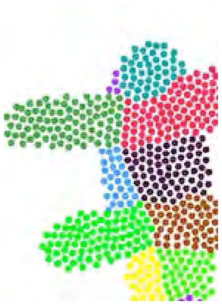
Second international workshop
New Worlds of Computation 2011
LIFO, University of Orléans (France)
Monday & Tuesday May 23–24, 2011

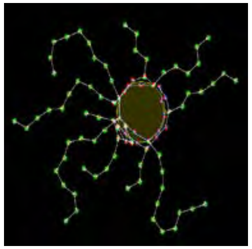
Morphogenetic Engineering:



Biological Development

as a new model of

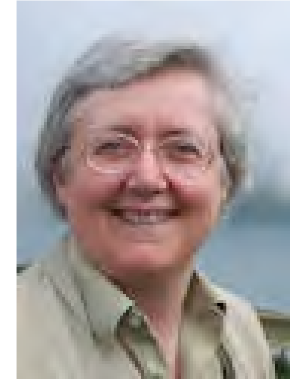
Programmed Self-Organization



René Doursat
CNRS – Complex Systems Institute, Paris – Ecole Polytechnique

ISC PARIS ÎLE DE FRANCE
INSTITUT DES SYSTEMES COMPLEXES

Susan Stepney, York



- Stanislaw Ulam [said] that using a term like nonlinear science is like referring to the bulk of **zoology as the study of non-elephant animals**.
- The elephant in the room here is the classical Turing machine. **Unconventional computation** is a similar term: **the study of non-Turing computation**.
- The **classical Turing machine** was developed as an **abstraction of** how **human "computers", clerks** following predefined and prescriptive rules, calculated various mathematical tables.
- Unconventional computation can be inspired by the whole of wider nature. We can look to physics (...), to chemistry (reaction-diffusion systems, complex chemical reactions, DNA binding), and to biology (bacteria, flocks, social insects, evolution, growth and self-assembly, immune systems, neural systems), to mention just a few.
- PARALLELISM – INTERACTION – NATURE

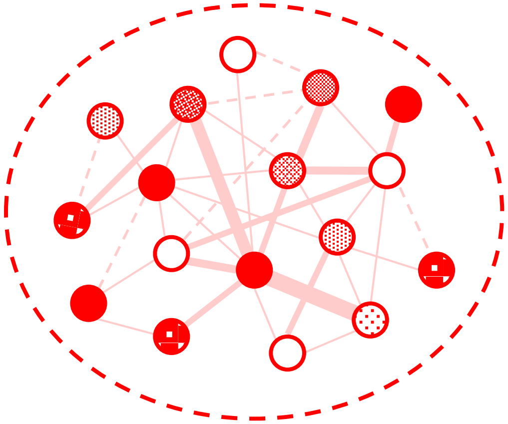
→ *COMPLEX SYSTEMS*

1. What are Complex Systems?

- Decentralization
- Emergence
- Self-organization

1. What are Complex Systems?

➢ Complex systems can be found everywhere around us



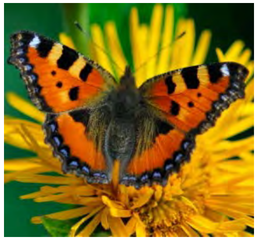
a) decentralization: the system is made of myriads of "simple" agents (local information, local rules, local interactions)

b) emergence: function is a bottom-up collective effect of the agents (asynchrony, homeostasis, 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

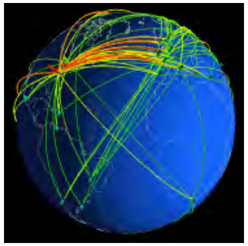


biological development
○ = cell

the brain & cognition
○ = neuron

insect colonies
○ = ant

Internet & Web
○ = host/page



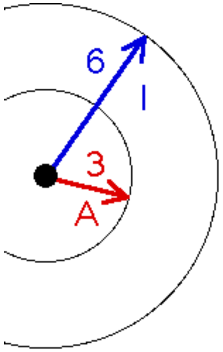
social networks
○ = person

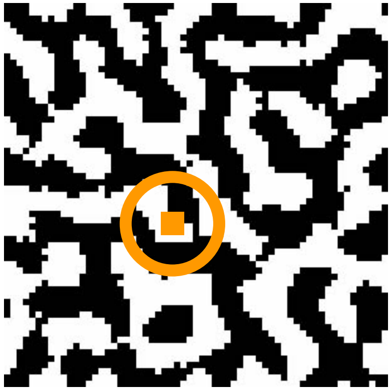
1. What are Complex Systems?

➢ 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)





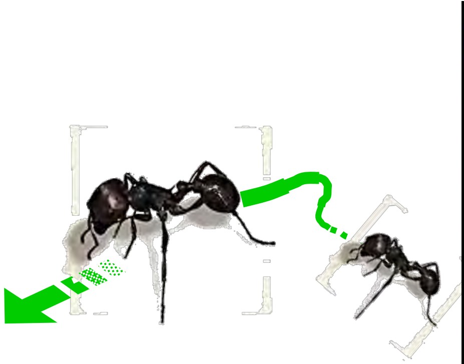
NetLogo Fur simulation

➢ Ex: Swarm intelligence – Insect colonies

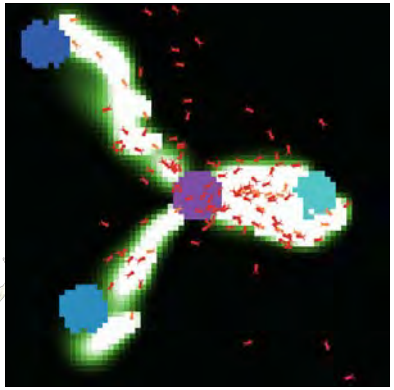
✓ trails form by ants that follow and reinforce each other's pheromone path

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)

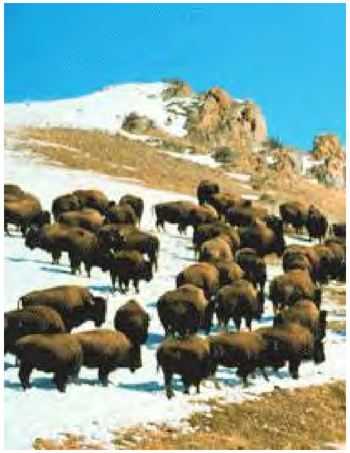


NetLogo Ants simulation

1. What are Complex Systems?

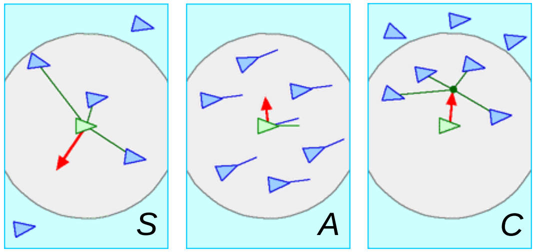
➢ Ex: Collective motion – Flocking, schooling, herding

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

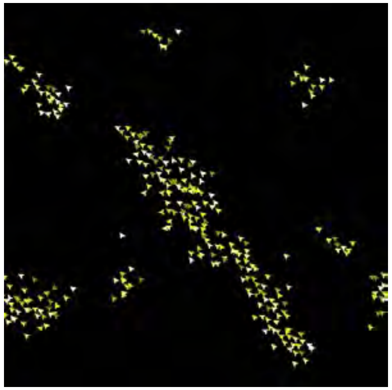


Bison herd
(Montana State University, Bozeman)

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



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

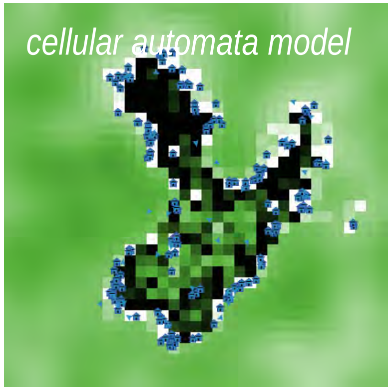


NetLogo Flocking simulation

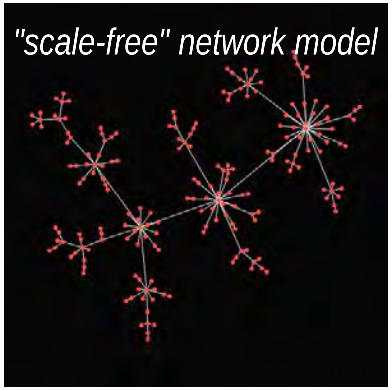
➢ Ex: Diffusion and networks – Cities and social links

