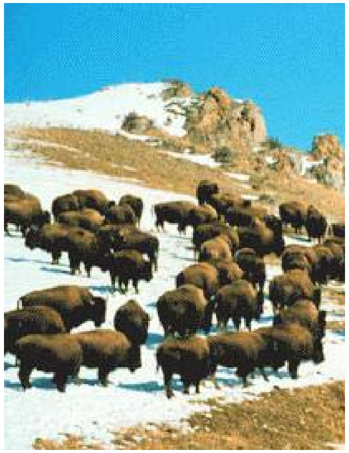


NetLogo Ants simulation

1. What are Complex Systems?

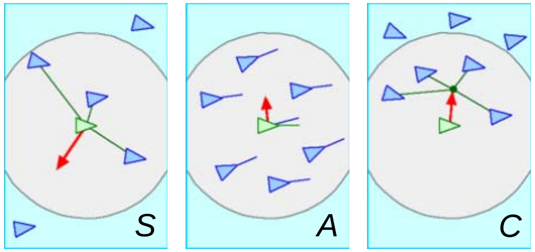
➢ Ex: Collective motion – Flocking, schooling, herding

Fish school
(Eric T. Schultz, University of Connecticut)

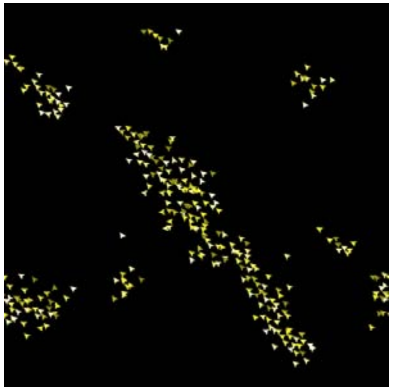


Bison herd
(Montana State University, Bozeman)

✓ thousands of animals that adjust their position, orientation and speed wrt to their nearest neighbors



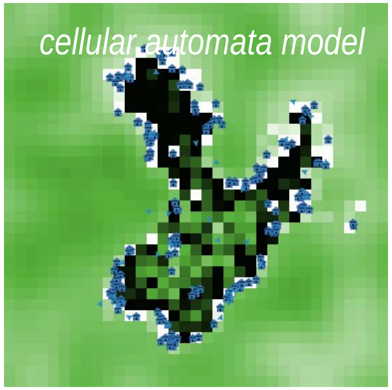
Separation, alignment and cohesion
("Boids" model, Craig Reynolds)



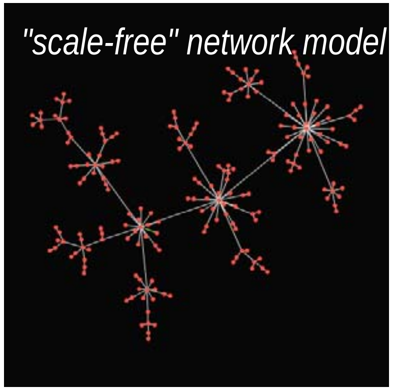
NetLogo Flocking simulation

➢ Ex: Diffusion and networks – Cities and social links

✓ clusters and cliques of people who aggregate in geographical or social space



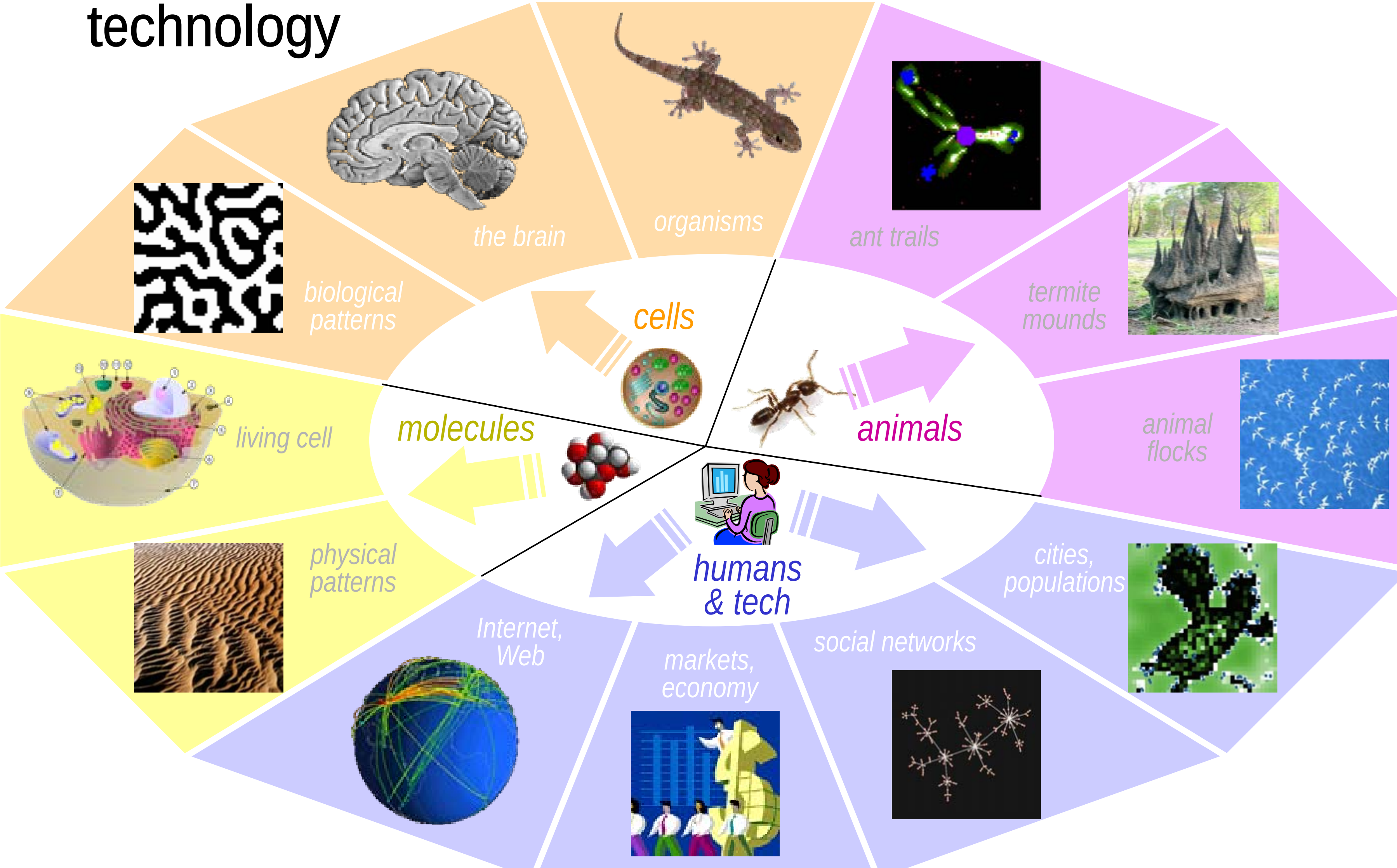
NetLogo urban sprawl simulation



NetLogo preferential attachment

1. What are Complex Systems?

- All kinds of agents: molecules, cells, animals, humans & technology



1. What are Complex Systems?

3 main differences with traditional architecting

a) Decentralization: the system is made of myriads of "simple" agents

- ✓ **local information** (no group-level knowledge): each agent carries a piece of the global system’s state
- ✓ **local rules** (no group-level goals): each agent follows an individual agenda
- ✓ **local interactions** (no group-level scope): each agent communicates with "neighboring" agents, possibly via long-range links

b) Emergence: function is a bottom-up collective effect of the agents

- ✓ **asynchronous dependencies:** agents "threaded" in parallel modify each other’s actions (possibly via cues they leave in the environment)
- ✓ **balance:** creation by +feedback (imitation), control by –feedback (inhibition)
- ✓ **combinatorial creativity:** the system exhibits new (surprising) properties that the agents do not have; different properties can emerge from the same agents

1. What are Complex Systems?

3 main differences with traditional architecting

c) **Self-organization:** the system operates *and changes* on its own

- ✓ **autonomy:** there is no external map, grand architect, or explicit leader
- ✓ **robustness**: proper function is maintained despite (some) damage
- ✓ **adaptation:** the system dynamically and "optimally" varies with a changing environment; agents modify themselves to create a new class of functional collective behaviors → *learning and/or evolution*

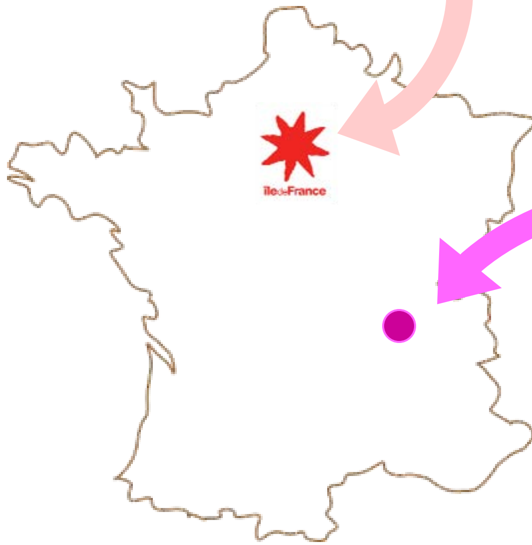
- decentralized, emergent, self-organized processes are the rule in nature and large-scale human superstructures
- however, they are counterintuitive to our human mind, which prefers central-causal, predictable, planned/rigid systems
- ... and yet again, autonomy, robustness, adaptation are highly desirable properties! *How can we have it both ways, i.e. "care and let go"?*

1. What are Complex Systems?

INSTITUT DES SYSTEMES COMPLEXES Paris Ile-de-France

4th French Complex Systems Summer School, 2010

RNSC National



Lyon Rhône-Alpes

1. What are Complex Systems?

- A vast archipelago of 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

Architecture And Self-Organization

1. What are Complex Systems?

- Decentralization
- Emergence
- Self-organization

Complex systems seem so different from architected systems, and yet...

2. Architects Overtaken by their Architecture

Designed systems that became suddenly complex

3. Architecture Without Architects

Self-organized systems that *look* like they were designed

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From biological cells to robots and networks

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Or how to organize spontaneity

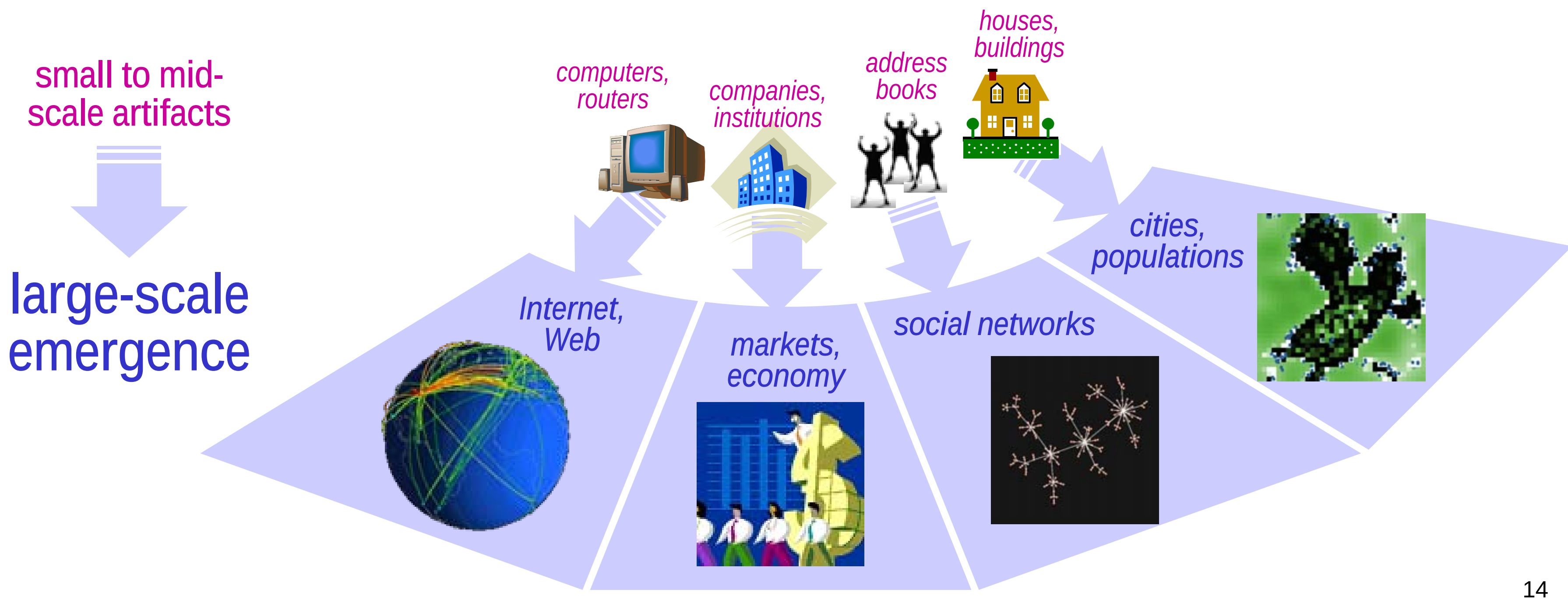
2. Architects Overtaken by their Architecture

➢ At large scales, human superstructures are "natural" CS

by their unplanned, spontaneous emergence and adaptivity...

... arising from a multitude of traditionally designed artifacts

geography: cities, populations	⇐	houses, buildings
people: social networks	⇐	address books
wealth: markets, economy	⇐	companies, institutions
technology: Internet, Web	⇐	computers, routers

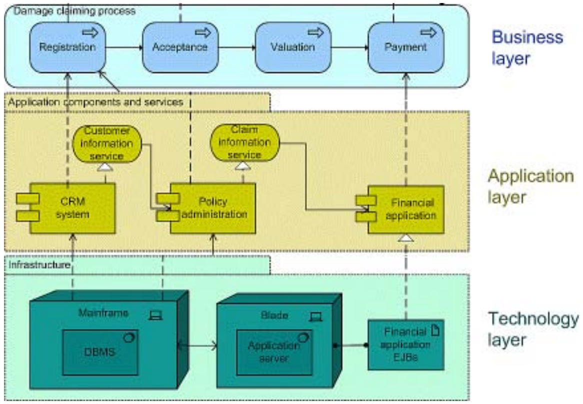


2. Architects Overtaken by their Architecture

➢ At mid-scales, human artifacts are classically architected

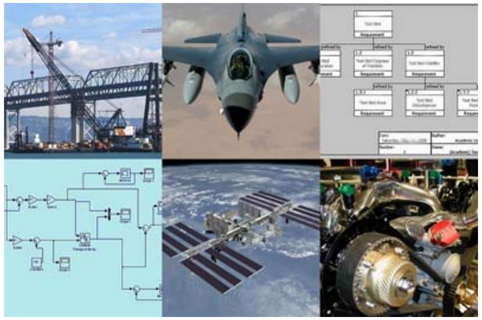
- ✓ a goal-oriented, top-down process toward one solution behaving in a limited # of ways
  - specification & design: hierarchical view of the entire system, exact placement of elts
  - testing & validation: controllability, reliability, predictability, optimality

ArchiMate EA example

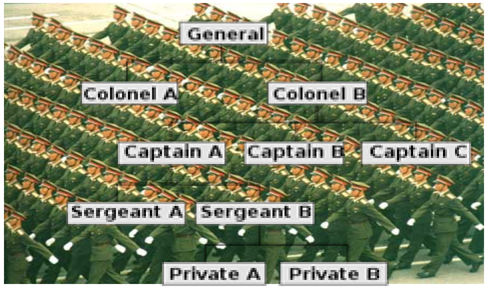


➢ New inflation: artifacts/orgs made of a huge number of parts

- ✓ the (very) "complicated" systems of classical engineering and social centralization
  - electronics, machinery, aviation, civil construction, etc.
  - spectators, orchestras, administrations, military (reacting to external cues/leader/plan)
- ✓ not "complex" systems:
  - little/no decentralization, little/no emergence, little/no self-organization

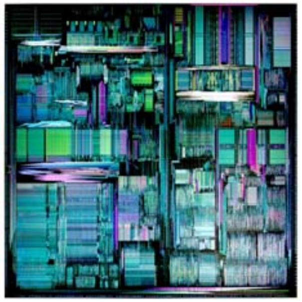


Systems engineering
Wikimedia Commons

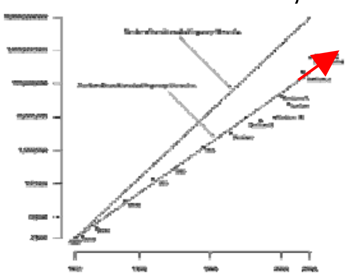


2. Architects Overtaken by their Architecture

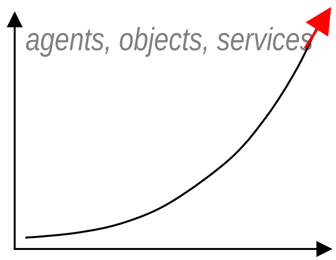
- ➢ Burst to large scale: *de facto* complexification of ICT systems
  - ✓ ineluctable breakup into, and *proliferation* of, modules/components



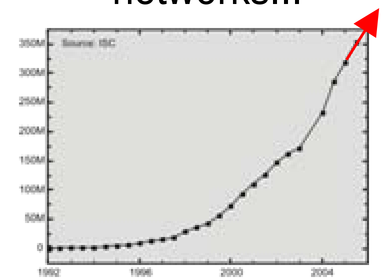
in hardware, software, networks...



number of transistors/year



number of O/S lines of code/year



number of network hosts/year

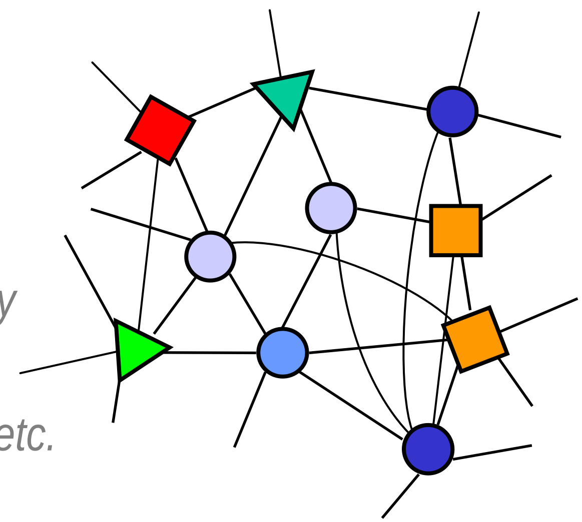
→ *trying to keep the lid on complexity won't work in these systems:*

- cannot place every part anymore
- cannot foresee every event anymore
- cannot control every process anymore

... but do we still *want* to?