✓clusters and cliques of homes/people that aggregate in geographical or social space

http://en.wikipedia.org/wiki/Urban_sprawl



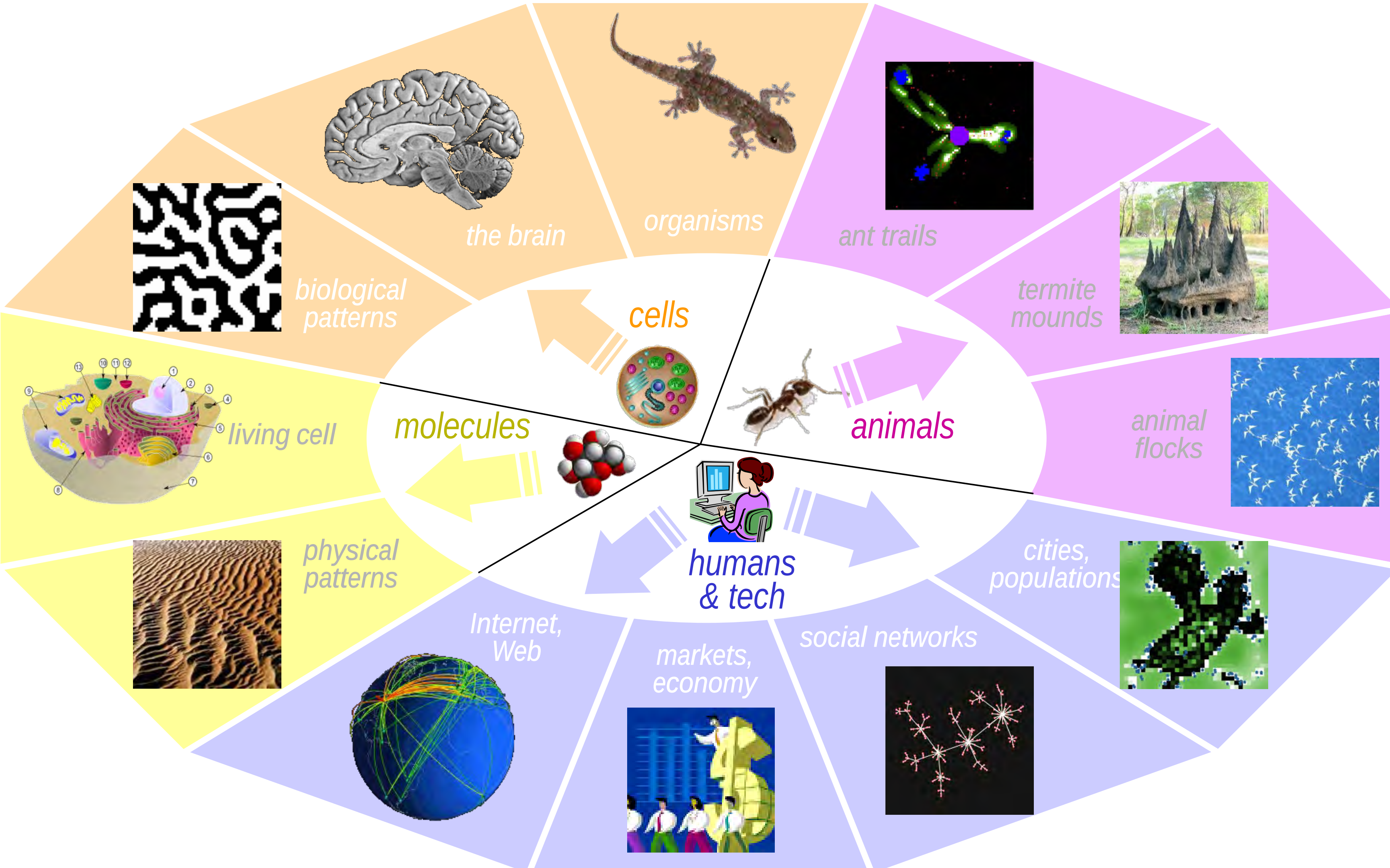
NetLogo urban sprawl simulation



NetLogo preferential attachment

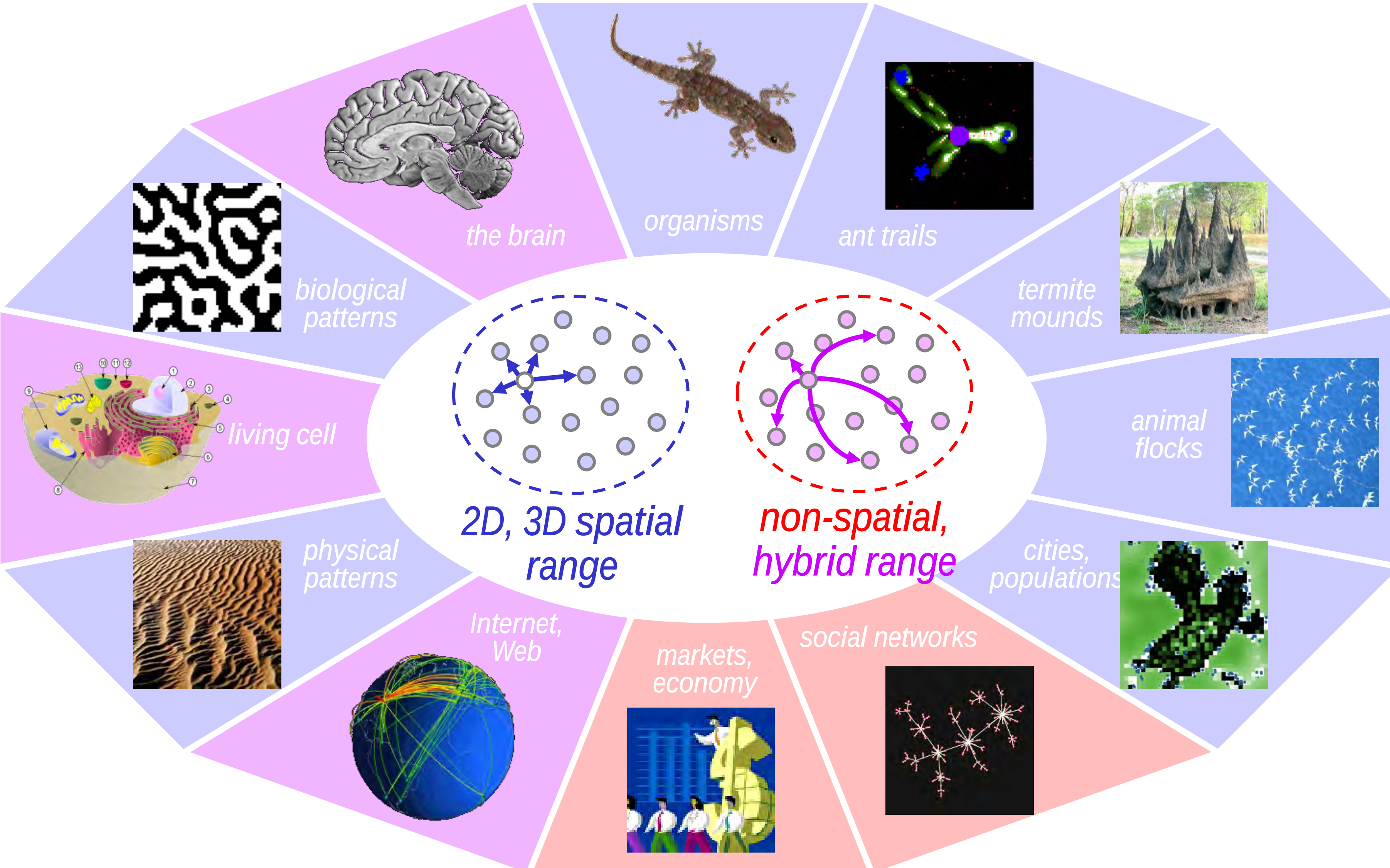
1. What are Complex Systems?

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



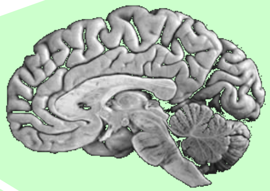
1. What are Complex Systems?

Categories of complex systems by range of interactions

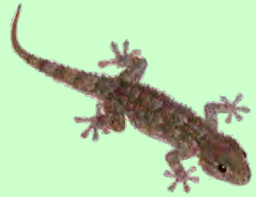


1. What are Complex Systems?

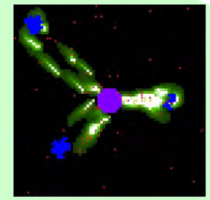
Natural and *human-caused* *categories of complex systems*



the brain



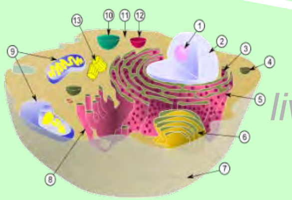
organisms



ant trails

termite mounds

biological patterns



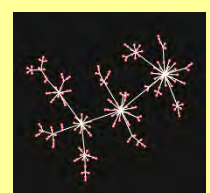
living cell

animal flocks

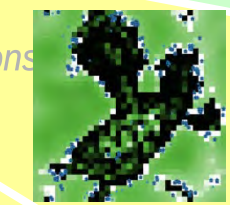
physical patterns

Internet, Web

markets, economy



social networks



cities, populations

- ... yet, even human-caused systems are "natural" in the sense of their *unplanned, spontaneous emergence*

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)
- cellular automata

→ *Toward a unified "complex systems" science and engineering?*

adaptation: change in typical functional regime of a system

- evolutionary methods
- genetic algorithms
- machine learning

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

1. What are Complex Systems?

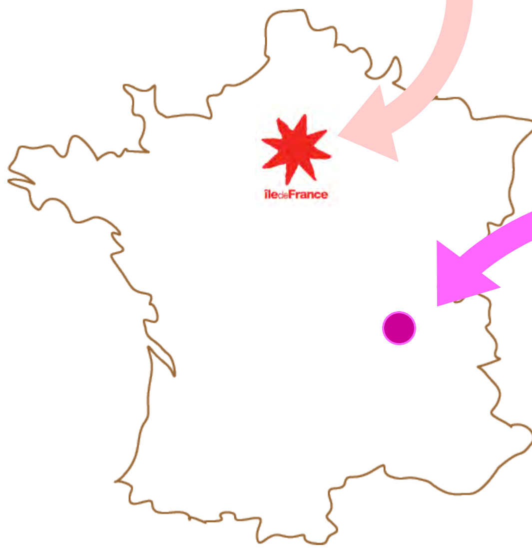
INSTITUT DES SYSTEMES COMPLEXES

Paris Ile-de-France

4th French Complex Systems Summer School, 2010

RNSC

National



IXXI

Lyon Rhône-Alpes

Resident Researchers

Pierre Baudot

Information Theory - Adaptation - Topology – Thermodynamics of perception.

mathematical neuroscience

René Doursat

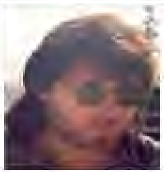
Artificial development (self-assembly, pattern formation, spatial computing, evolutionary computation) - Mesoscopic neurodynamics (segmentation, schematization, categorization, perception, cognitive linguistics).

artificial life / neural computing

Marie-Noëlle Comin

Urban systems, networks of cities, innovation, Europe, EU's Framework Programme for Research and Technological Development, converging technologies, NBIC (nanotechnology, biotechnology, information technology and cognitive science).

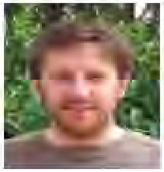
urban systems / innovation networks



Francesco Ginelli

Nonequilibrium statistical mechanics (Active matter, collective motion, flocking, nonequilibrium wetting, directed percolation, long range interactions) - Dynamical system theory (Lyapunov exponents, Lyapunov vectors, synchronization, stable chaos, spatiotemporal chaos, structural stability, hyperbolicity).

statistical mechanics / collective motion



Ivan Junier

Bio-related: Genetic regulation - Cellular organization - DNA/chromatin modeling - -omics (Genomics,Transcriptomics,proteomics,...) - Condensed matter theory - Inference problems in statistical physics - Network analysis (topology, geometry) - Dynamical behaviors of complex systems.
Statistical physics: Out-of equilibrium syst
Thermodynamic description of small syster

structural genomics

Taras Kowaliw

Evolutionary computation, artificial development, computer vision, visualization and electronic art.

computational evolution / development

Telmo Menezes

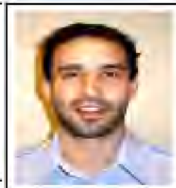
Complex network analysis and simulation - Social networks - Evolutionary search for multi-agent models, Genetic programming applied to programmable networks - Bio-inspired algorithms.

social networks

Bivas Mitra

Peer-to-Peer networks, Blog networks, Complex networks, Statistical mechanics, Networks modeling, Optical networks, Wireless Internet.

peer-to-peer networks



Romain Reuillon

High performance computing - Grid computing - Scientific workflows - Model exploration - Distributed stochastic simulations - Parallell pseudo-random number generation - Coffee maker.

high performance computing

Jean-Baptiste Rouquier

Complex networks: communities, structure, dynamics. Links between fields. Large datasets.
Cellular automata: model of complex systems, perturbation, asynchronism, robustness.

complex networks / cellular automata

Camilo Melani

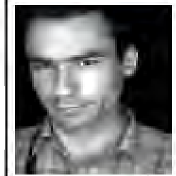
Grid Computing,Bioemergences Platform (workflow), Mophodynamics reconstruction, Images processing algorithms.

embryogenesis

David Chavalarias

Web mining and Quantitative Epistemology - Cognitive economics and modelling of cultural dynamics - Collective discovery and scientific discovery.

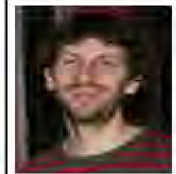
web mining / social intelligence



Srdjan Ostojic

Neuroscience théoriques - Spiking Neurons - Dynamiques Stochastic-ques.

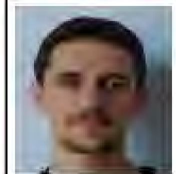
spiking neural dynamics



Andrea Perna

Morphogenesis, Collective behavior, Spatial patterns, Spatial networks.

spatial networks / swarm intelligence



Fernando Peruani

Biophysique – Active Matter – Complex Networks.

active matter / complex networks

Francesco d'Ovidio

Applied nonlinear dynamics - Transport and mixing in geophysical flows - Interaction of physical and ecological processes in the ocean.

nonlinear dynamics / oceanography

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Complex Systems & Computation

1. What are Complex Systems?

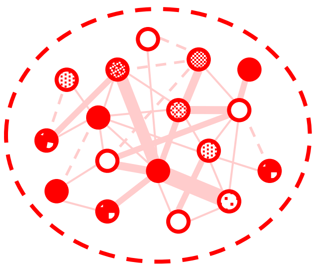
- Decentralization
- Emergence
- Self-organization

5. A New World of CS Computation

Or how to exploit and organize spontaneity

5. A New World of Complex Systems Computation

➢ Between natural and engineered emergence

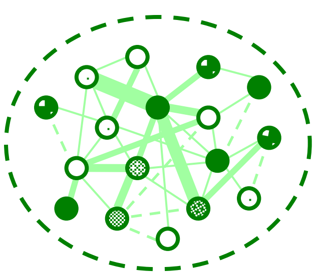


CS science: observing and understanding "natural", spontaneous emergence (including human-caused)
→ *Agent-Based Modeling (ABM)*

But CS computation is not without paradoxes:

- Can we plan autonomy?
- Can we control decentralization?
- Can we program adaptation?

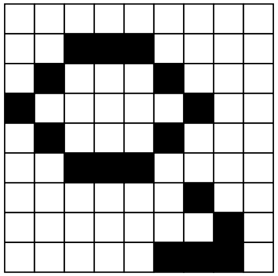
CS computation: *fostering and guiding complex systems at the level of their elements*



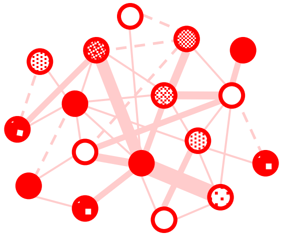
CS engineering: creating and programming a new "artificial" emergence
→ *Multi-Agent Systems (MAS)*

➢ Nature: the ABM scientific perspective of social/bio sciences

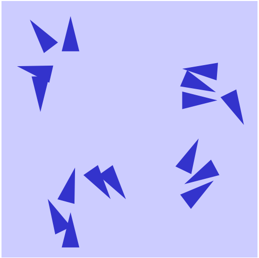
- ✓ *agent-* (or individual-) *based modeling* (ABM) arose from the need to model systems that were too complex for analytical descriptions
- ✓ main origin: cellular automata (CA)
  - von Neumann self-replicating machines → Ulam's "paper" abstraction into CAs → Conway's *Game of Life*
  - based on *grid* topology



- ✓ other origins rooted in economics and social sciences
  - related to "methodological individualism"
  - mostly based on grid and *network* topologies



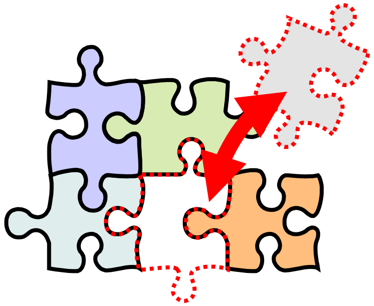
- ✓ later: extended to ecology, biology and physics
  - based on grid, network and 2D/3D *Euclidean* topologies



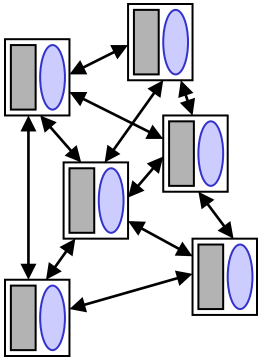
→ *the rise of fast computing made ABM a practical tool*

5. A New World of Complex Systems Computation

- ICT: the MAS engineering perspective of computer science
  - ✓ in software engineering, the need for clean *architectures*
    - historical trend: breaking up big monolithic code into *layers*, *modules* or *objects* that communicate via application programming *interfaces* (APIs)
    - this allows fixing, upgrading, or replacing parts without disturbing the rest
  - ✓ in AI, the need for ***distribution*** (formerly "DAI")
    - break up big systems into smaller units creating a decentralized computation: *software/intelligent agents*



  - ✓ difference with object-oriented programming:
    - agents are "proactive" / autonomously threaded
  - ✓ difference with distributed (operating) systems:
    - agents don't appear transparently as one coherent system



→ *the rise of pervasive networking made distributed systems both a necessity and a practical technology*

5. A New World of Complex Systems Computation

- ICT: the MAS engineering 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
  - → *CS computation 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

5. A New World of Complex Systems Computation

- Exporting models of natural complex systems to ICT
  - already a tradition, mostly in offline search and optimization

	ex: neurons & brain	ex: ant colonies	ex: genes & evolution
ABM	biological neural models	trail formation, swarming	laws of genetics
	binary neuron, linear synapse	agents that move, deposit & follow "pheromone"	genetic program, binary code, mutation
MAS	artificial neural networks (ANNs) applied to machine learning & classification	ant colony optimization (ACO) applied to graph theoretic & networking problems	genetic algorithms (GAs), evolutionary computation for search & optimization

TODAY: simulated in a Turing machine / von Neumann architecture

5. A New World of Complex Systems Computation

- Exporting natural complex systems to ICT
  - ✓ ... looping back onto unconventional physical implementation