2. Architects Overtaken by their Architecture

- Large-scale: *de facto* complexification of organizations, via techno-social networks
  - ✓ ubiquitous ICT capabilities connect people and infrastructure in unprecedented ways
  - ✓ giving rise to complex techno-social "ecosystems" composed of a multitude of human users and computing devices
  - ✓ explosion in size and complexity in all domains of society:
    - healthcare
    - education
    - business
    - energy & environment
    - defense & security
    - finance
  - ✓ from a centralized oligarchy of providers of
    data, knowledge, management, information, energy
  - ✓ to a dense heterarchy of ***proactive participants:***
    patients, students, employees, users, consumers, etc.



→ *in this context, impossible to assign every single participant a predetermined role*

2. Architects Overtaken by their Architecture

The "New Deal" of the ICT age

a) Overtaken

- ✓ how things turned around from top-down "architecting as usual" (at mid scales) and went bottom-up (at large-scales)—hopefully not yet belly-up
- ✓ large-scale techno-social systems exhibit spontaneous collective behavior that we don't quite understand or control yet

b) Embrace

- ✓ they also open the door to entirely new forms of enterprise characterized by increasing decentralization, emergence, and **dynamic adaptation**

c) Take over

- ✓ thus it is time to design new collaborative technologies to harness and guide this natural (and unavoidable) force of self-organization
- ✓ try to focus on the agents' potential for self-assembly, not the system

→ 4. Embryomorphic Engineering → 5. "Meta-Design"

ARCHITECTURE AND SELF-ORGANIZATION

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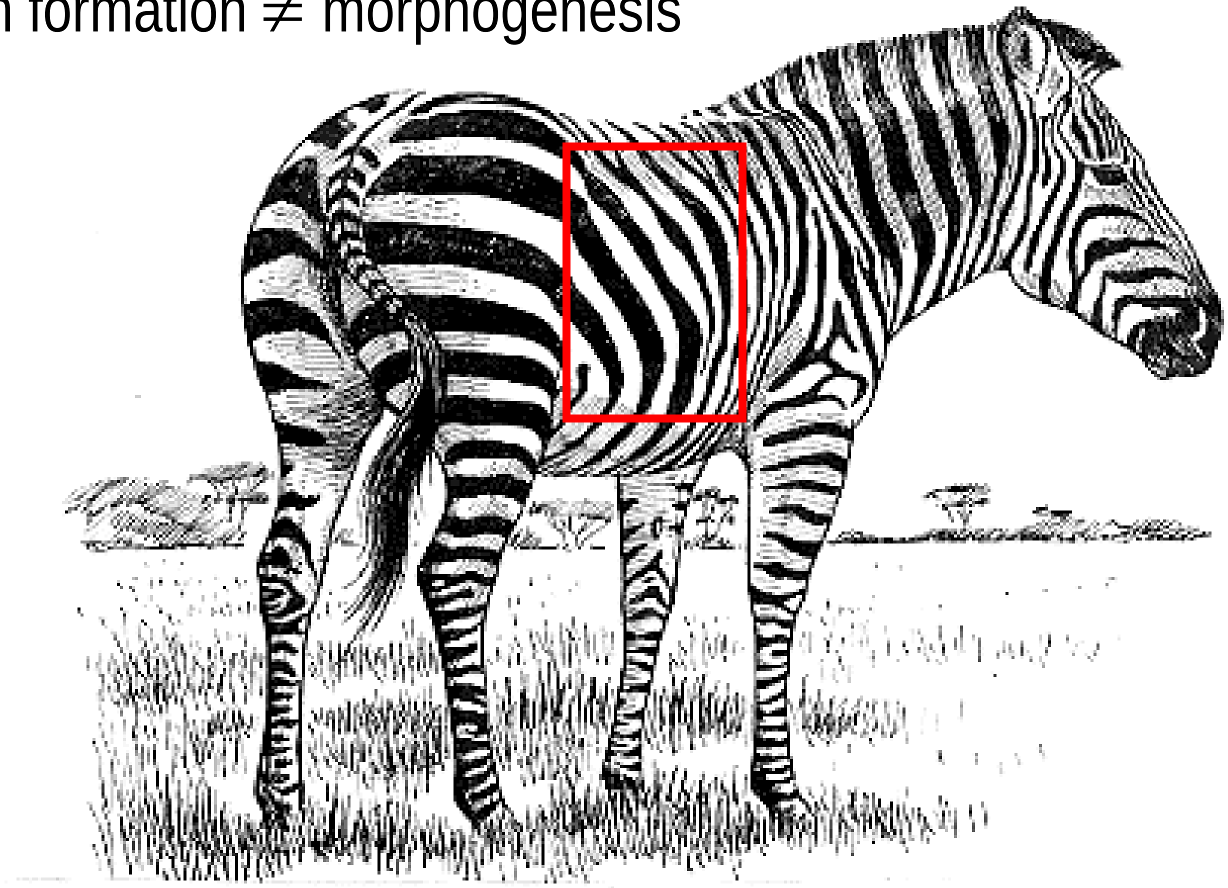
3. Architecture Without Architects

- Morphological (self-dissimilar) systems:

  pattern formation ≠ morphogenesis



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

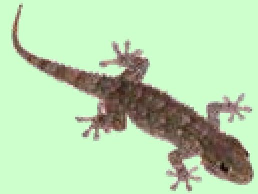
—attributed to A. Turing, after his 1952 paper on morphogenesis

3. Architecture Without Architects

- "Simple"/random vs. architectured complex systems

biological patterns


the brain


organisms

ant trails


termite mounds


living cell

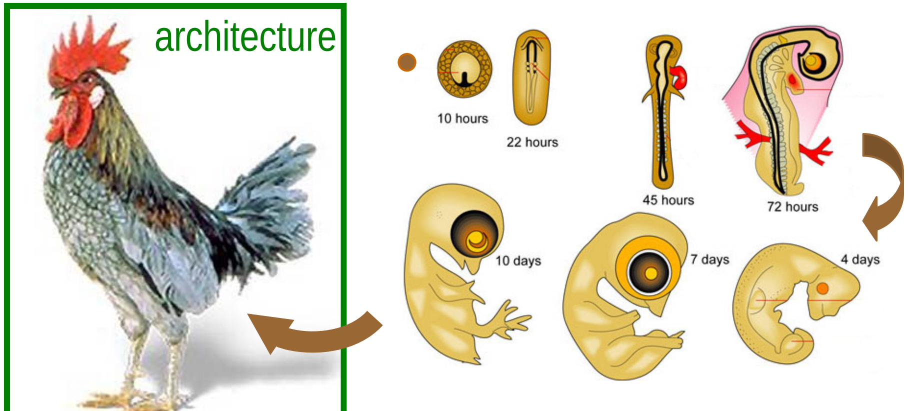
animal flocks

physical patterns

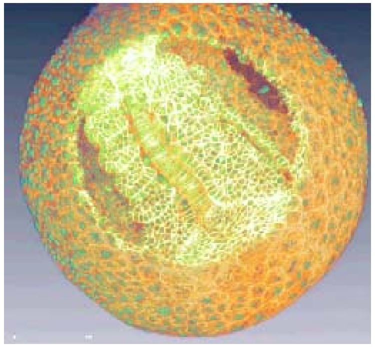
- biology strikingly demonstrates the possibility of **combining** pure self-organization and elaborate architecture, i.e.:
  - ✓ a non-trivial, sophisticated morphology
    - *hierarchical* (multi-scale): regions, parts, details
    - *modular*: reuse of parts, quasi-repetition
    - *heterogeneous*: differentiation, division of labor
  - ✓ *random* at agent level, *reproducible* at system level

3. Architecture Without Architects

➢ Ex: Morphogenesis – Biological development



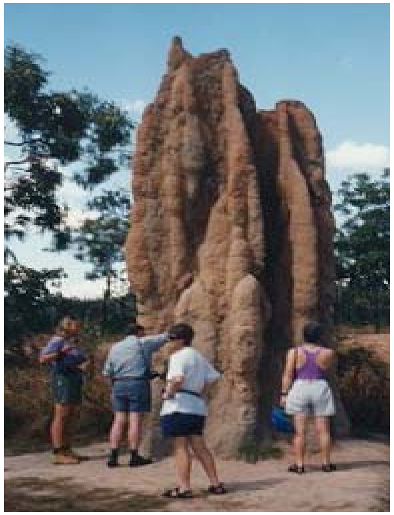
www.infovisual.info



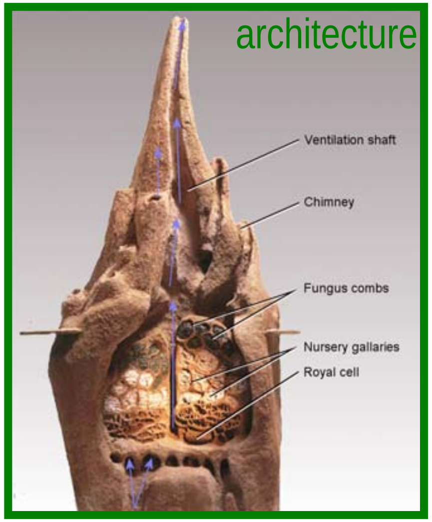
Nadine Peyriéras, Paul Bourgine et al.
(Embryomics & BioEmergences)

- cells build sophisticated organisms by division, genetic differentiation and biomechanical self-assembly

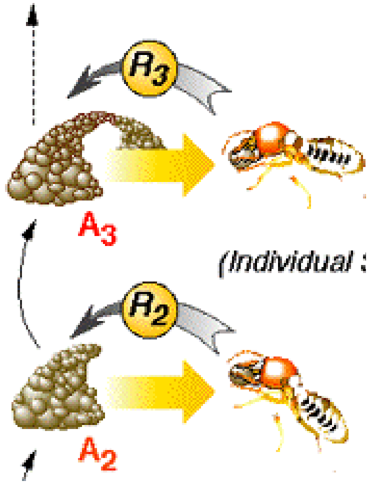
➢ Ex: Swarm intelligence – Termite mounds



Termite mound
(J. McLaughlin, Penn State University)



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



Termite stigmergy
(after Paul Grassé; from Solé and Goodwin, "Signs of Life", Perseus Books)

- termite colonies build sophisticated mounds by **"stigmergy"** = loop between modifying the environment and reacting differently to these modifications

3. Architecture Without Architects

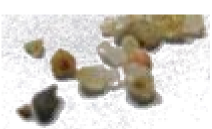
From “statistical” to “morphological” CS

in inert matter / insect constructions / multicellular organisms

more intrinsic, sophisticated architecture

physical
pattern formation

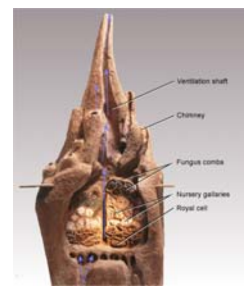
grains of sand + air



ant trail

network of ant trails

ant nest

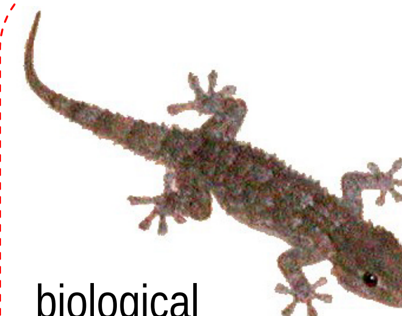


termite mound

social insect
constructions

insects

new inspiration

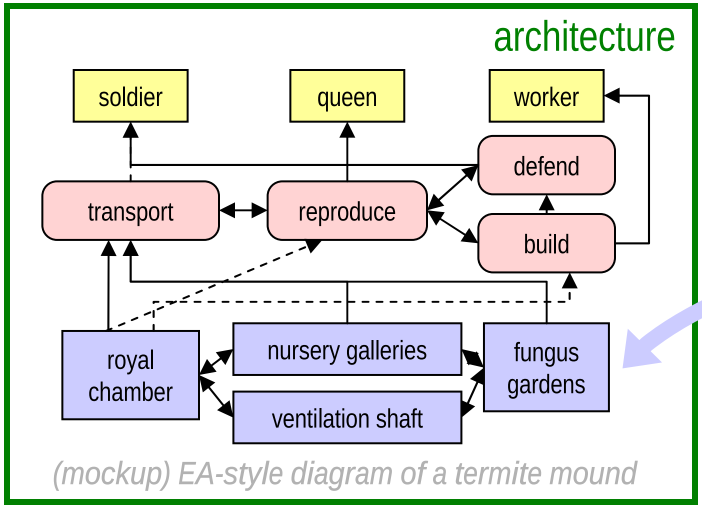


biological
morphogenesis

cells

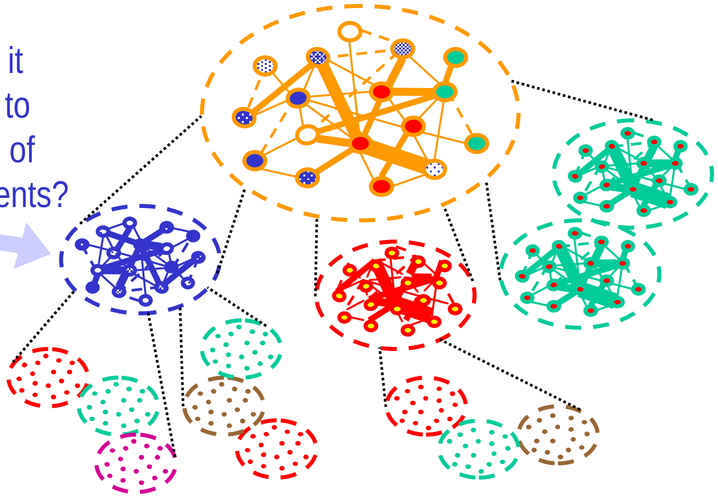
3. Architecture Without Architects

- Complex systems can possess a strong architecture, too
  - ✓ "complex" doesn't imply "homogeneous"...
    → *heterogeneous agents and diverse patterns, via positions*
  - ✓ "complex" doesn't imply "flat"...
    → *modular, hierarchical, detailed architecture*
  - ✓ "complex" doesn't imply "random"...
    → *reproducible patterns relying on programmable agents*



(mockup) EA-style diagram of a termite mound

but then what does it mean for a module to be an "emergence" of many fine-grain agents?

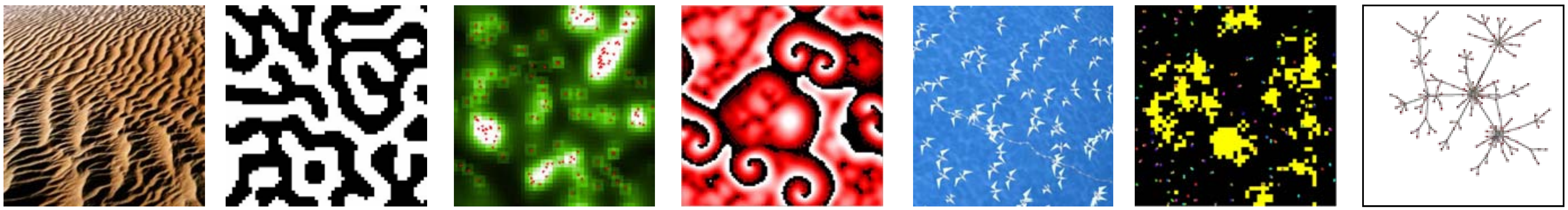


→ *cells and social insects have successfully "aligned business and infrastructure" for millions of years without any architect telling them how to*

3. Architecture Without Architects

➢ Many self-organized systems exhibit random patterns...

(a) "simple"/random self-organization



more architecture

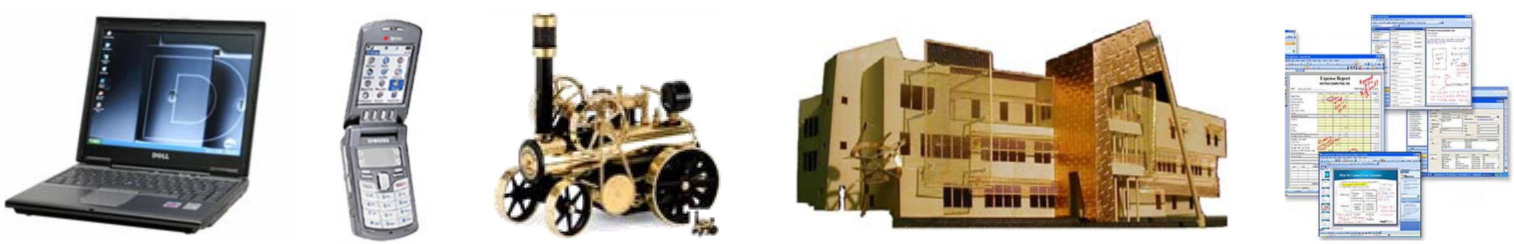
gap to fill

??

... while "complicated" architecture is designed by humans

more self-organization

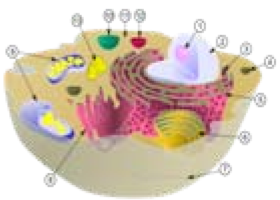
(d) direct
design
(top-down)



3. Architecture Without Architects

- Many self-organized systems exhibit random patterns...
- The only natural emergent *and* structured CS are biological
- *Can we transfer some of their principles to human-made systems and organizations?*

(b) natural self-organized architecture



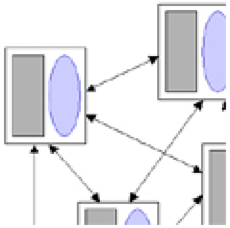

natural

artificial

more architecture

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

. . . .