DNA computing

chemical, wave-based computing

synthetic biology

artificial neural networks (ANNs) applied to machine learning & classification

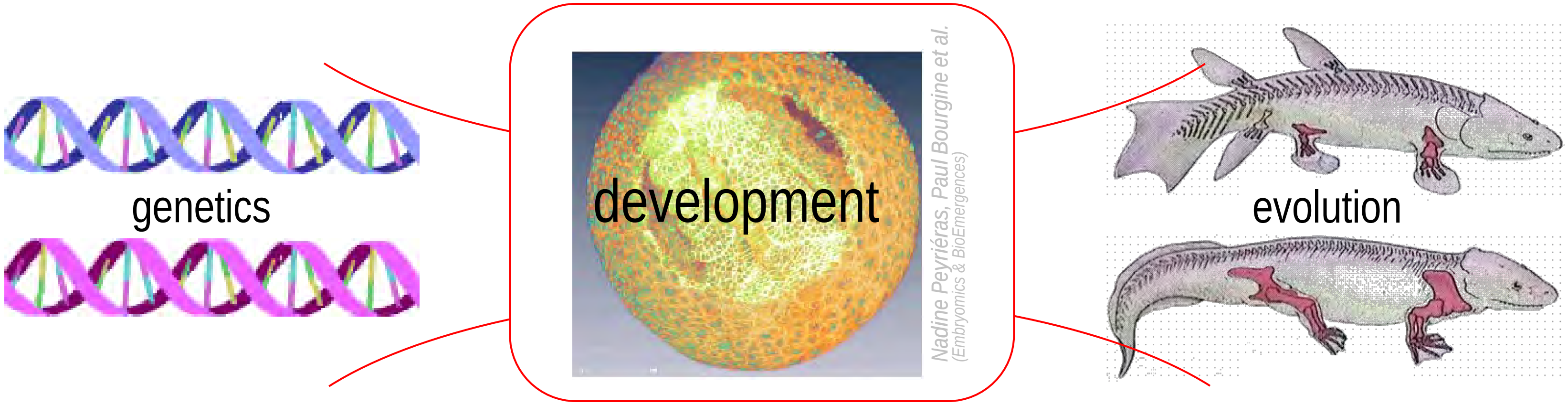
ant colony optimization (ACO) applied to graph theoretic & networking problems

genetic algorithms (GAs), evolutionary computation for search & optimization

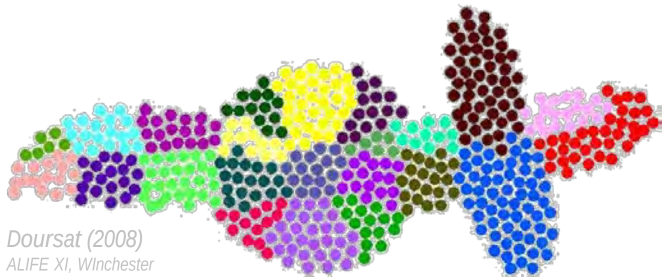
TOMORROW: implemented in bioware, nanoware, etc.

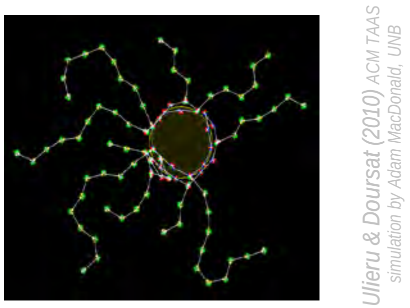
5. A New World of Complex Systems Computation

- A new line of bio-inspiration: biological morphogenesis
  - ✓ designing multi-agent models for decentralized systems engineering



Morphogenetic Engineering





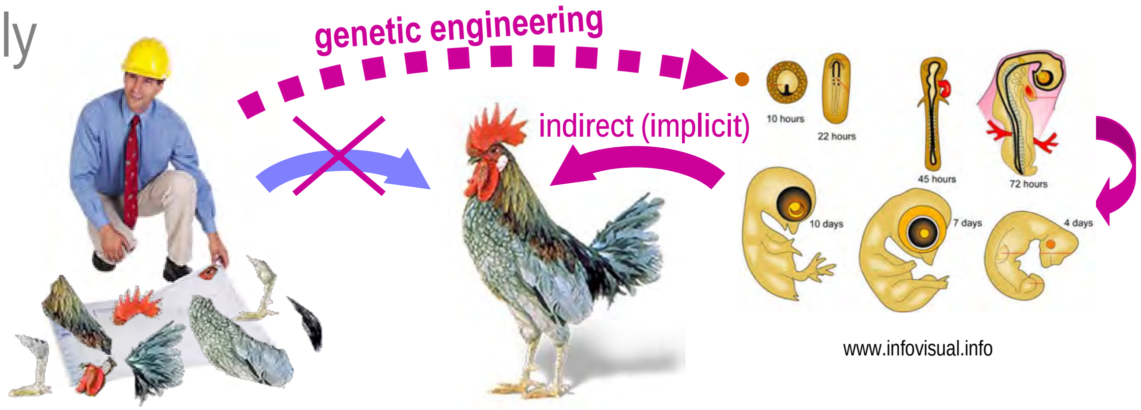
whether Turing machine... ... or bioware, nanoware, etc.

5. A New World of Complex Systems Computation

- ME and other emerging ICT fields are all proponents of the shift from design to "meta-design"
  - ✓ <u>fact</u>: organisms endogenously *grow* but artificial systems *are built* exogenously

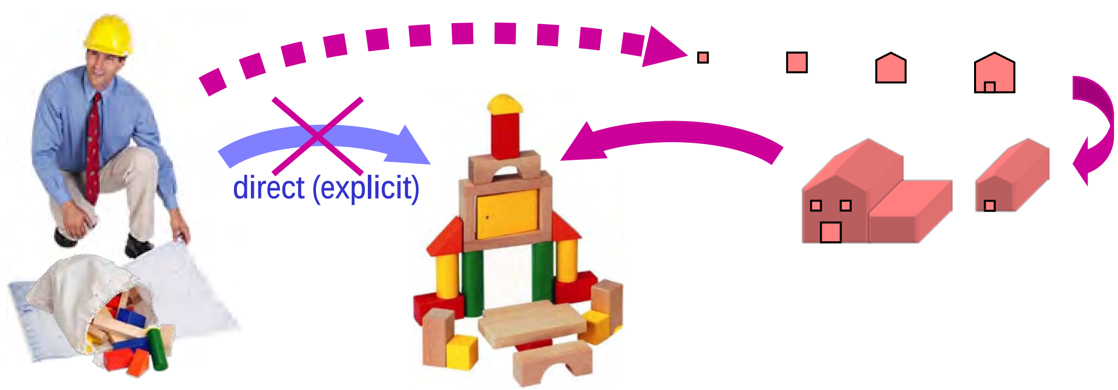
systems design

systems "meta-design"



  - ✓ <u>challenge</u>: 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"), <u>program the components</u> from the bottom ("genotype")



➢ Getting ready to organize spontaneity

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

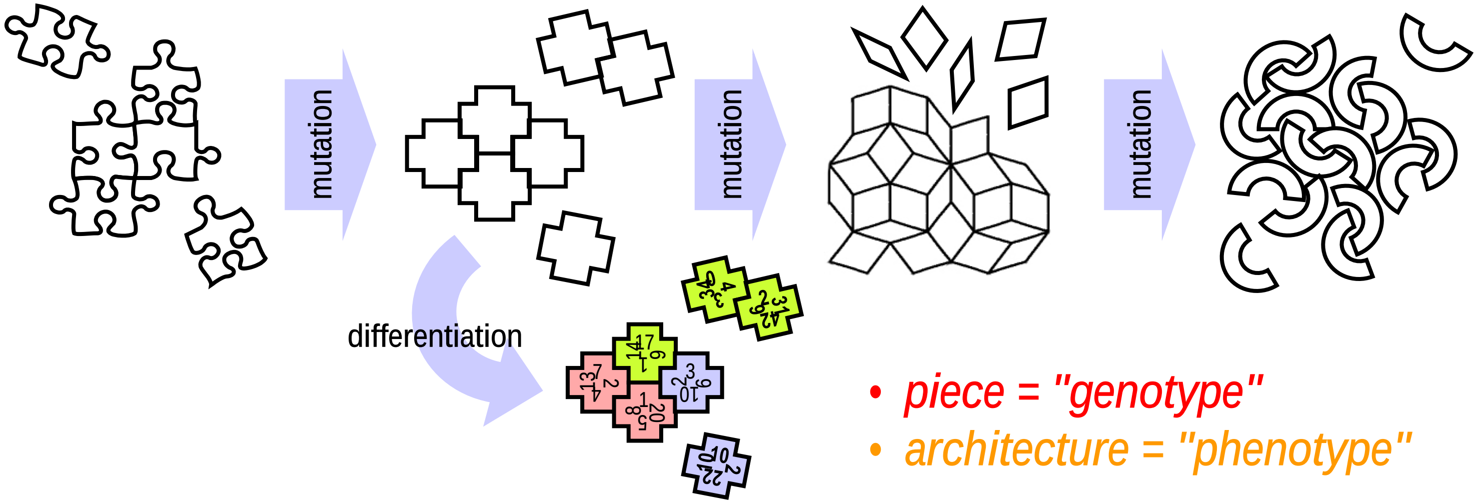
✓ Instead of assembling a construction yourself, shape its building blocks in a way that they self-assemble for you—and come up with new solutions

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"*

COMPLEX SYSTEMS & COMPUTATION

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

5. A New World of CS Computation

Or how to exploit and organize spontaneity

2. Architects Overtaken by their Architecture

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

by their unplanned, spontaneous emergence and adaptivity...

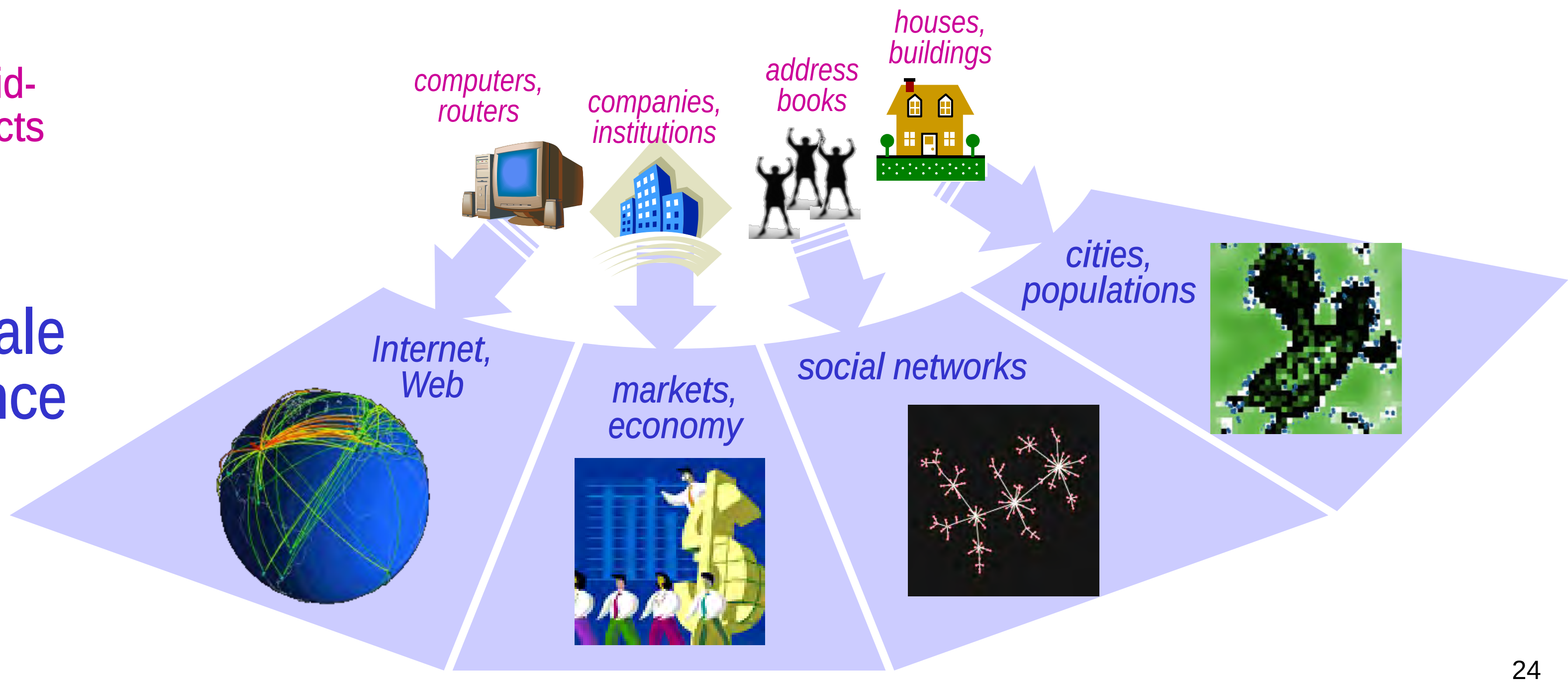
... arising from a multitude of traditionally designed artifacts

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

small to mid-scale artifacts

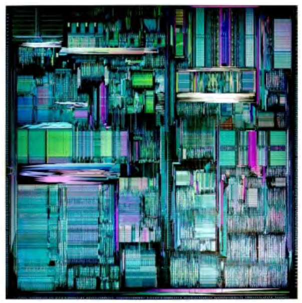
⇓

large-scale emergence

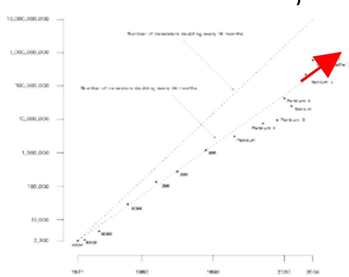


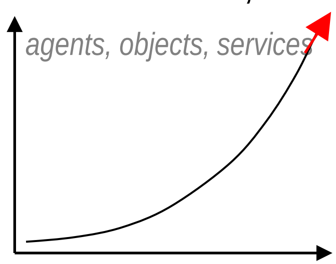
2. Architects Overtaken by their Architecture

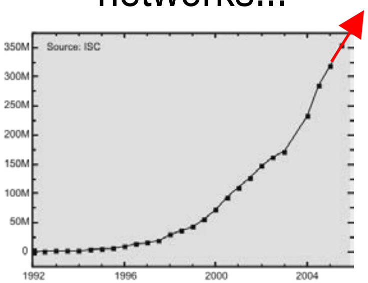
- Burst to large scale: *de facto* complexification of ICT systems
  - ✓ ineluctable breakup into, and *proliferation* of, modules/components



in hardware, software, networks...







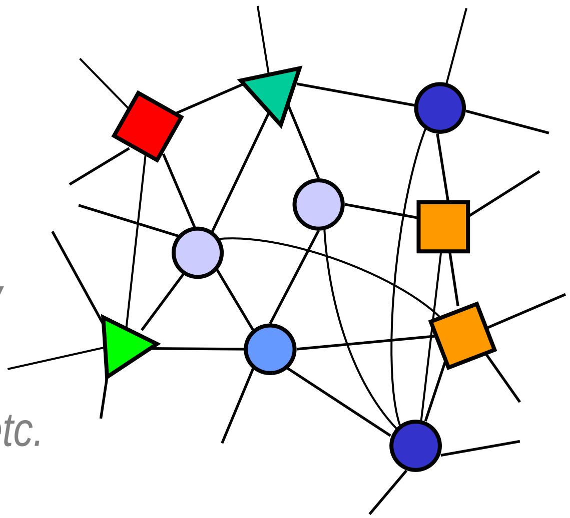
number of transistors/year | number of O/S lines of code/year | number of network hosts/year

→ *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*

COMPLEX SYSTEMS & COMPUTATION

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

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

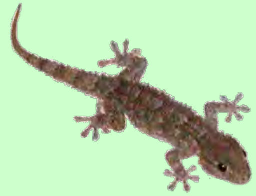
but were not

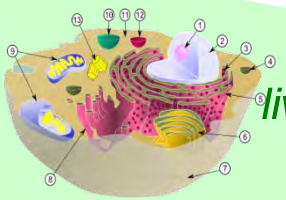
5. A New World of CS Computation

Or how to exploit and organize spontaneity

3. Architecture Without Architects

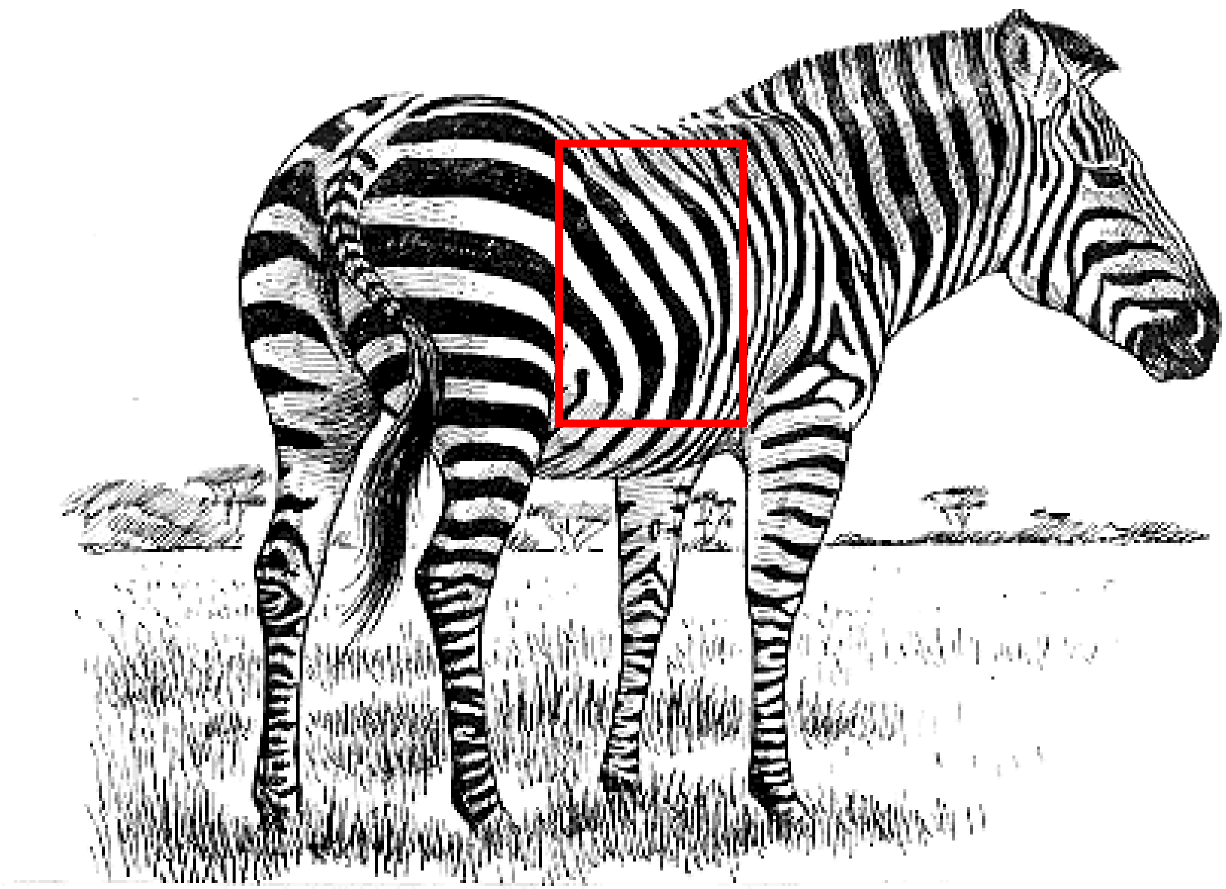
- "Simple"/random vs. architectured complex systems