. . . .

more self-organization

- self-forming robot swarm
- self-programming software
- self-connecting micro-components
- self-reconfiguring manufacturing plant
- self-stabilizing energy grid
- self-deploying emergency taskforce

. . . self-architecting enterprise?

3. Architecture Without Architects

RECAP

Toward a reconciliation of complex systems and ICT

3. **Architecture Without Architects:** ICT-like CS
   - ✓ Some natural complex systems strikingly demonstrate the possibility of combining pure self-organization and elaborate architectures

→ *how can we extract and transfer their principles to human artifacts—such as EA?*

2. **Architects Overtaken by their Architecture:** CS-like ICT
   - ✓ Conversely, mid- to large-scale techno-social systems already exhibit complex systems effects—albeit still uncontrolled and, for most of them, unwanted at this point

→ *how can we regain (relative) control over these "golems"?*

ARCHITECTURE AND SELF-ORGANIZATION

1. What are Complex Systems?

- Decentralization
- Emergence
- Self-organization

2. Architects Overtaken by their Architecture

Designed systems that became suddenly complex

3. Architecture Without Architects

Self-organized systems that *look* like they were designed

but were not

4. Embryomorphic Engineering

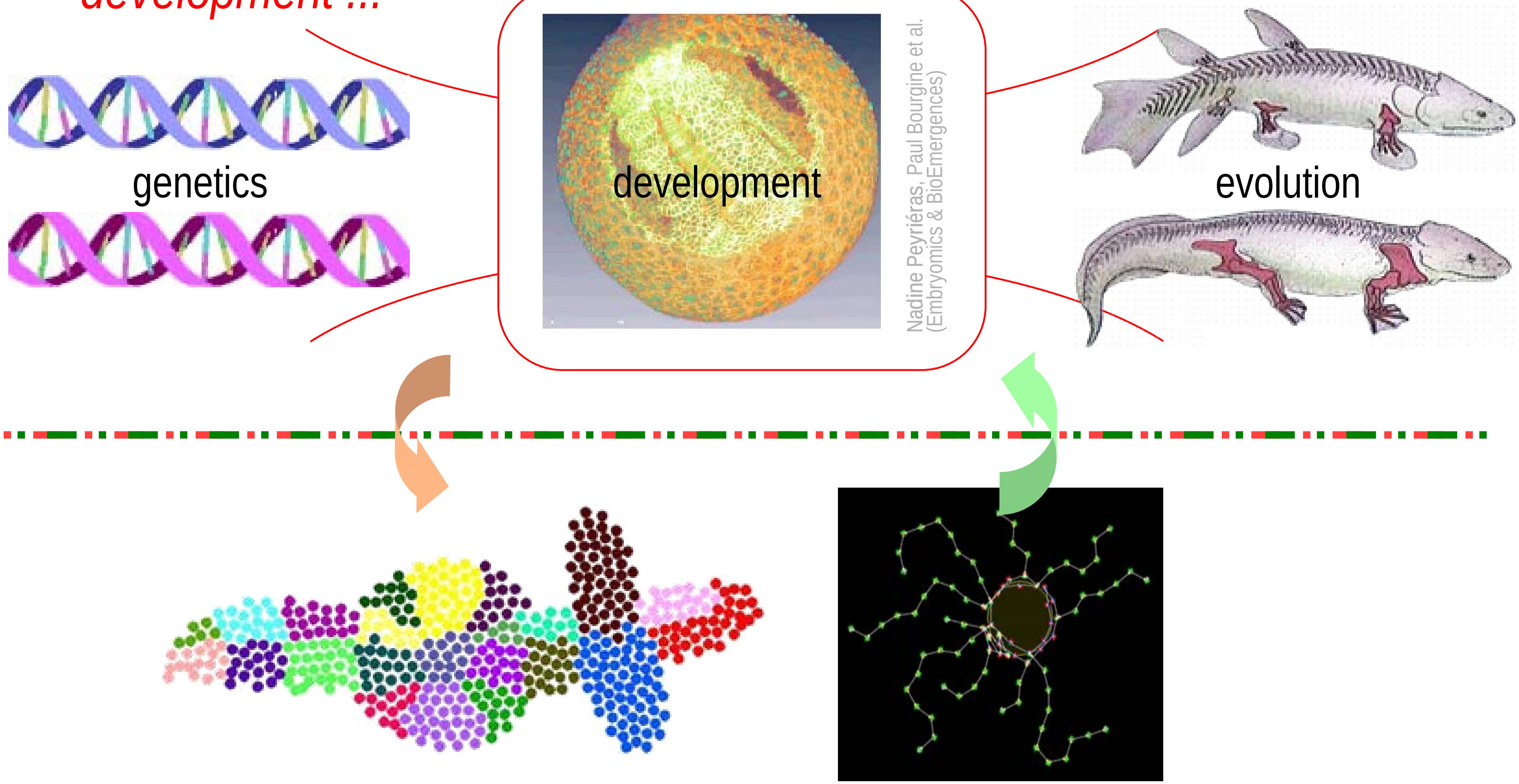
From biological cells to robots and networks

5. The New Challenge of "Meta-Design"

Or how to organize spontaneity

4. Embryomorphic Engineering (ME)

- A major source of inspiration: biological morphogenesis — the epitome of a self-architecting system
  - → *thus, part of ME: exploring computational multi-agent models of evolutionary development ...*



... toward possible outcomes in distributed, decentralized engineering systems

A closer look at morphogenesis: it couples assembly and patterning

➢ Sculpture → forms

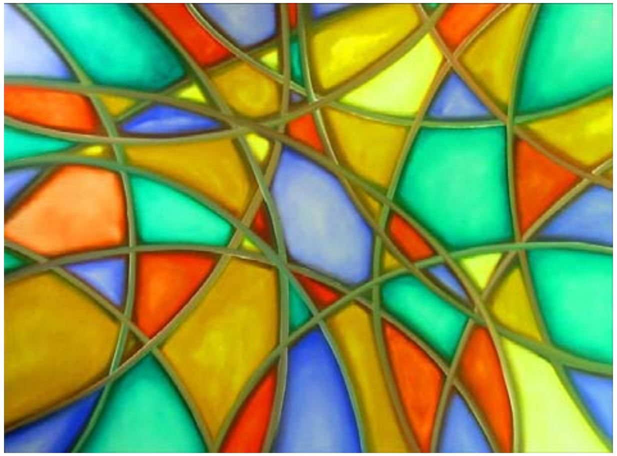
Ádám Szabó, *The chicken or the egg* (2005)
http://www.szaboadam.hu

"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"

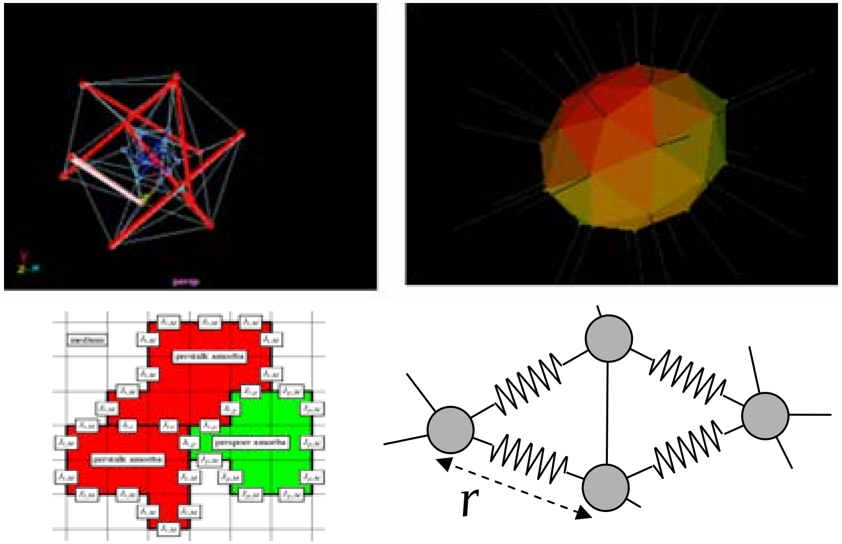
✓ new color regions appear (domains of genetic expression) triggered by deformations

4. Embryomorphic Engineering

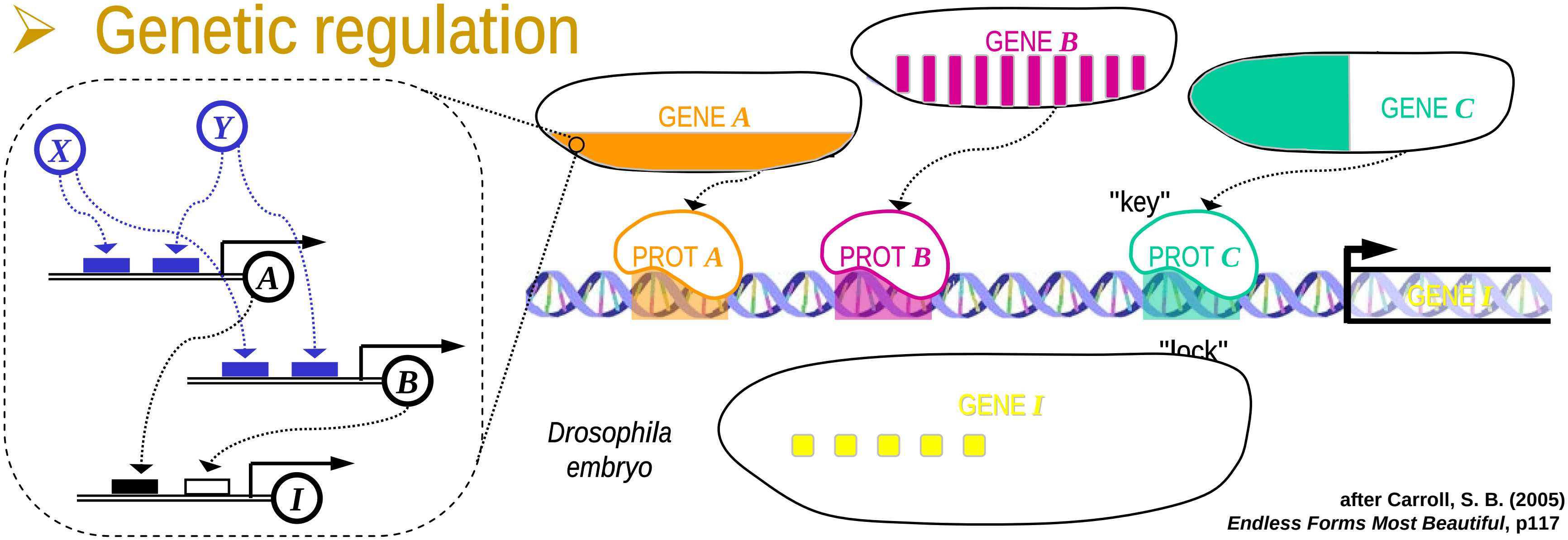
A closer look at morphogenesis: ⇔ it couples mechanics and genetics

➢ Cellular mechanics

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



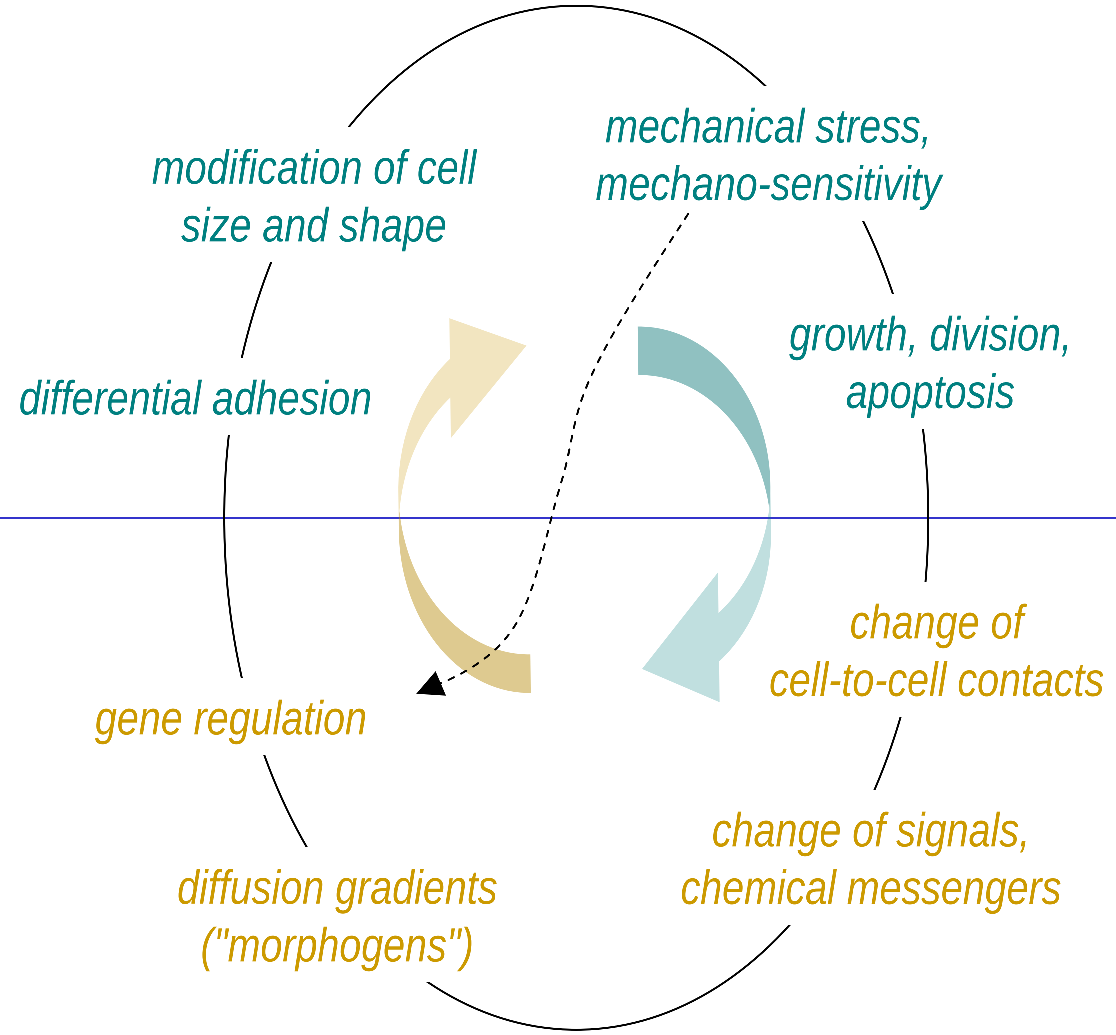
➢ Genetic regulation



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

A closer look at morphogenesis: ⇔ it couples mechanics and genetics

- Cellular mechanics

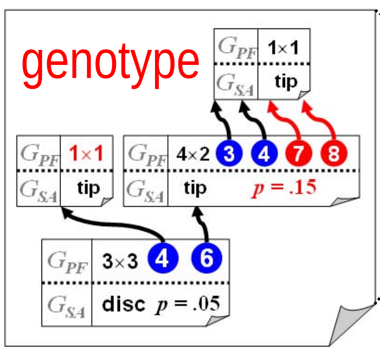


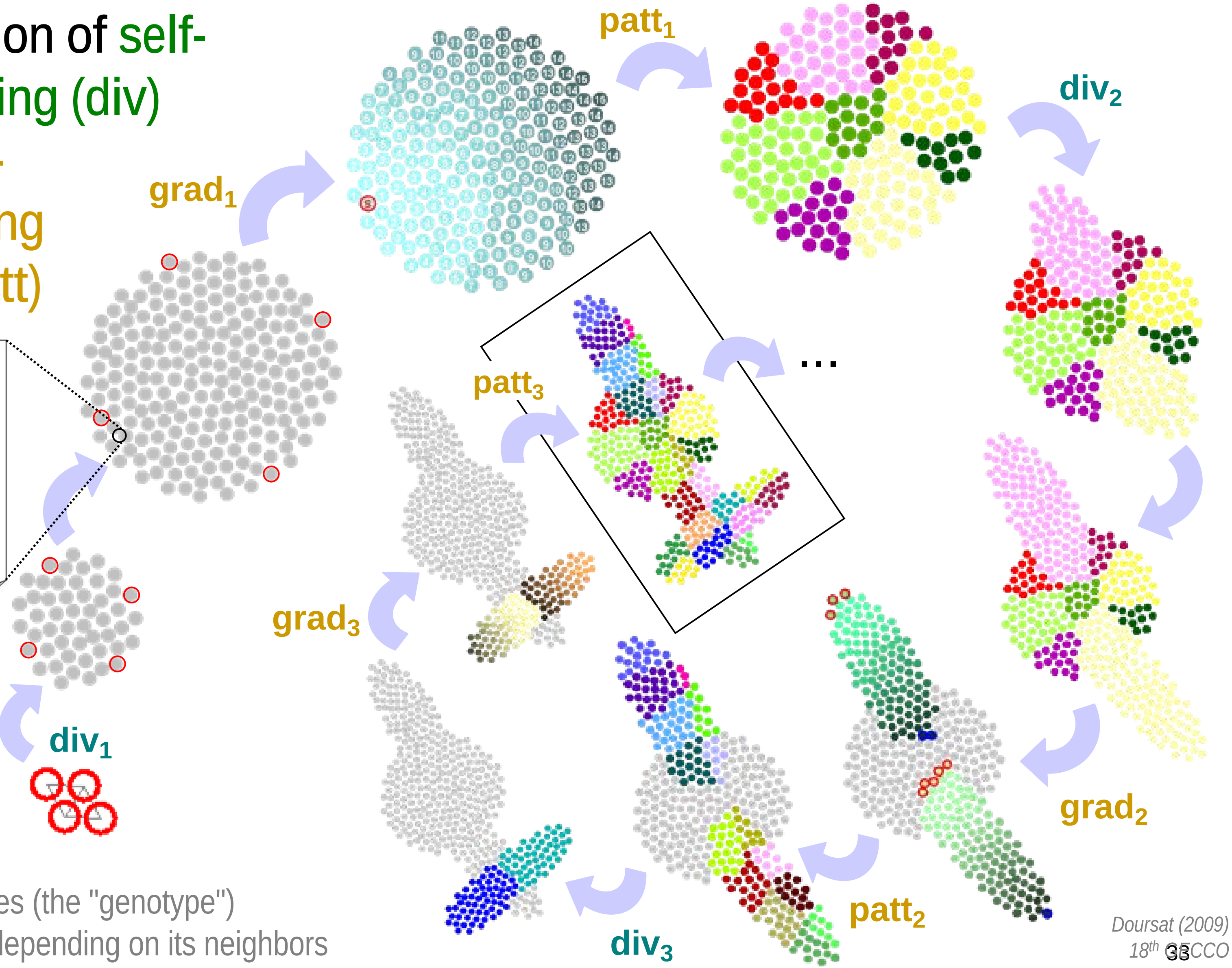
- Genetic regulation

4. Embryomorphic Engineering

Capturing the essence of morphogenesis in an Artificial Life agent model

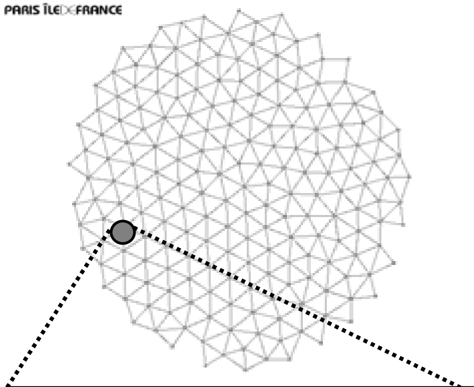
- Alternation of self-positioning (div) and self-identifying (grad/patt)