- 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

Pattern Formation → Morphogenesis



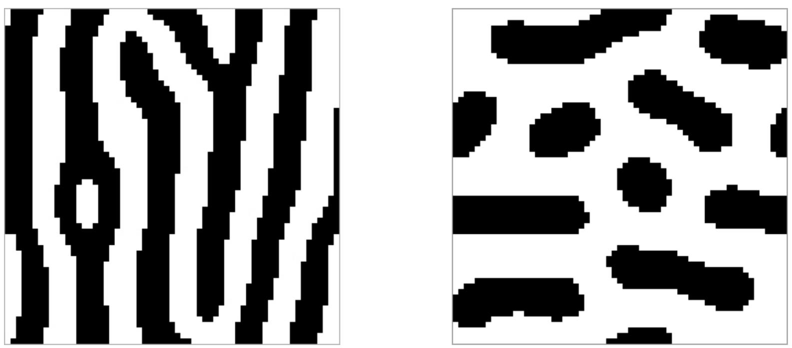
"I have the stripes, but where is the zebra?" OR

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

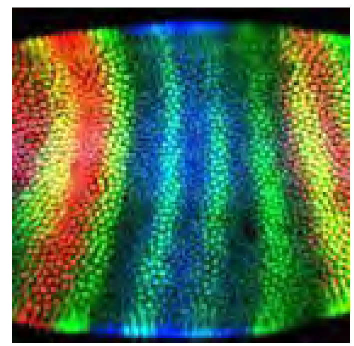
—attributed to A. Turing, after his 1952 paper on morphogenesis

Statistical vs. morphological systems

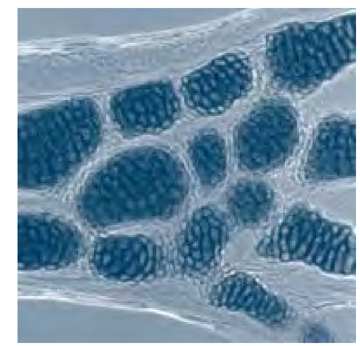
➢ Physical pattern formation is “free” –
Biological (multicellular) pattern formation is “guided”



reaction-diffusion
with NetLogo



fruit fly embryo
Sean Caroll, U of Wisconsin



larval axolotl limb condensations
Gerd B. Müller

≠

ISC PARIS ÎLE-DE-FRANCE

Statistical vs. morphological systems

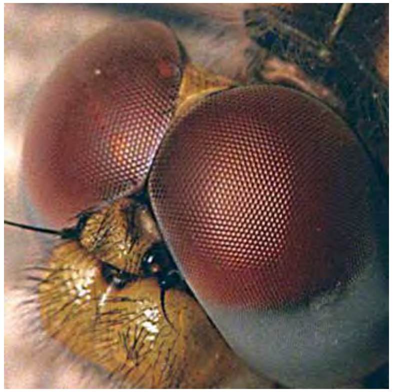
➢ **Multicellular forms = a bit of "free" + a lot of "guided"**

✓ domains of free patterning embedded in a guided morphology

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

spots, stripes in skin

angelfish, www.sheddaquarium.org



ommatidia in compound eye

dragonfly, www.phy.duke.edu/~hsg/54

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

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

flowers in tree

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

segments in insect

centipede, images.encarta.msn.com

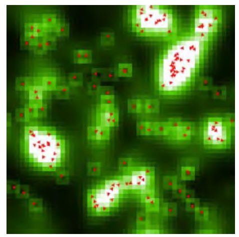
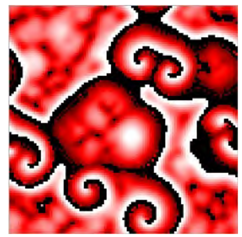
3. Architecture Without Architects

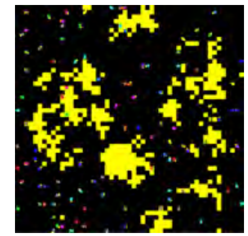
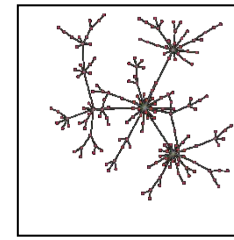
➢ Many self-organized systems exhibit random patterns...

(a) "simple"/random self-organization

NetLogo simulations: Fur, Slime, BZ Reaction, Flocking, Termite, Preferential Attachment



more architecture

gap to fill ??

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

(d) direct <u>design</u> (top-down)



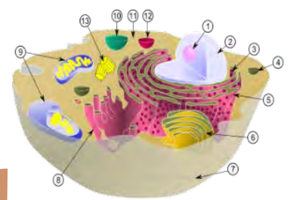


more self-organization

3. Architecture Without Architects

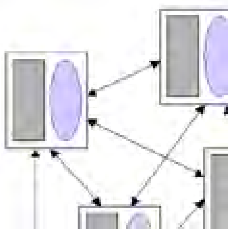
- Many self-organized systems exhibit random patterns...
- The only natural emergent *and* structured CS are biological
- *Can we transfer some of their principles to human-made systems and organizations?*

(b) natural
self-organized
architecture



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

. . . .



SYMBRION Project

. . . .

more architecture

natural

artificial

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

Complex Systems & Computation

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but were not

4. Morphogenetic Engineering

From cells and insects to robots and networks

5. A New World of CS Computation

Or how to exploit and organize spontaneity

A closer look at morphogenesis: it couples assembly and patterning

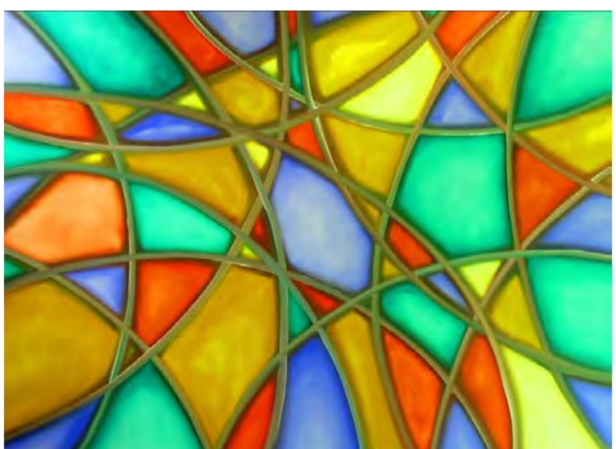
- Sculpture → forms

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

- Painting → colors



"patterns from shaping"

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

Niki de Saint Phalle

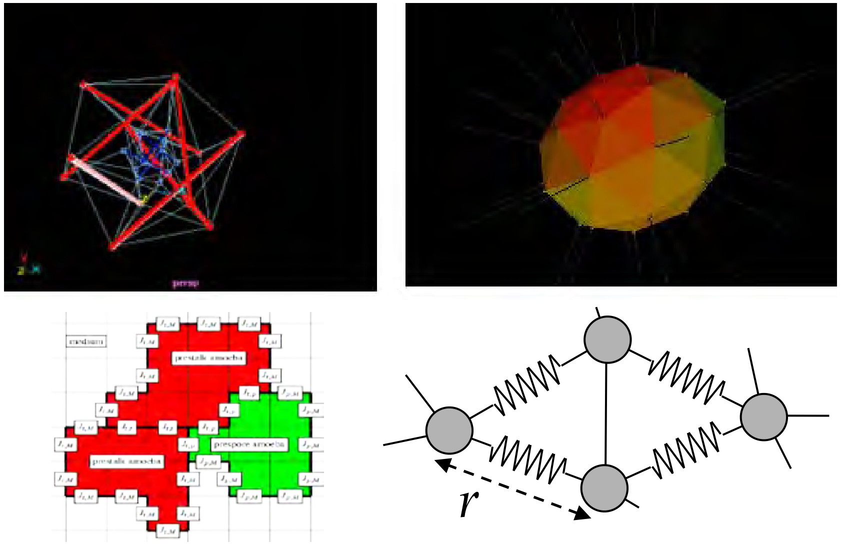
4. Morphogenetic Engineering: Devo

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

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

tensional integrity (Ingber)