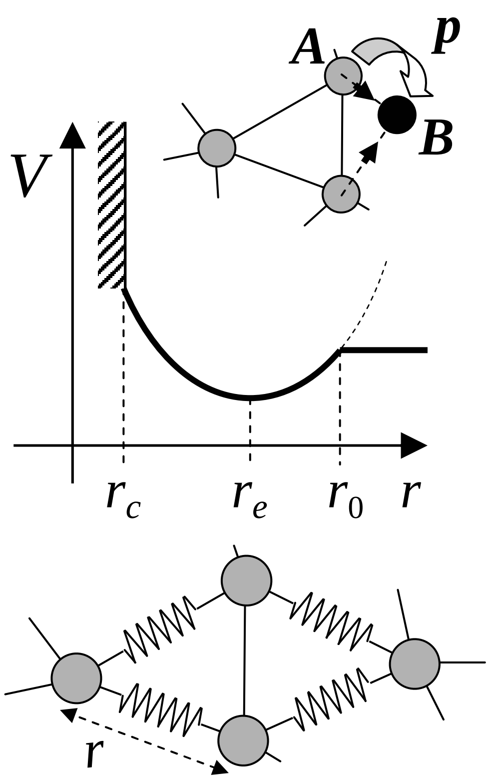
each agent
follows the same set
of self-architecting rules (the "genotype")
but reacts differently depending on its neighbors

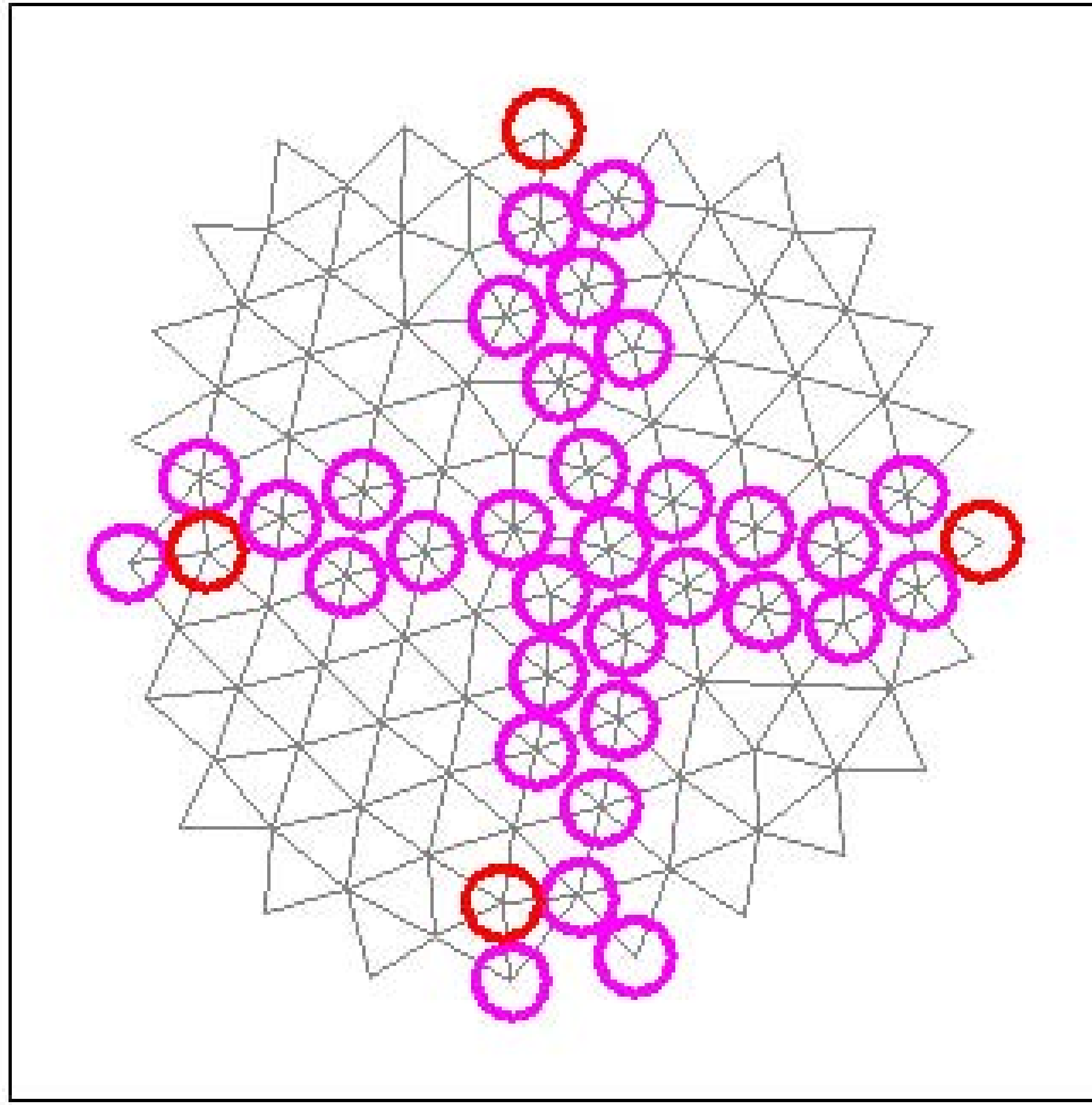
div

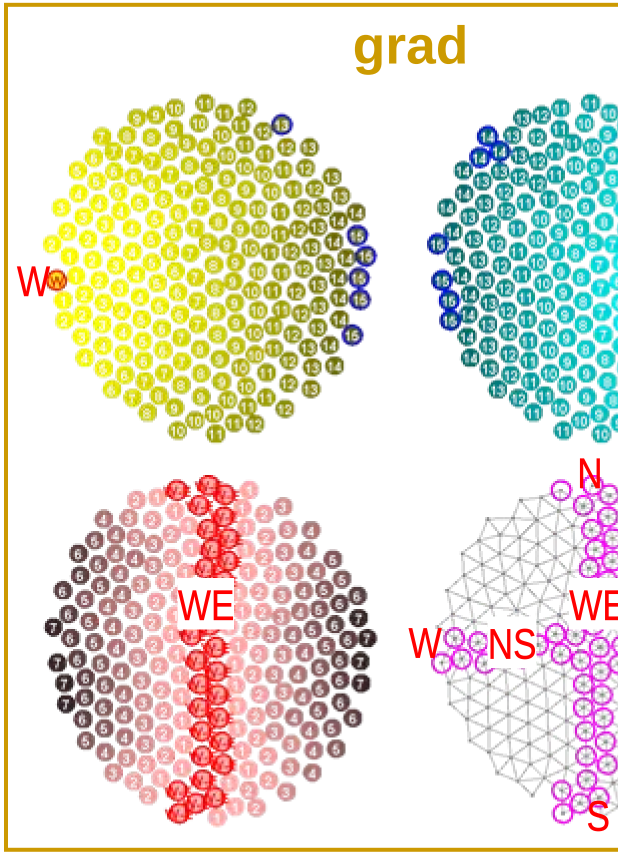


G_{SA}: $r_c < r_e = 1 << r_0$

$p = 0.05$






grad
W
N
WE
W
NS
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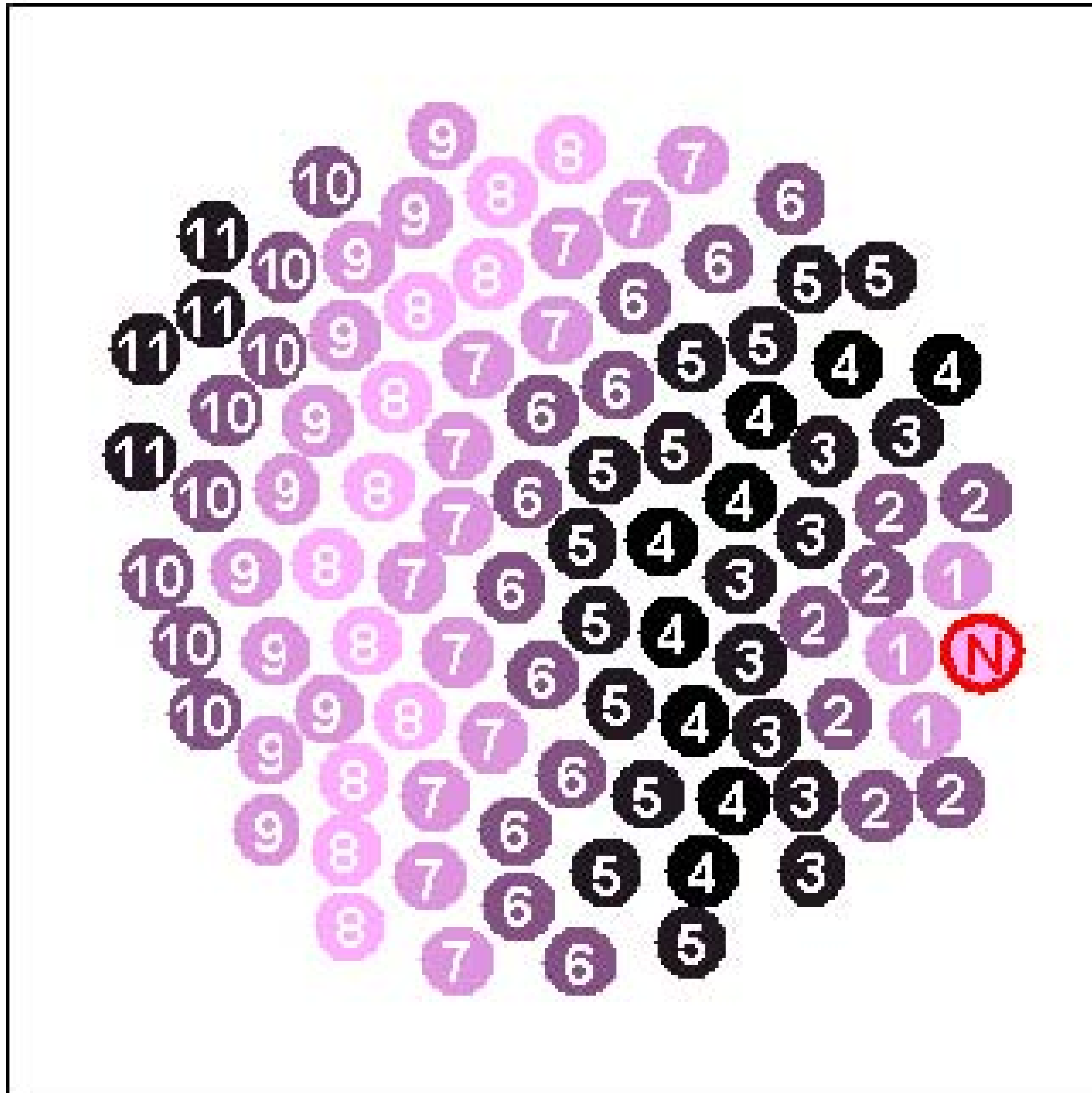
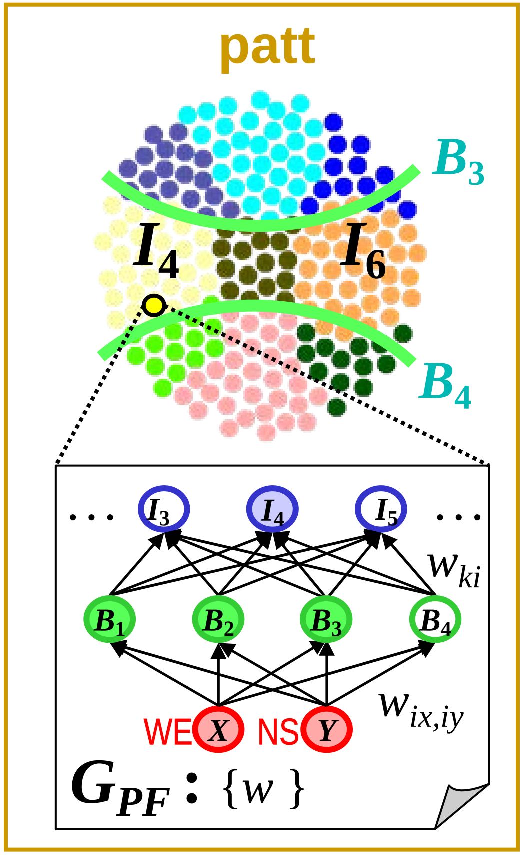
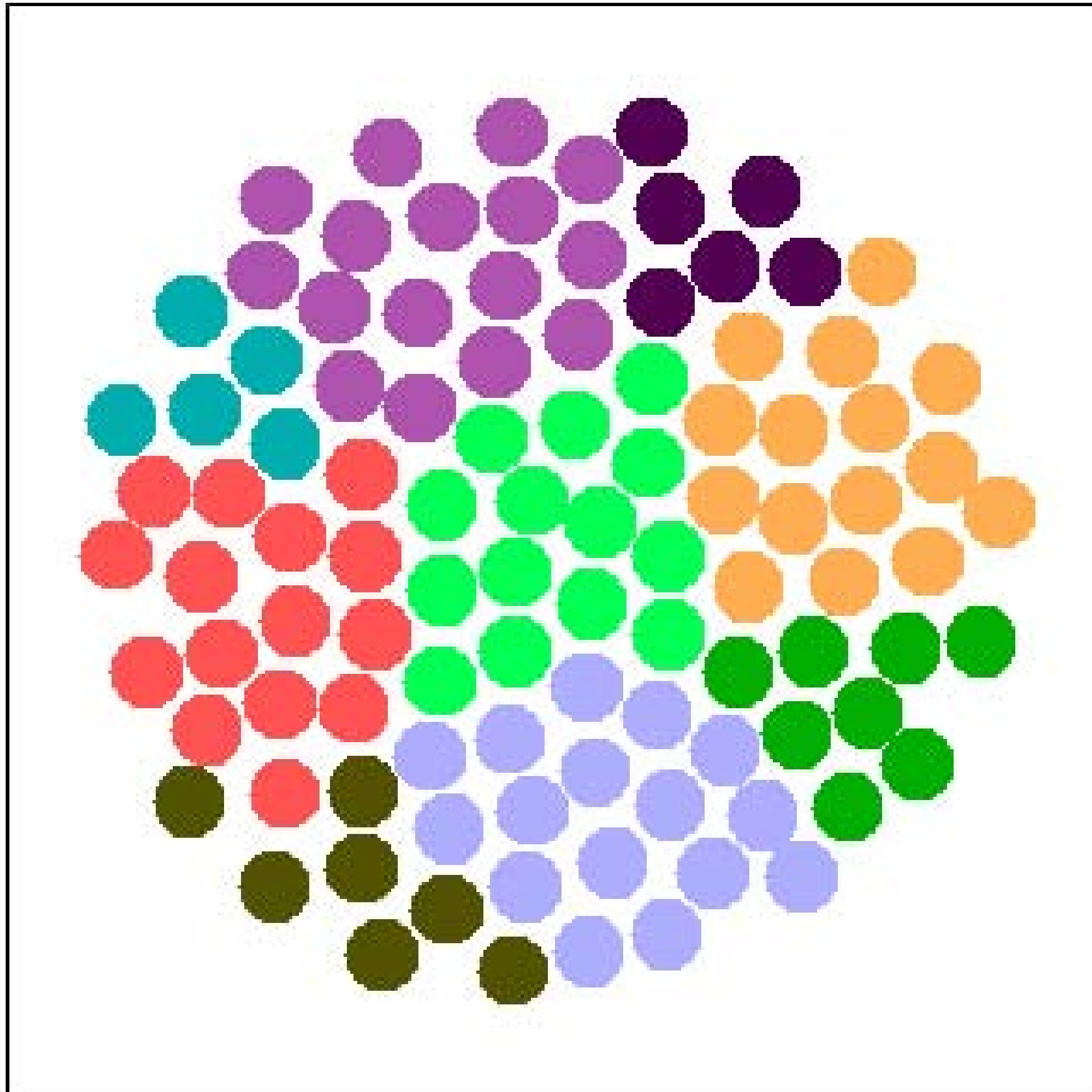
S