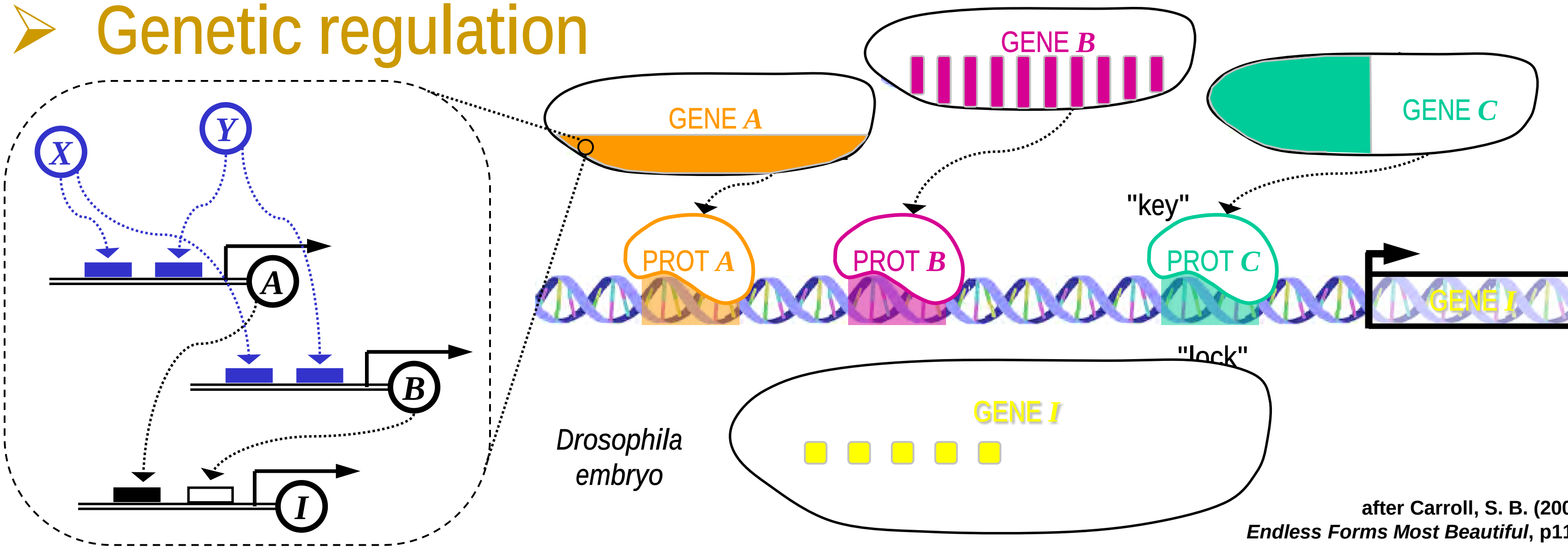
cellular Potts model (Graner, Glazier, Hogeweg)



(Delile & Doursat)

(Doursat)

- **Genetic regulation**

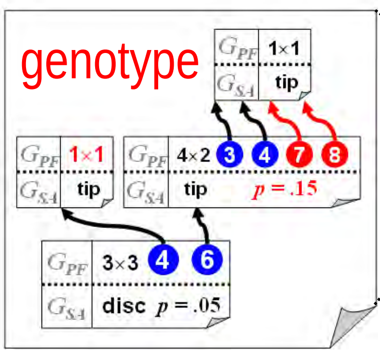


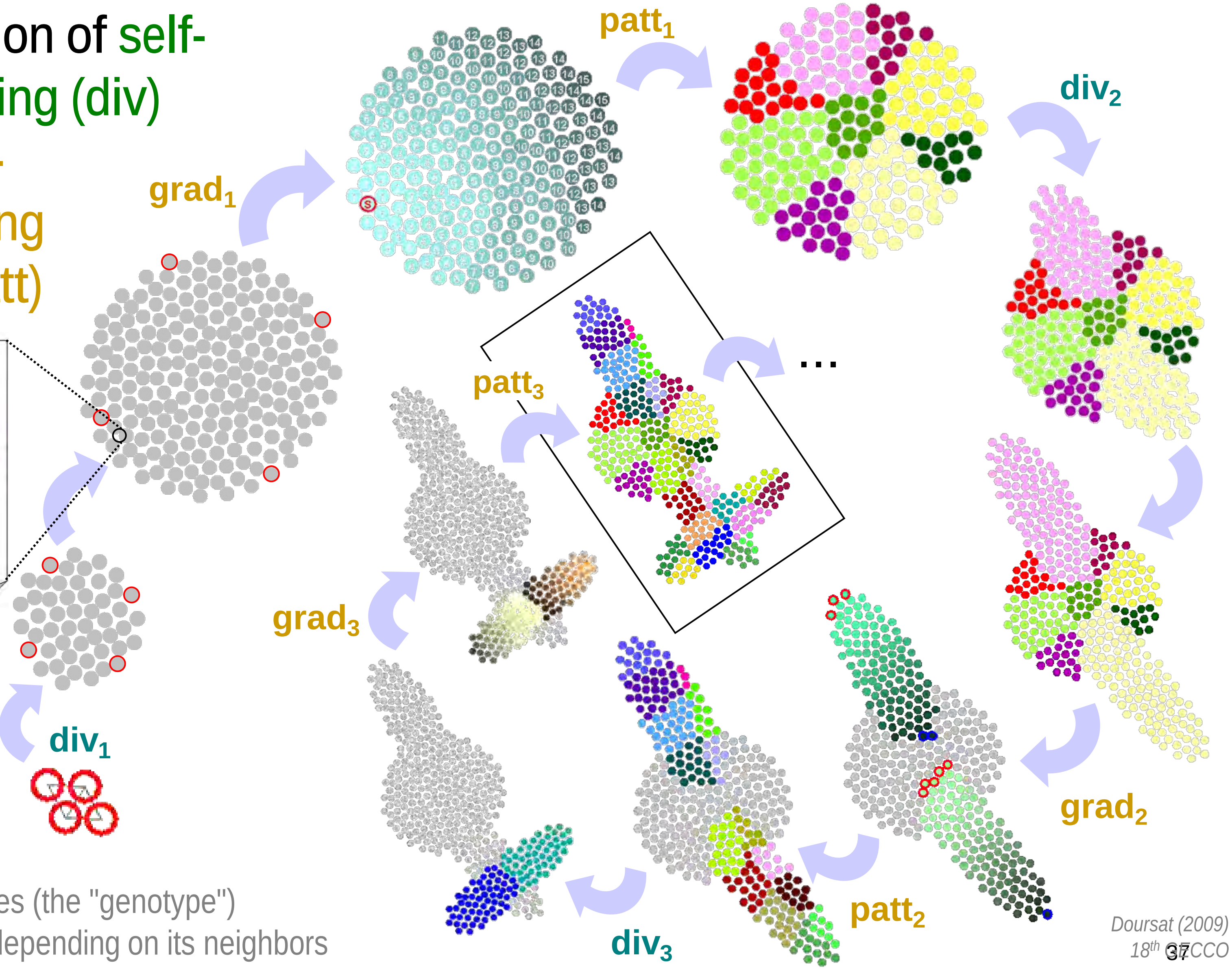
after Carroll, S. B. (2005)
Endless Forms Most Beautiful, p117