N


patt
B_3
I_4
I_6
B_4
. . . I_3 I_4 I_5 . . .
w_{ki}
B_1 B_2 B_3 B_4
$w_{ix,iy}$
WE X NS Y
G_{PF} : {w }

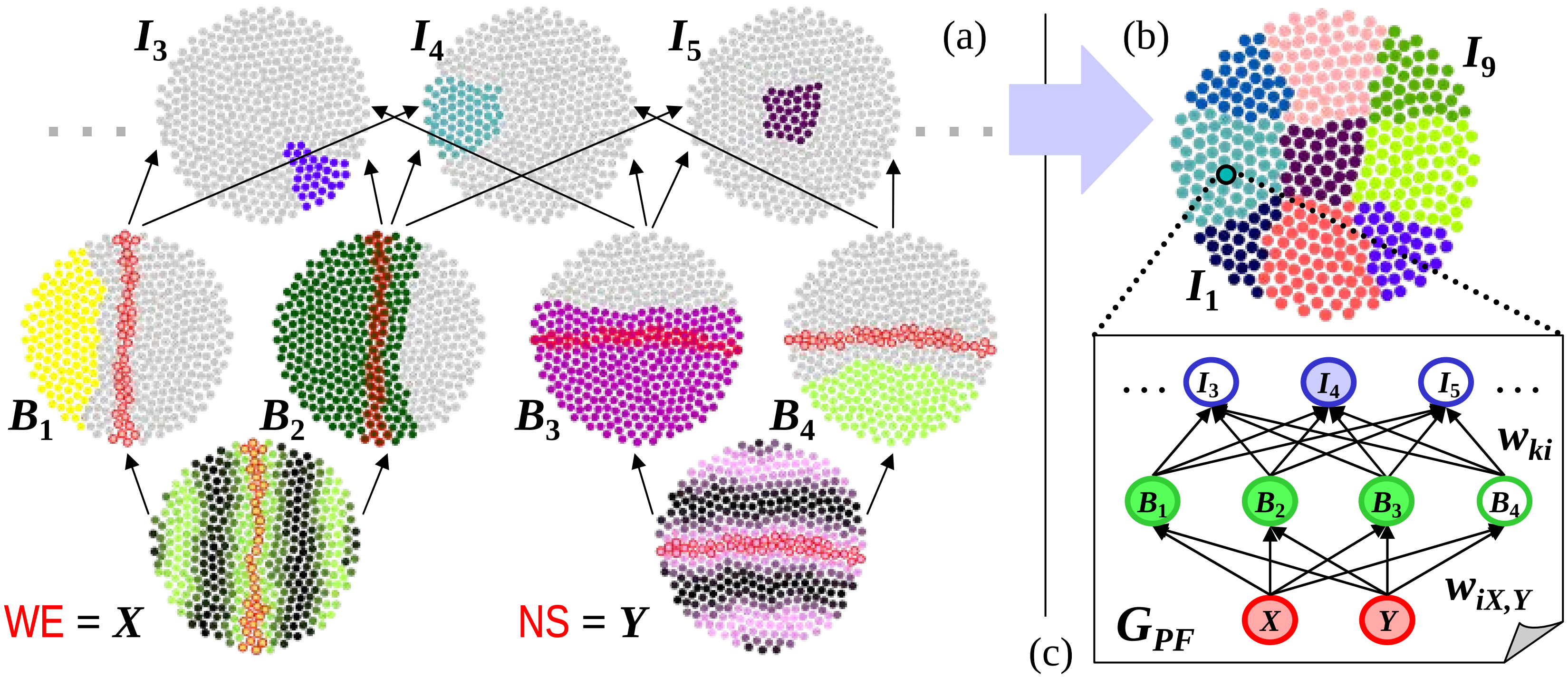


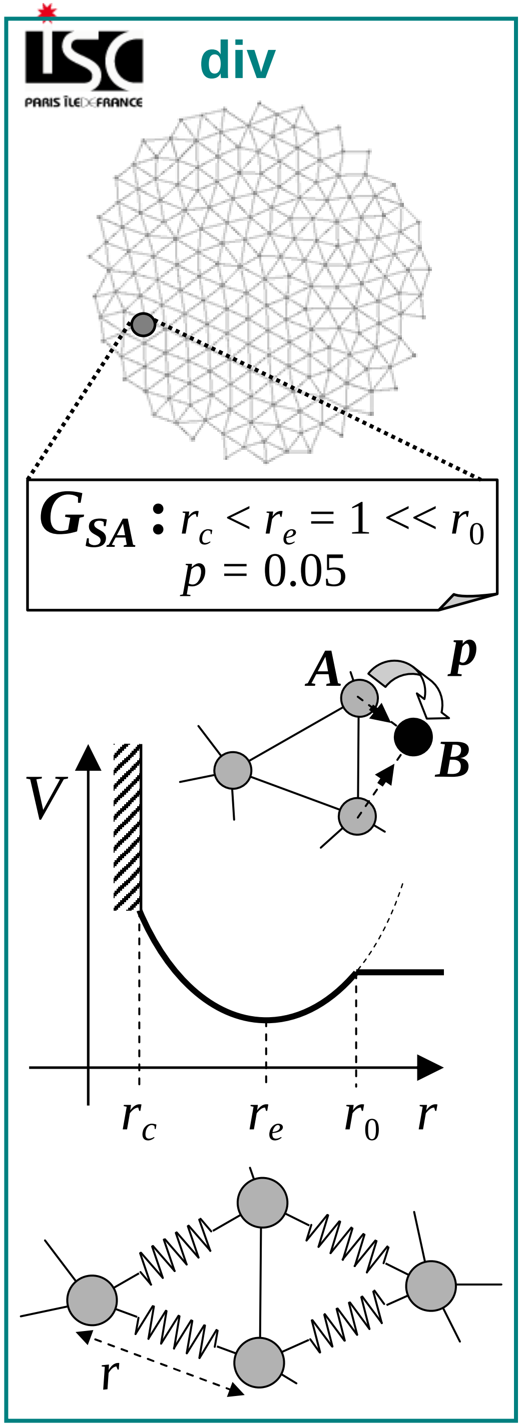
➤ Programmed patterning (patt): the hidden embryo atlas

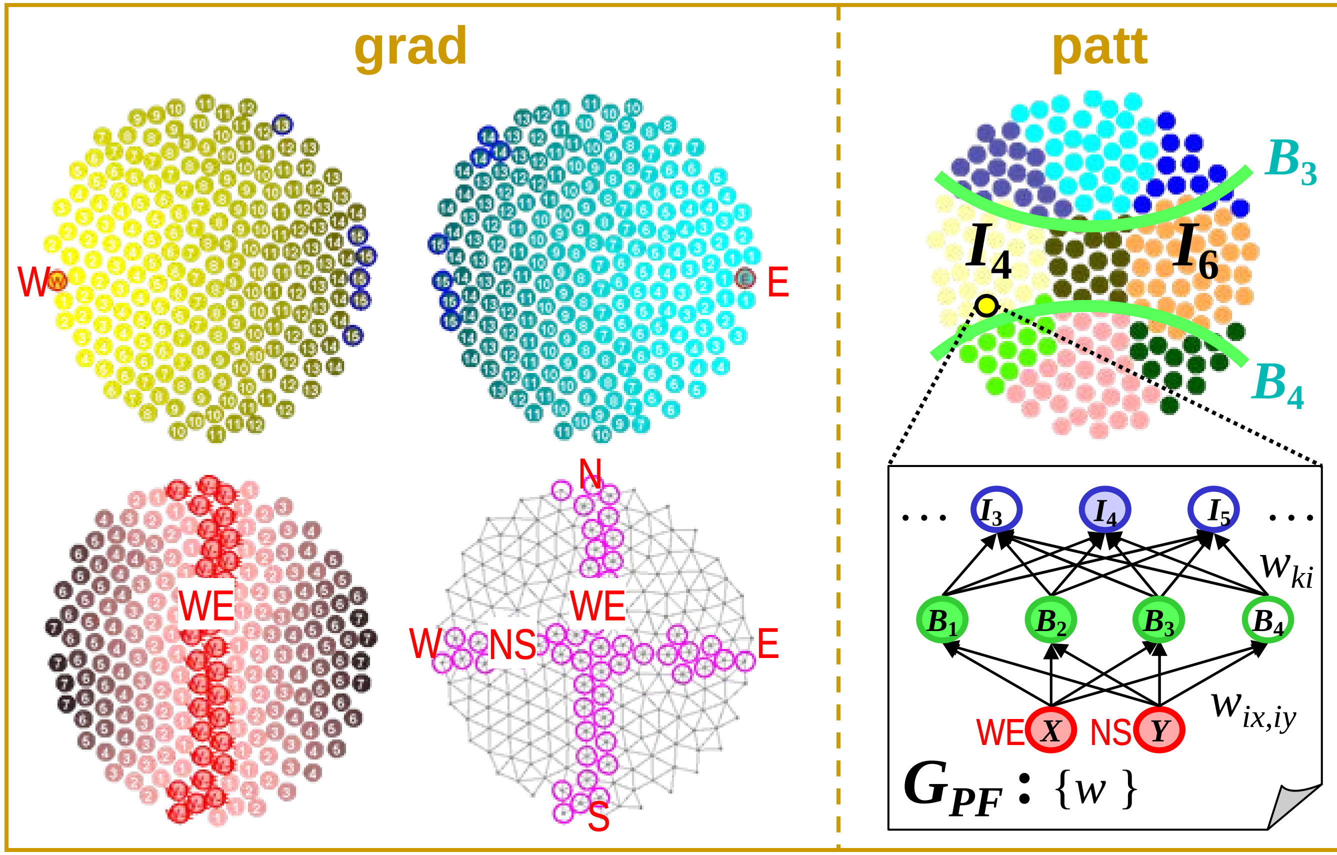
a) same swarm in different colormaps to visualize the agents' internal patterning variables X, Y, B_i and I_k (virtual *in situ hybridization)*

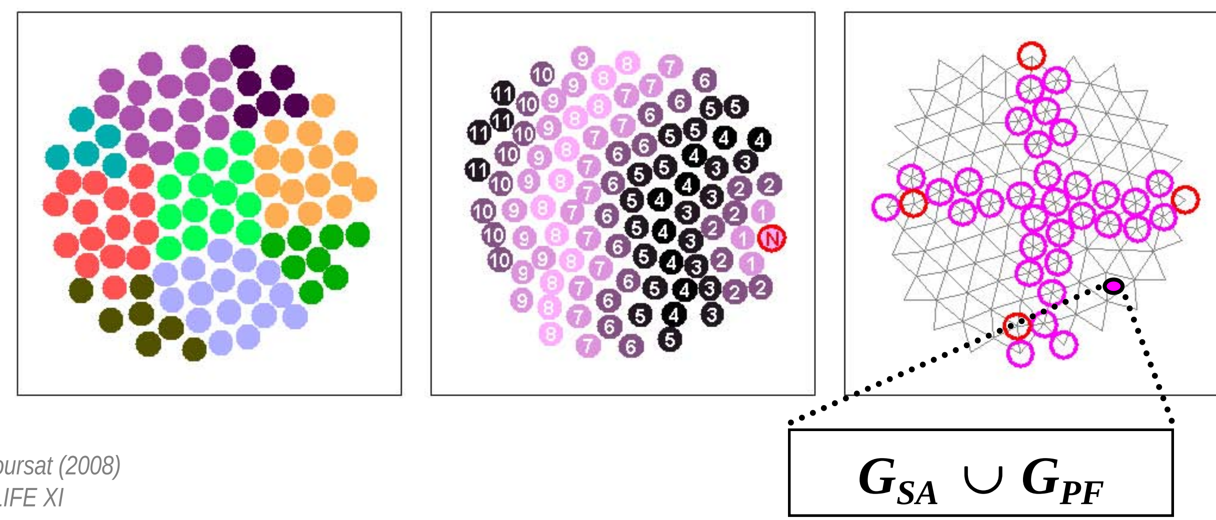
b) consolidated view of all identity regions I_k for $k = 1...9$

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.







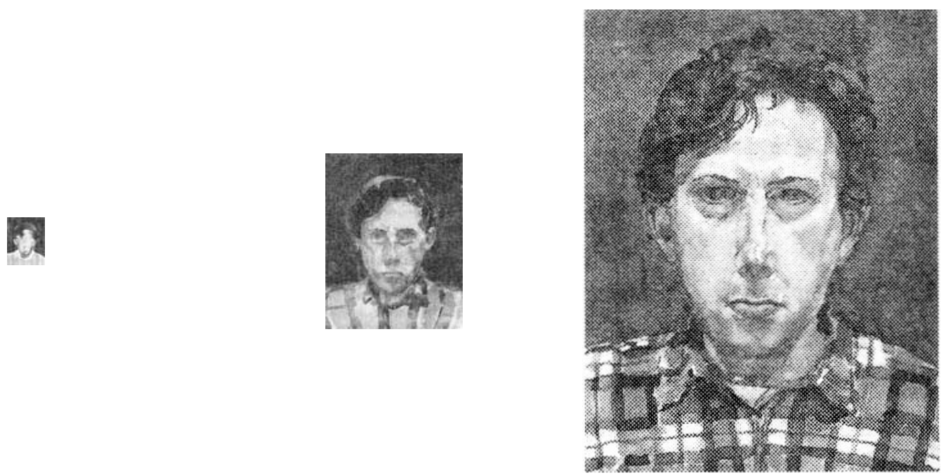


Doursat (2008)
ALIFE XI

➢ Morphological refinement by iterative growth

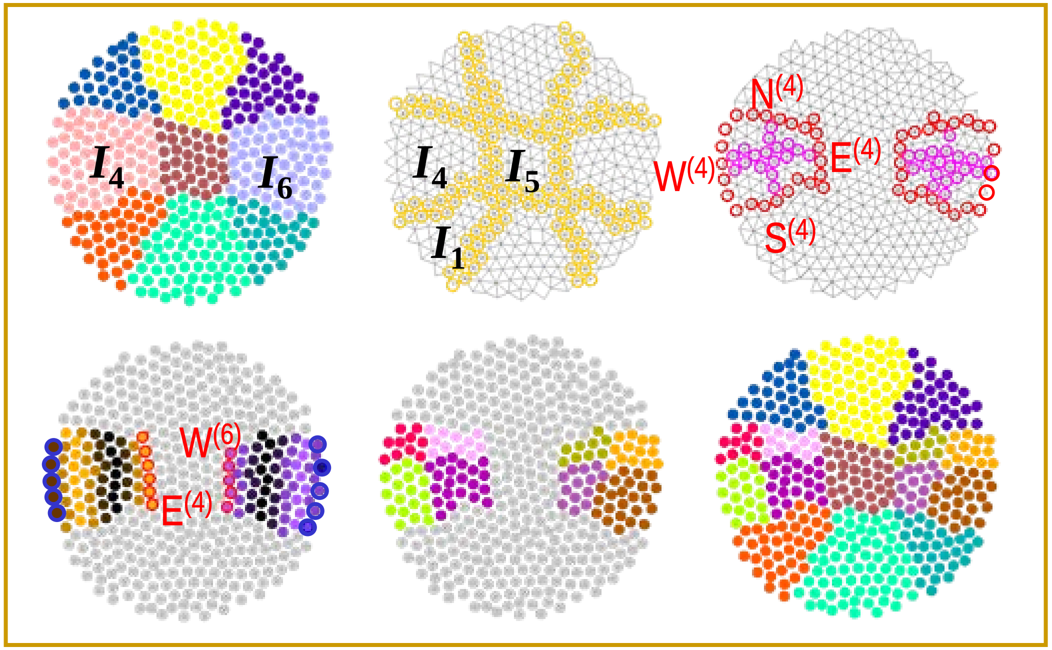
- ✓ details are not created in one shot, but gradually added. . .

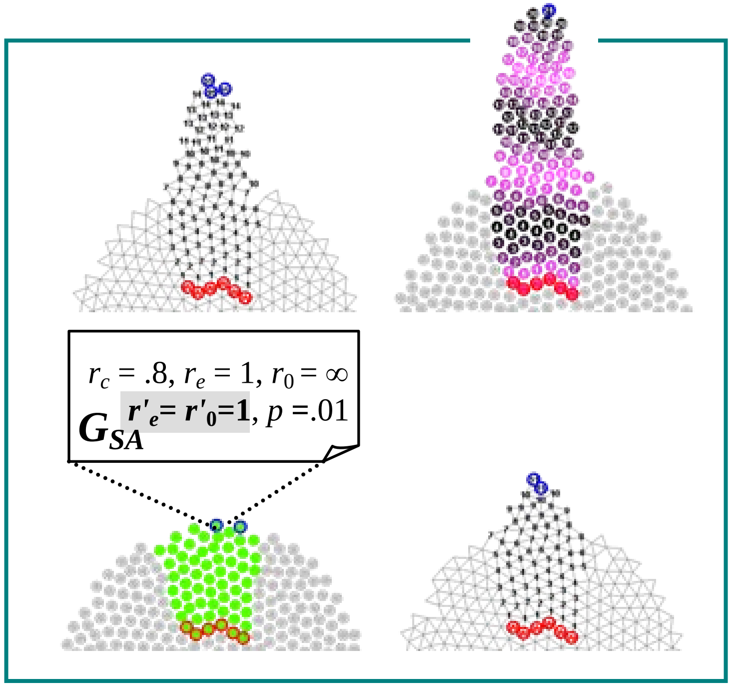
- ✓ . . . while, at the same time, the canvas grows



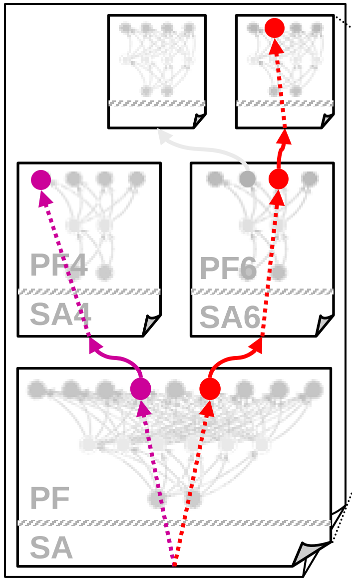
from Coen, E. (2000)
The Art of Genes, pp131-135

4. Embryomorphic Engineering

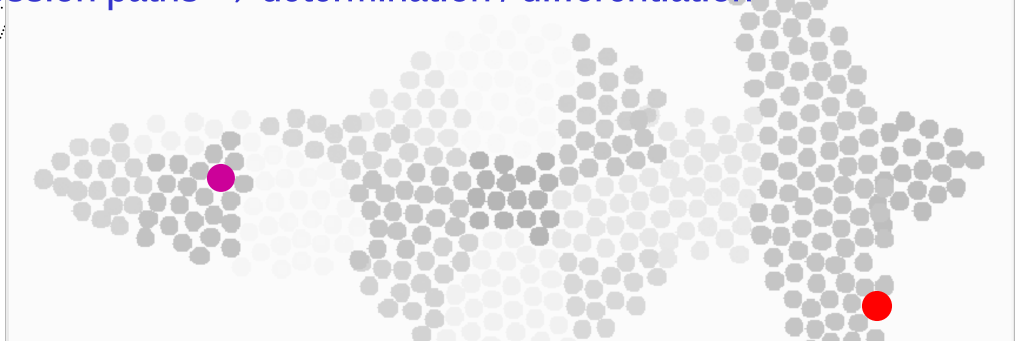




Doursat (2008)
ALIFE XI

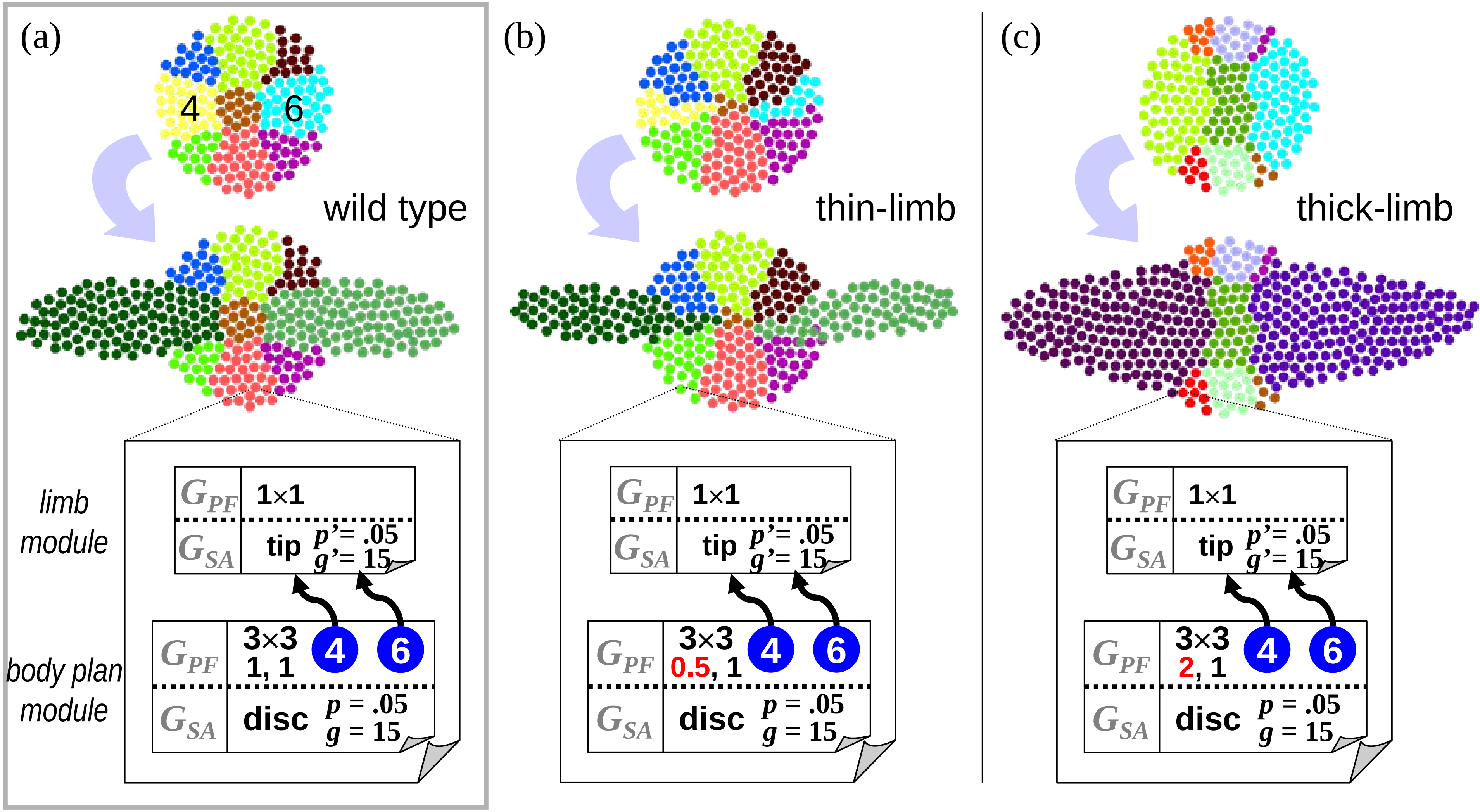


all cells have same GRN, but execute different expression paths → determination / differentiation

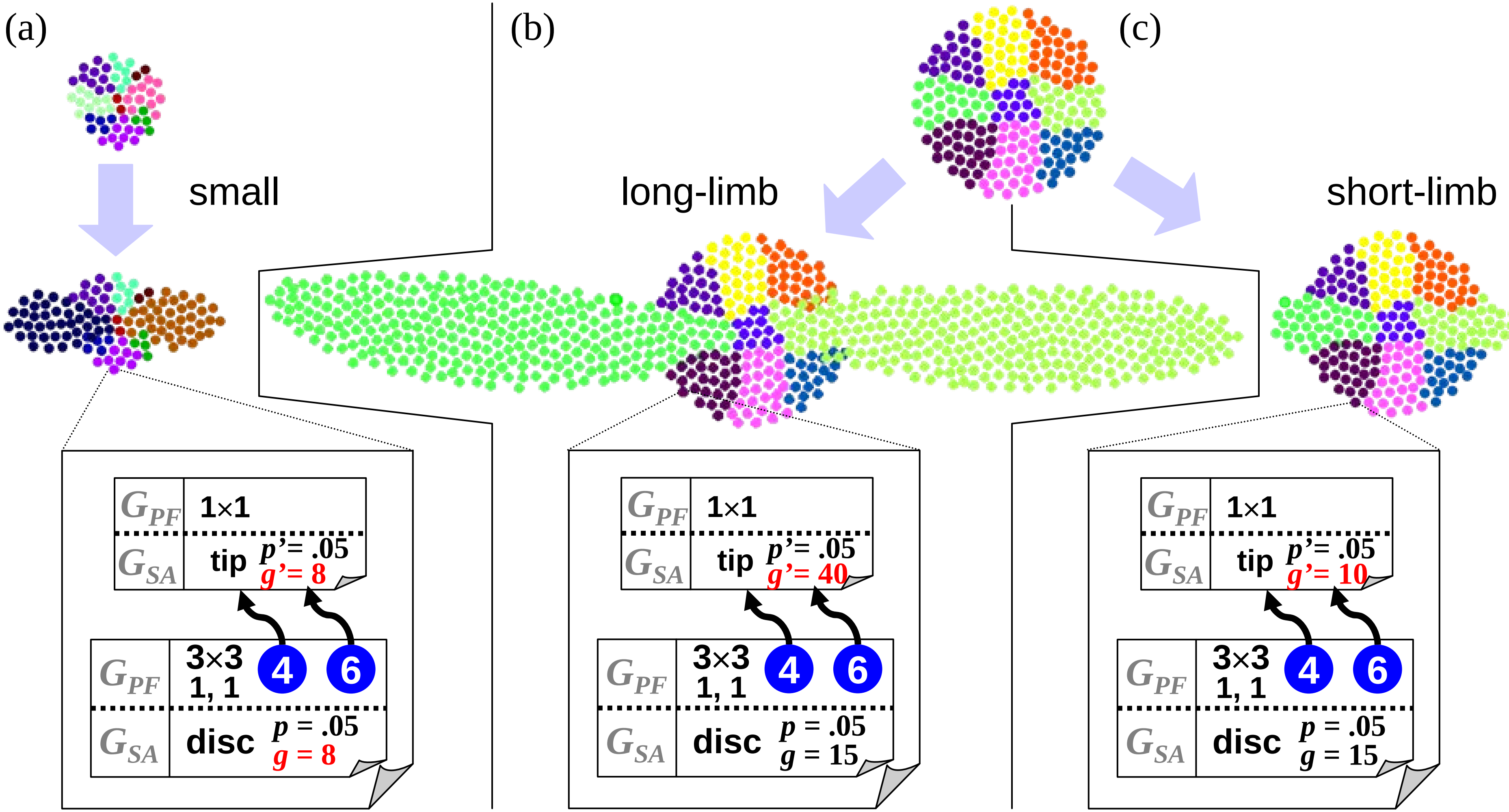


microscopic (cell) randomness, but mesoscopic (region) predictability

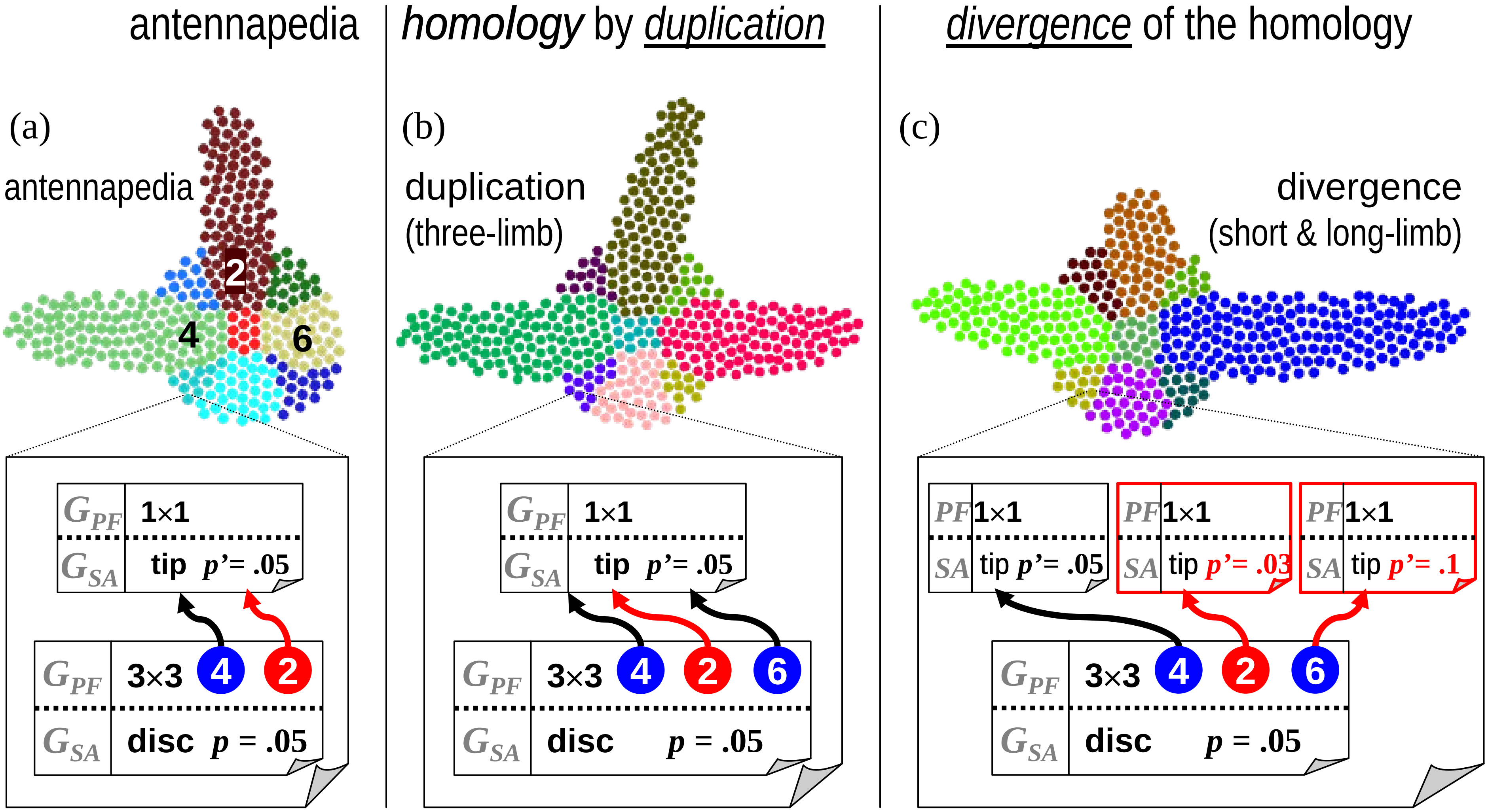
➢ Quantitative mutations: limb thickness



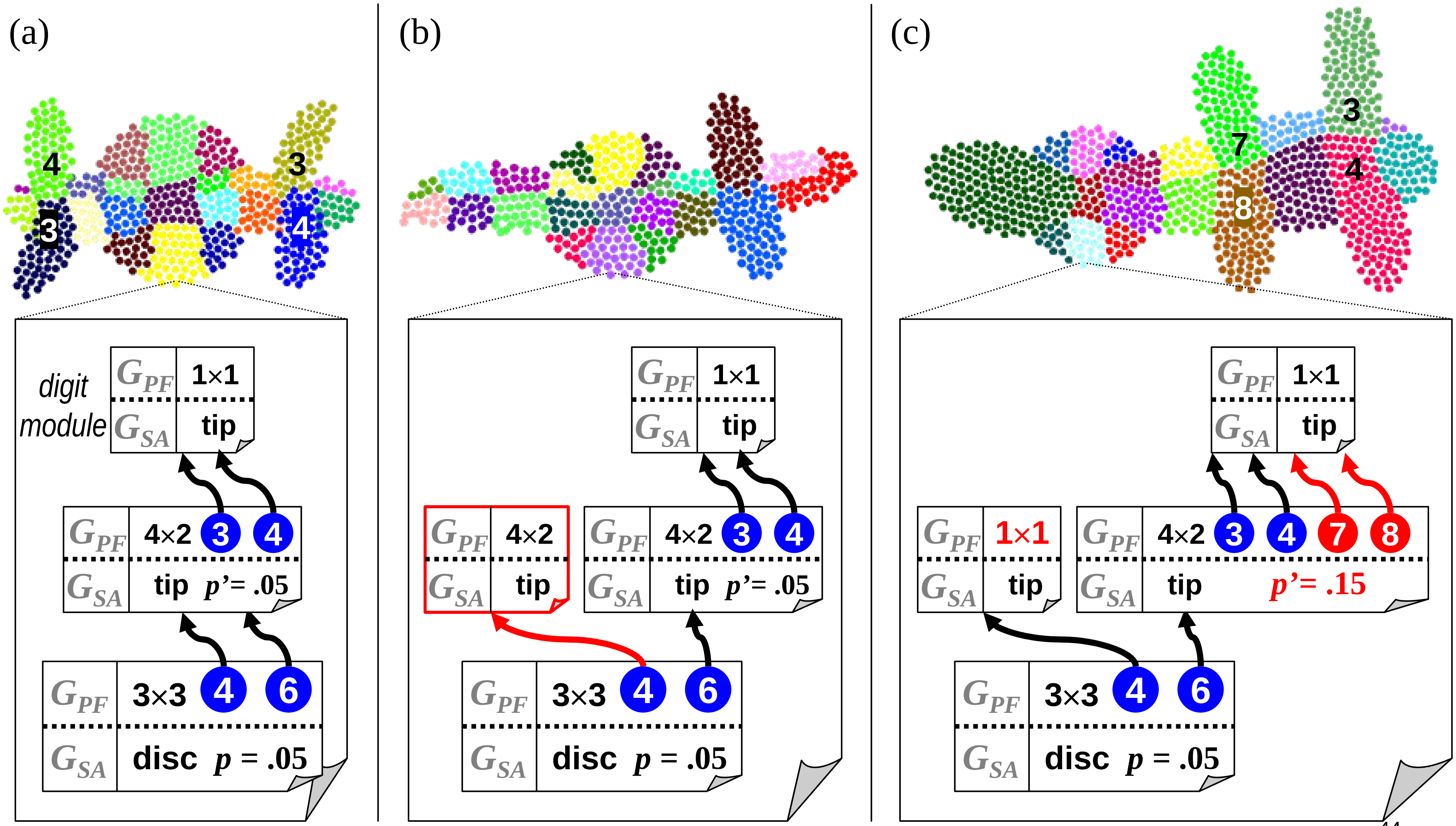
- Quantitative mutations: body size and limb length



➢ Qualitative mutations: limb position and differentiation

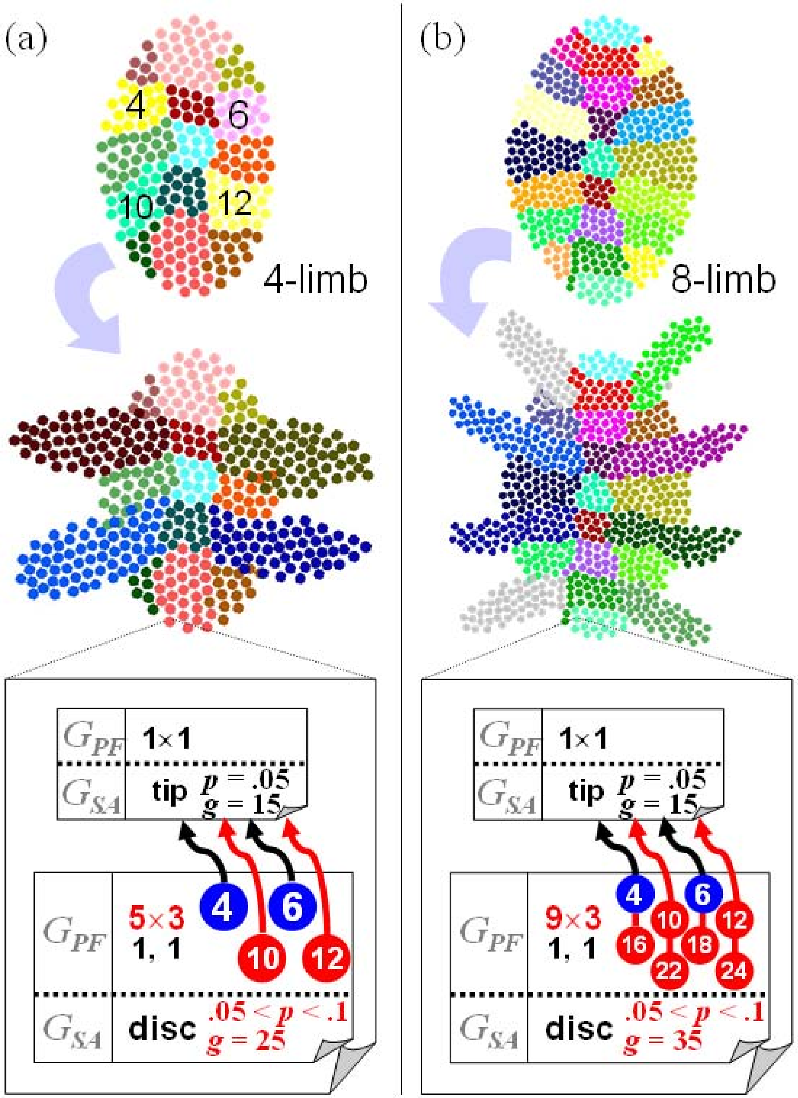


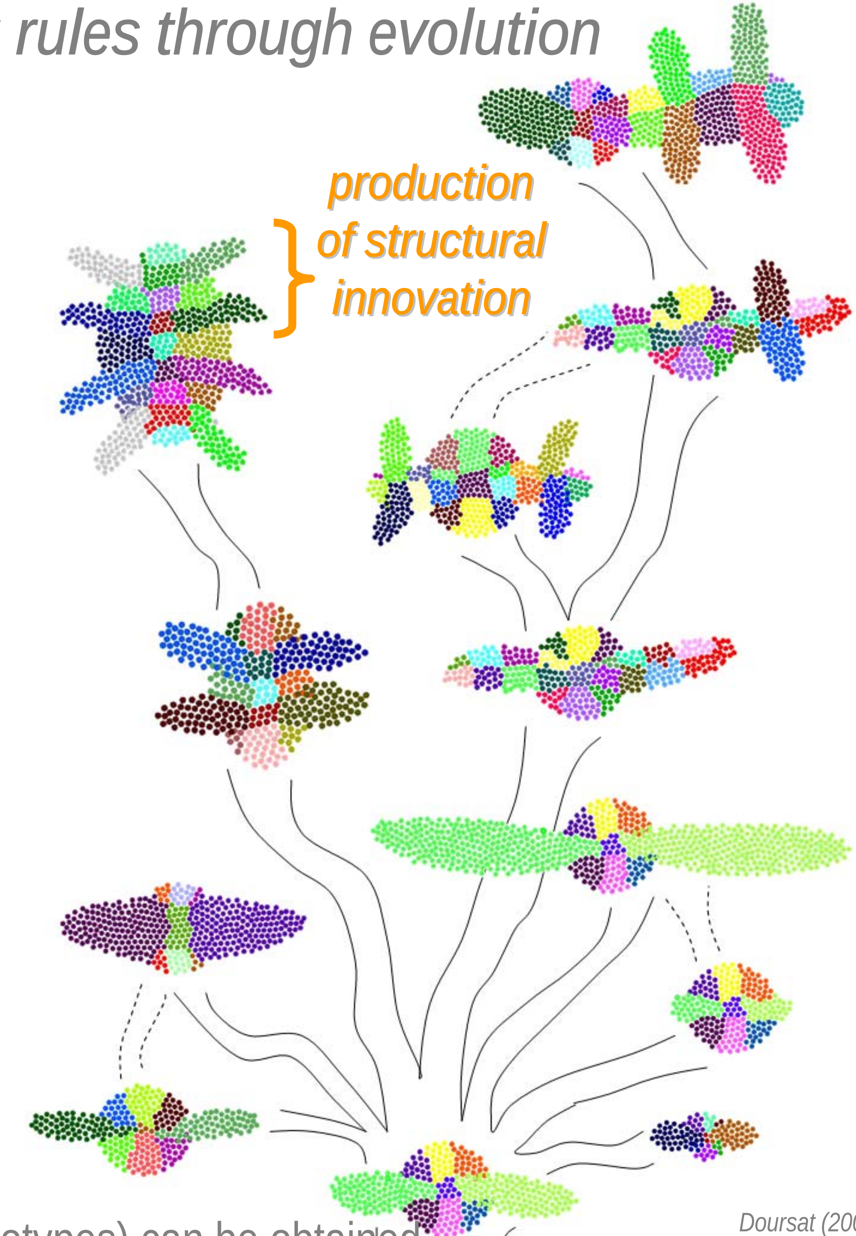
➢ Qualitative mutations: 3[rd]-level digits



4. Embryomorphic Engineering

Changing the agents' self-architecting rules through evolution



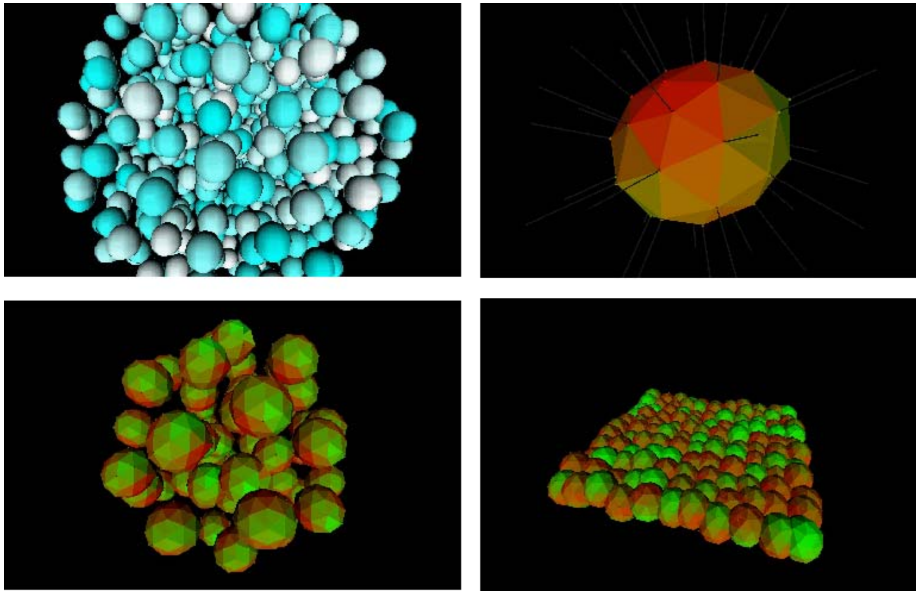


by tinkering with the genotype, new architectures (phenotypes) can be obtained

Doursat (2009)
18th GECCO

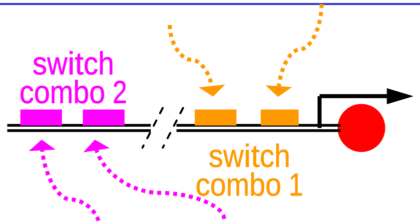
4. Embryomorphic Engineering

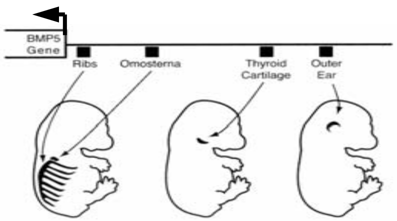
- ➢ More accurate mechanics
  - ✓ 3-D
  - ✓ individual cell shapes
  - ✓ collective motion, migration
  - ✓ adhesion



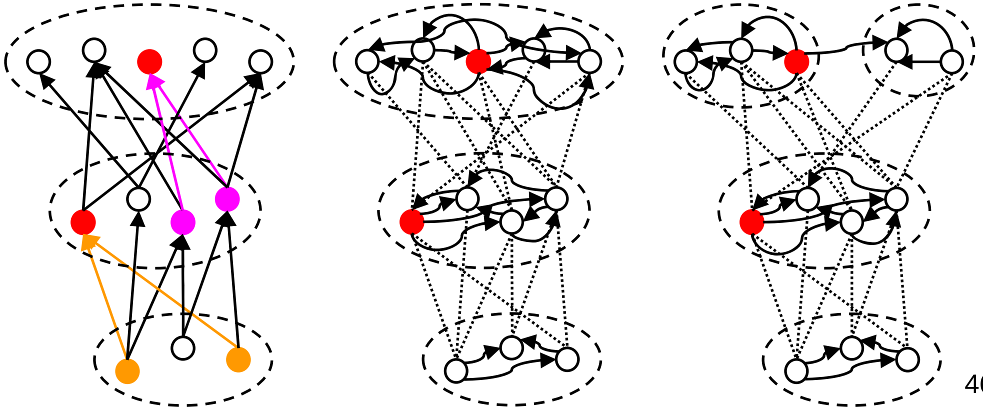
(Delile, Doursat, Peyrieras)

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



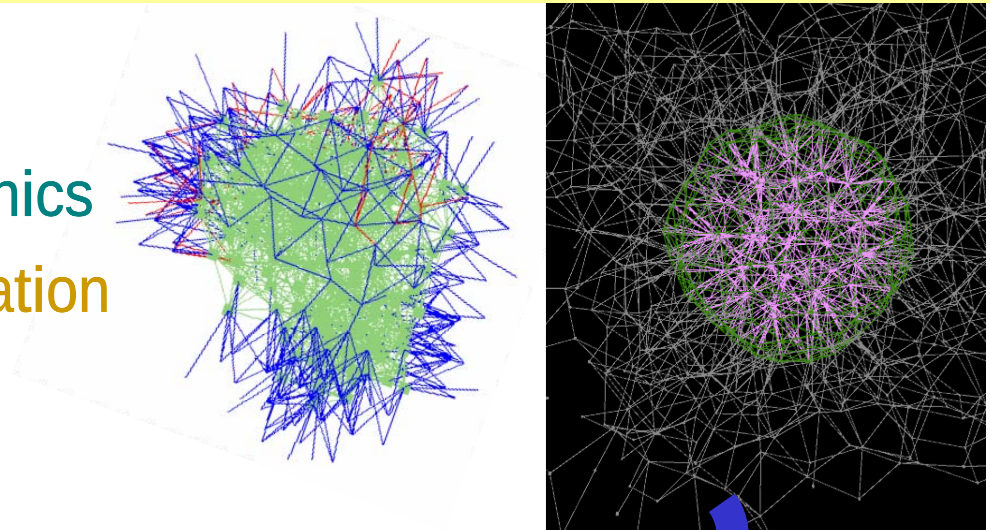


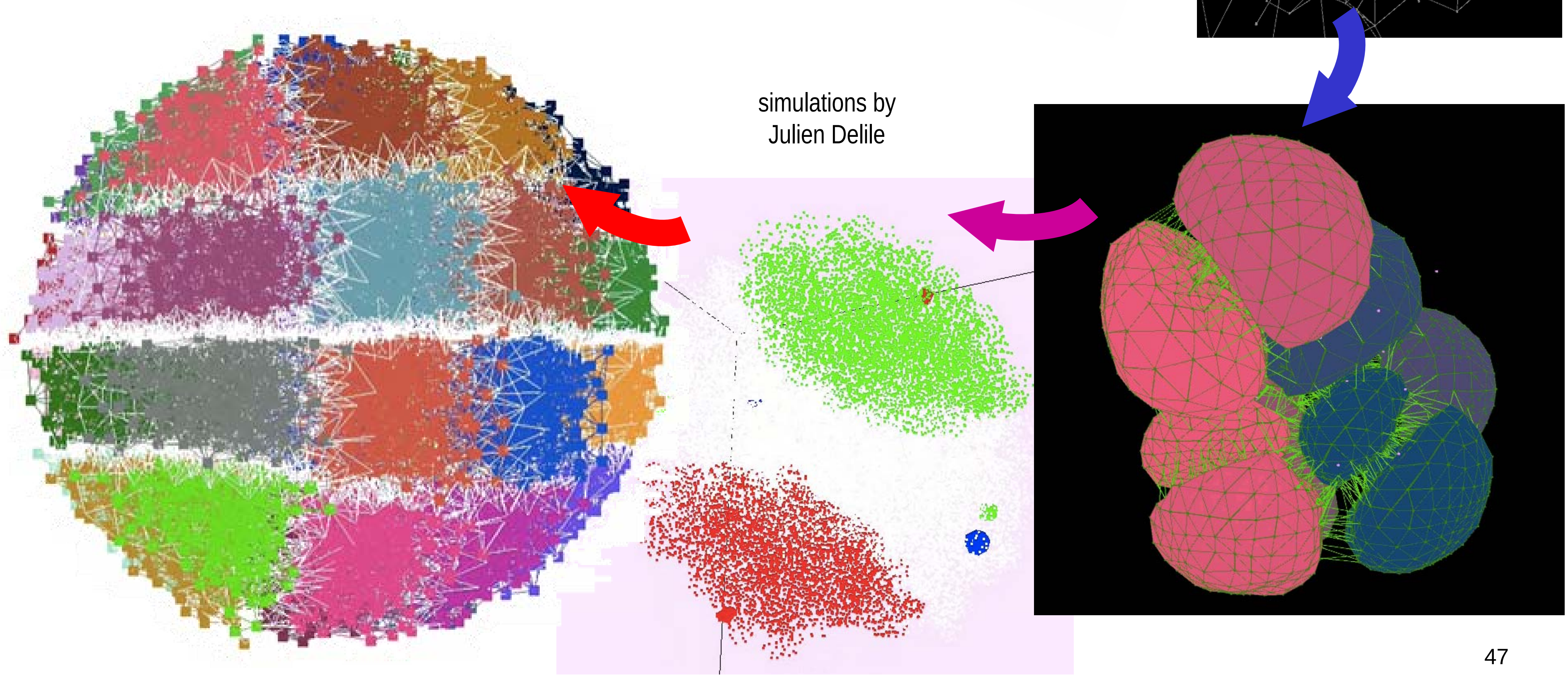
after David Kingsley, in Carroll, S. B. (2005) *Endless Forms Most Beautiful*, p125



4. Embryomorphic Engineering

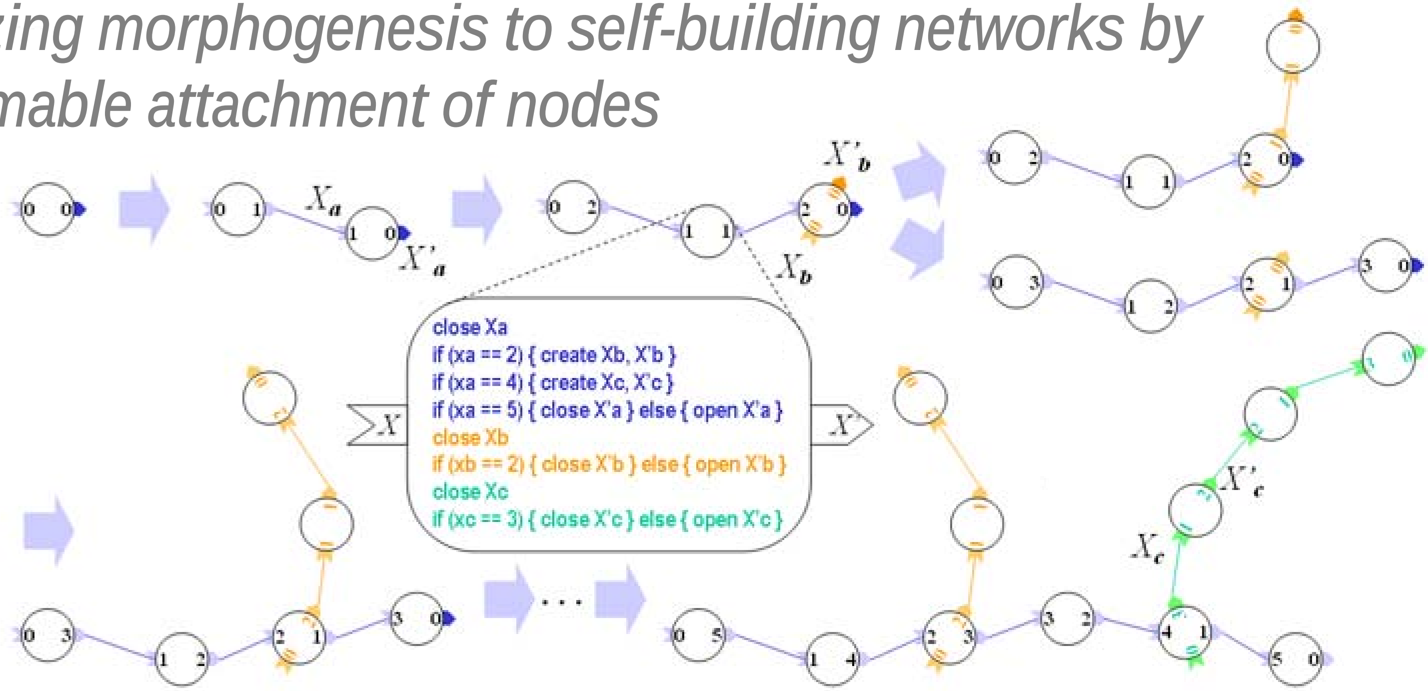
- Latest progress
  - ✓ 3D particle-based mechanics
  - ✓ kinetic-based gene regulation

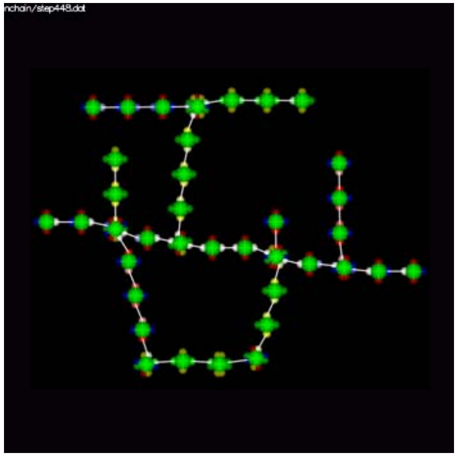




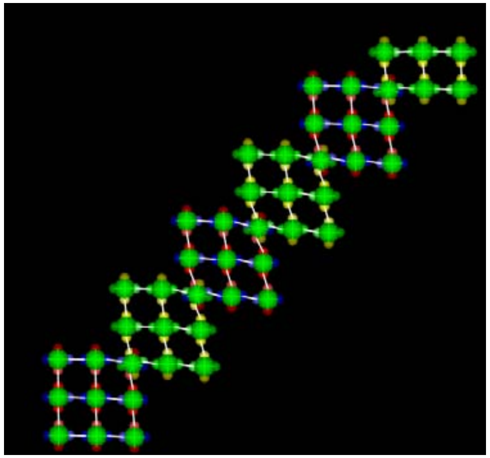
4. Embryomorphic Engineering

Generalizing morphogenesis to self-building networks by programmable attachment of nodes

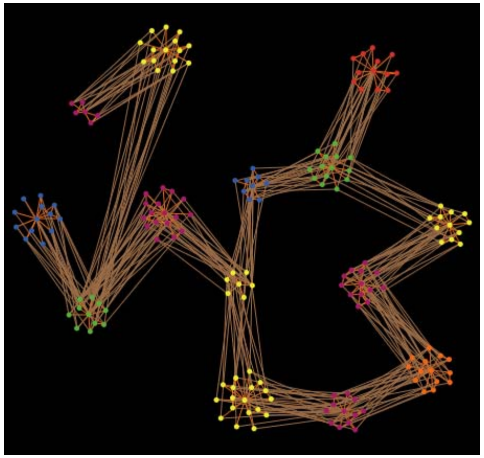




single-node composite branching



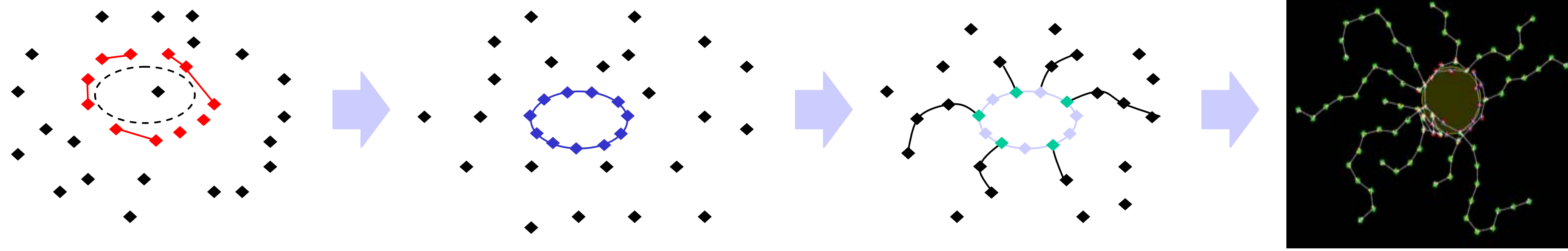
iterative lattice pile-up



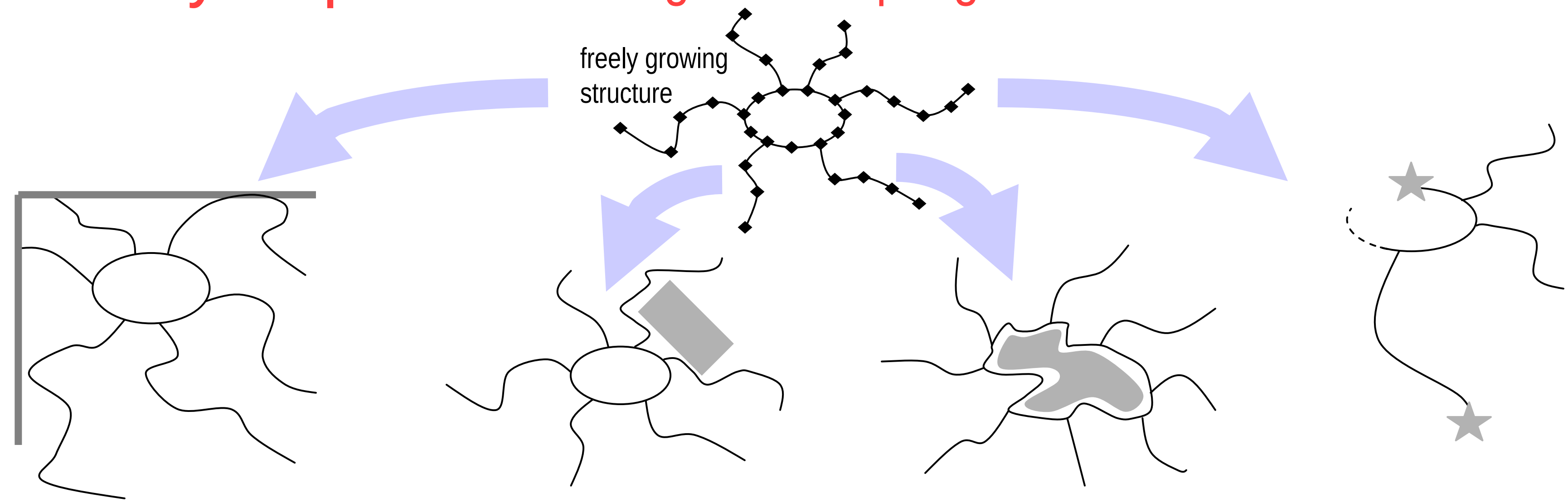
clustered composite branching

Doursat & Ulieru (2008) Autonomics

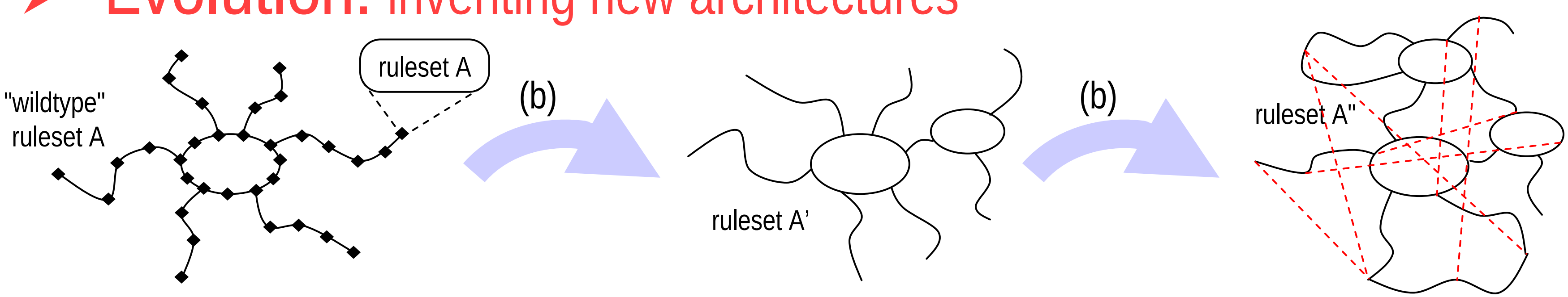
Development: growing an intrinsic architecture



Polymorphism: reacting and adapting to the environment



Evolution: inventing new architectures



4. Embryomorphic Engineering (ME)

ME is about programming the agents of emergence

a) Giving agents self-identifying and self-positioning abilities

- ✓ agents possess the same set of rules but execute different subsets depending on their position = "differentiation" in cells, "stigmergy" in insects

b) ME brings a new focus on "complex systems engineering"

- ✓ exploring the artificial design and implementation of **autonomous systems capable of developing sophisticated, heterogeneous morphologies** or architectures without central planning or external lead

c) Related *emerging ICT disciplines* and application domains

- ✓ *amorphous/spatial computing* (MIT)
- ✓ *organic computing* (DFG, Germany)
- ✓ *pervasive adaptation* (FET, EU)
- ✓ *ubiquitous computing* (PARC)
- ✓ *programmable matter* (CMU)

- ✓ swarm robotics, modular/reconfigurable robotics
- ✓ mobile ad hoc networks, sensor-actuator networks
- ✓ synthetic biology, etc.

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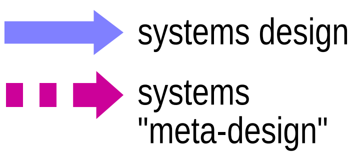
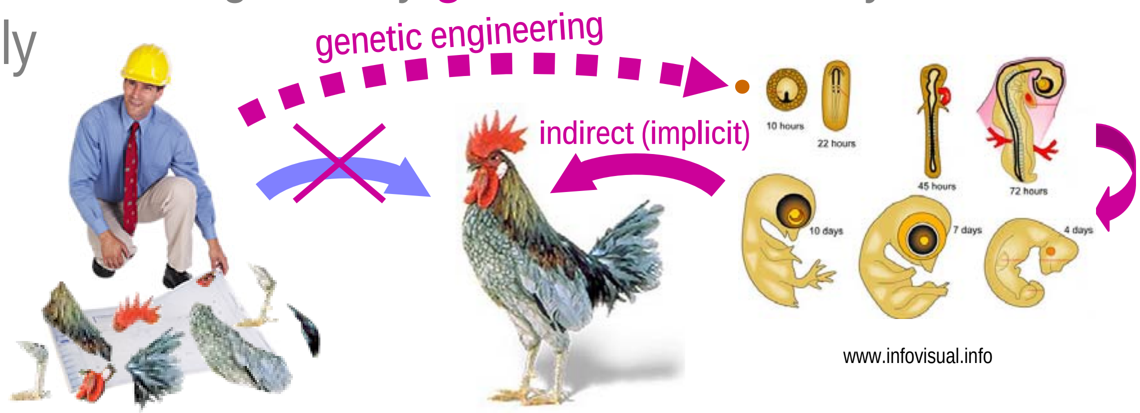
5. The New Challenge of "Meta-Design"

Or how to organize spontaneity

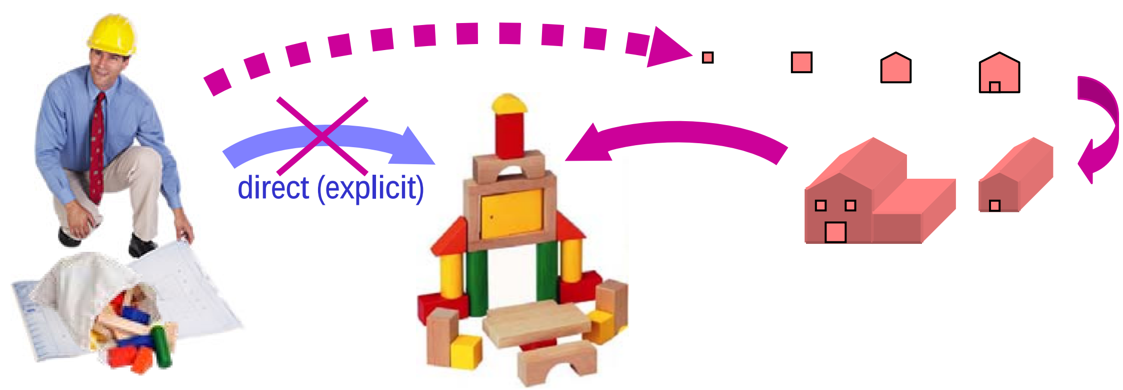
5. The New Challenge of "Meta-Design"

- ME and other emerging ICT fields are all proponents of the shift from design to "meta-design"
  - ✓ fact: organisms endogenously *grow* but artificial systems *are built* exogenously
  - ✓ challenge: can architects "step back" from their creation and only *set the generic conditions* for systems to self-assemble?

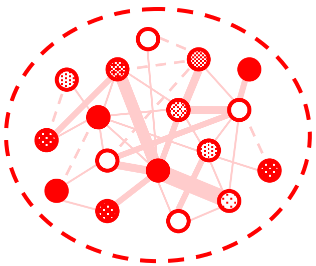




instead of building the system from the top ("phenotype"), program the components from the bottom ("genotype")



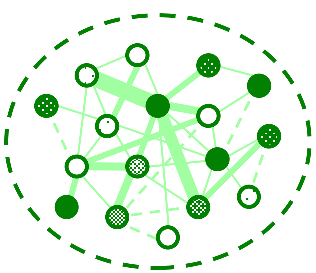
- Between natural and engineered emergence



CS science: observing and understanding "natural", spontaneous emergence (including human-caused)
→ *Agent-Based Modeling (ABM)*

But CS meta-design is not without its paradoxes...
- Can we plan their autonomy?
- Can we control their decentralization?
- Can we program their adaptation?

CS meta-design: *fostering and guiding complex systems (e.g. techno-social)*



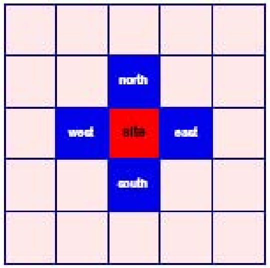
CS engineering: creating and programming a new "artificial" emergence
→ *Multi-Agent Systems (MAS)*

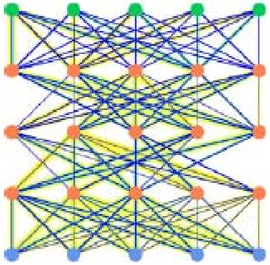
5. The New Challenge of "Meta-Design"

➢ People: the ABM modeling perspective of the social sciences

- ✓ *agent-* (or individual-) *based modeling* (ABM) arose from the need to model systems that were too complex for analytical descriptions
- ✓ main origin: cellular automata (CA)
  - von Neumann self-replicating machines → Ulam's "paper" abstraction into CAs → Conway's *Game of Life*
  - based on *grid* topology
- ✓ other origins rooted in economics and social sciences
  - related to "methodological individualism"
  - mostly based on grid and *network* topologies
- ✓ later: extended to ecology, biology and physics
  - based on grid, network and 2D/3D *Euclidean* topologies

→ *the rise of fast computing made ABM a practical tool*





Macal & North
Argonne National Laboratory

5. The New Challenge of "Meta-Design"

- ICT: the MAS multi-agent perspective of computer science
  - ✓ emphasis on software agent as a *proxy* representing human users and their interests; users state their prefs, agents try to satisfy them
    - ex: internet agents searching information
    - ex: electronic broker agents competing / cooperating to reach an agreement
    - ex: automation agents controlling and monitoring devices
  - ✓ main tasks of MAS programming: agent design and society design
    - an agent can be ± reactive, proactive, deliberative, social
    - an agent is caught between (a) its own (sophisticated) goals and (b) the constraints from the environment and exchanges with the other agents

→ *meta-design should blend both MAS and ABM philosophies*

- MAS: a few "heavy-weight" (big program), "selfish", intelligent agents
  ABM: many "light-weight" (few rules), highly "social", "simple" agents
- MAS: focus on game theoretic gains
  ABM: focus on collective emergent behavior

TAKEAWAY Getting ready to organize spontaneity

a) Construe systems as self-organizing building-block games

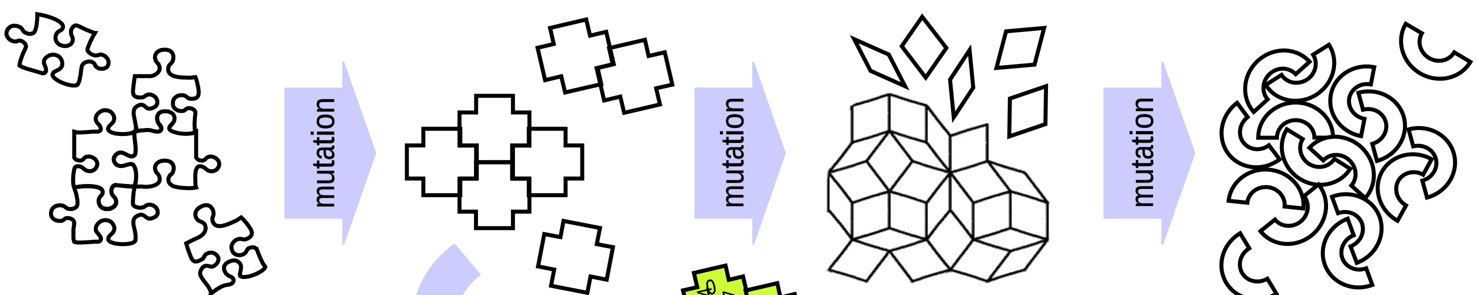
- ✓ Instead of assembling a construction yourself, shape its building blocks in a way that they self-assemble for you—and come up with new solutions

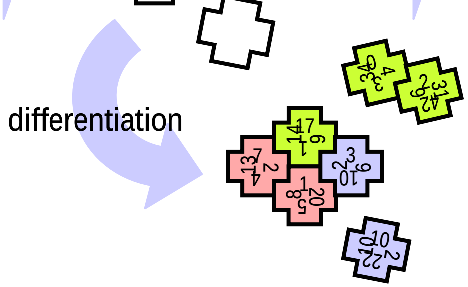
b) Design and program the pieces

- ✓ their potential to search, connect to, interact with each other, and react to their environment

c) Add evolution

- ✓ by variation (mutation) of the pieces' program and selection of the emerging architecture





- *piece = "genotype"*
- *architecture = "phenotype"*

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