4. Morphogenetic Engineering: Devo

Capturing the essence of morphogenesis in an Artificial Life agent model

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



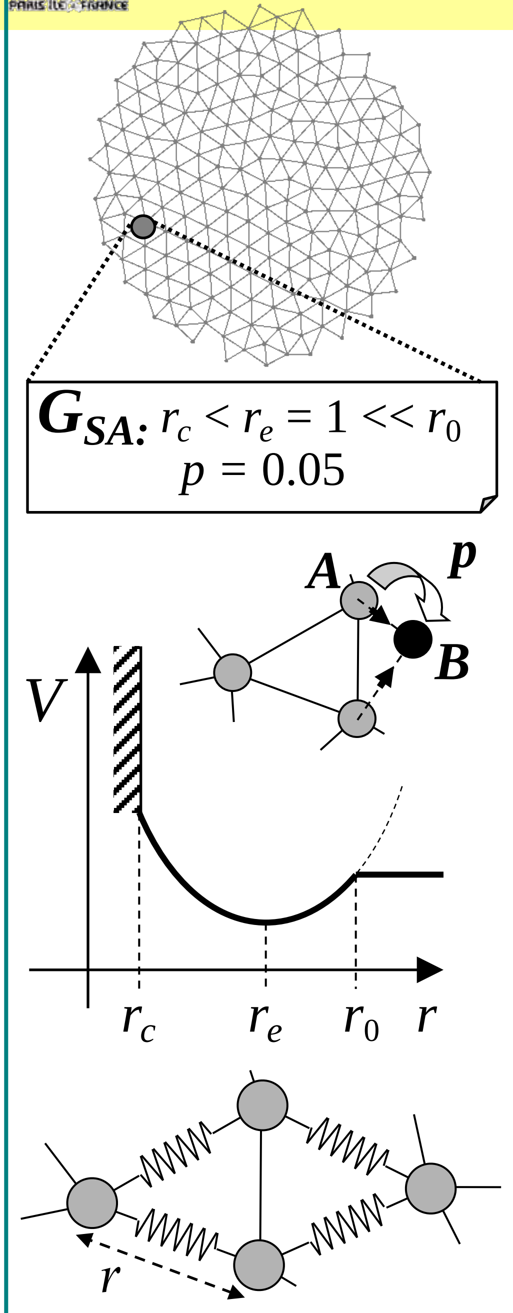


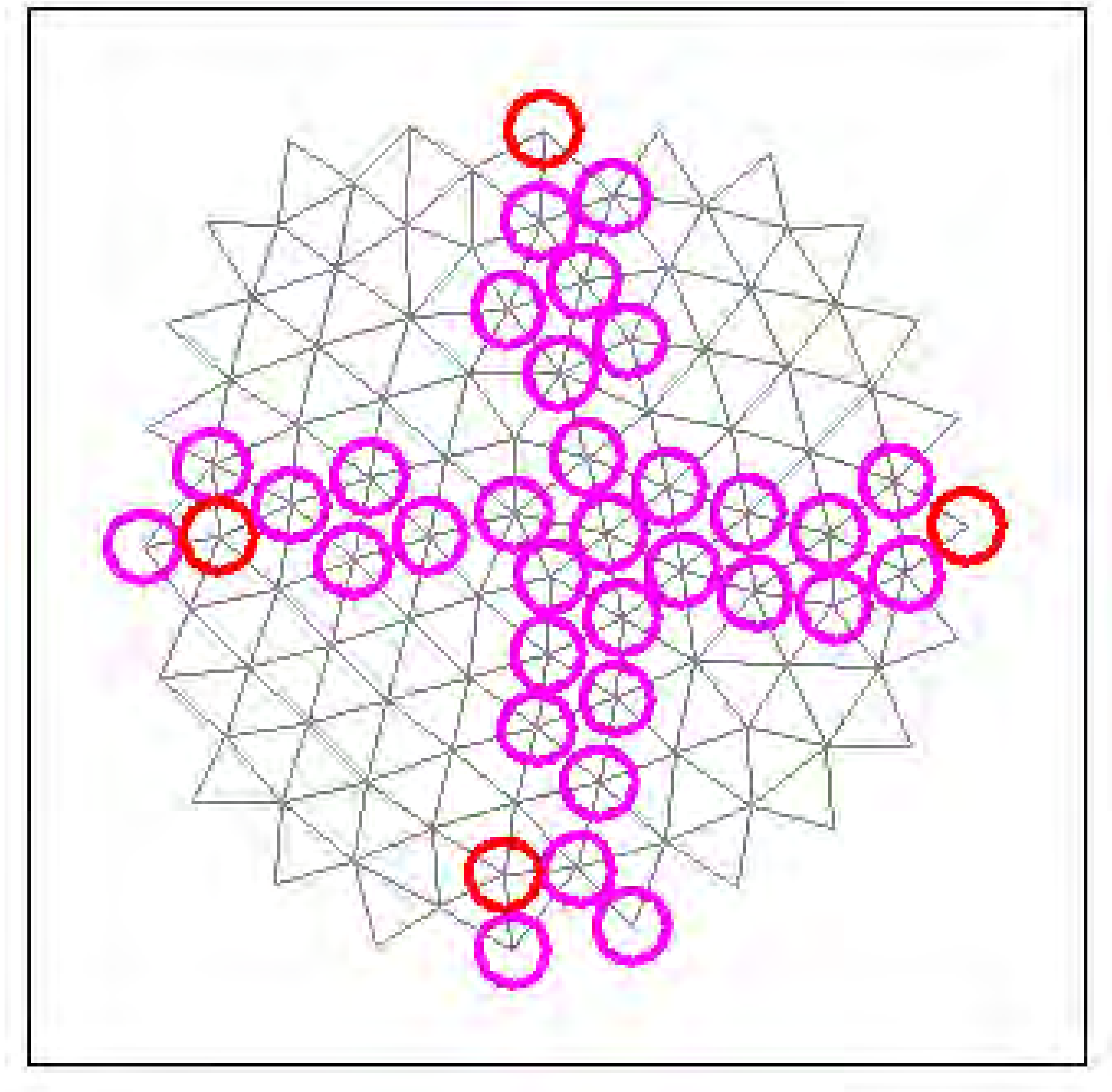
each agent
follows the same set
of self-architecting rules (the "genotype")
but reacts differently depending on its neighbors

Doursat (2009)
18th GECCO

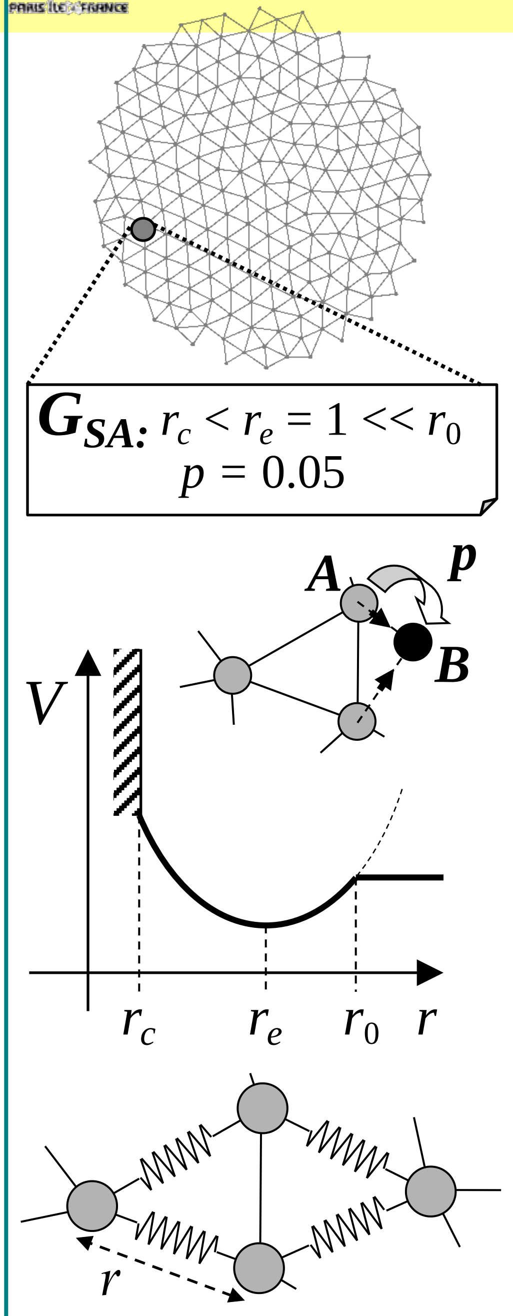
div

4. Morphogenetic Engineering: Devo





4. Morphogenetic Engineering: Devo

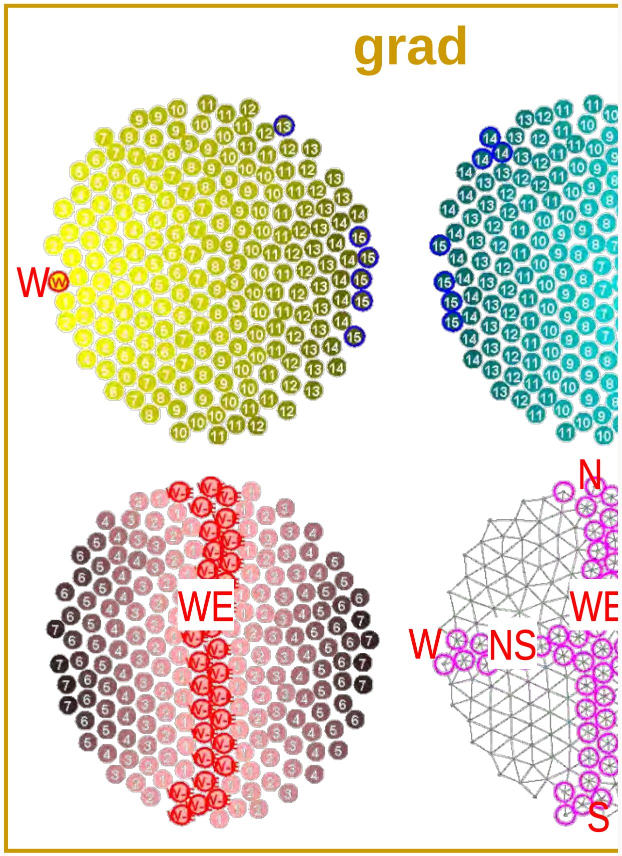


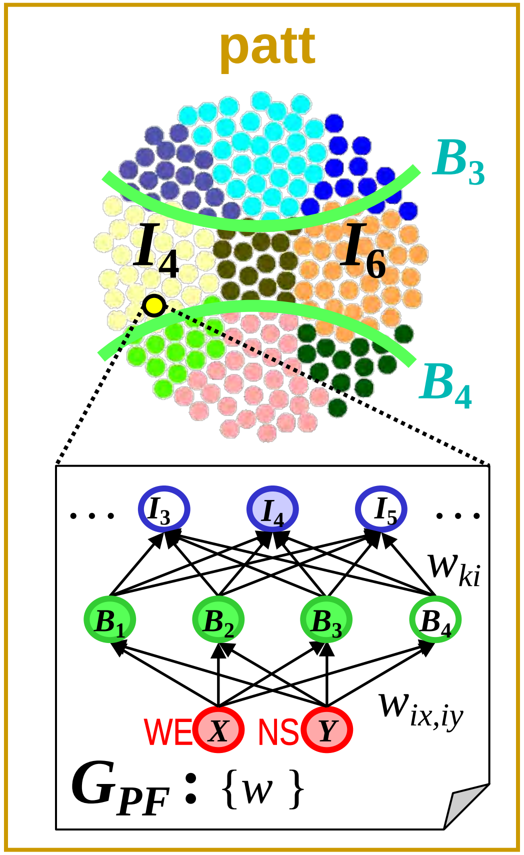
$$m\ddot{\mathbf{r}}^{cd} = -k\left(1 - \frac{r_0}{\left\|\mathbf{r}^{cd}\right\|}\right)\mathbf{r}^{cd} - \eta\dot{\mathbf{r}}^{cd}.$$

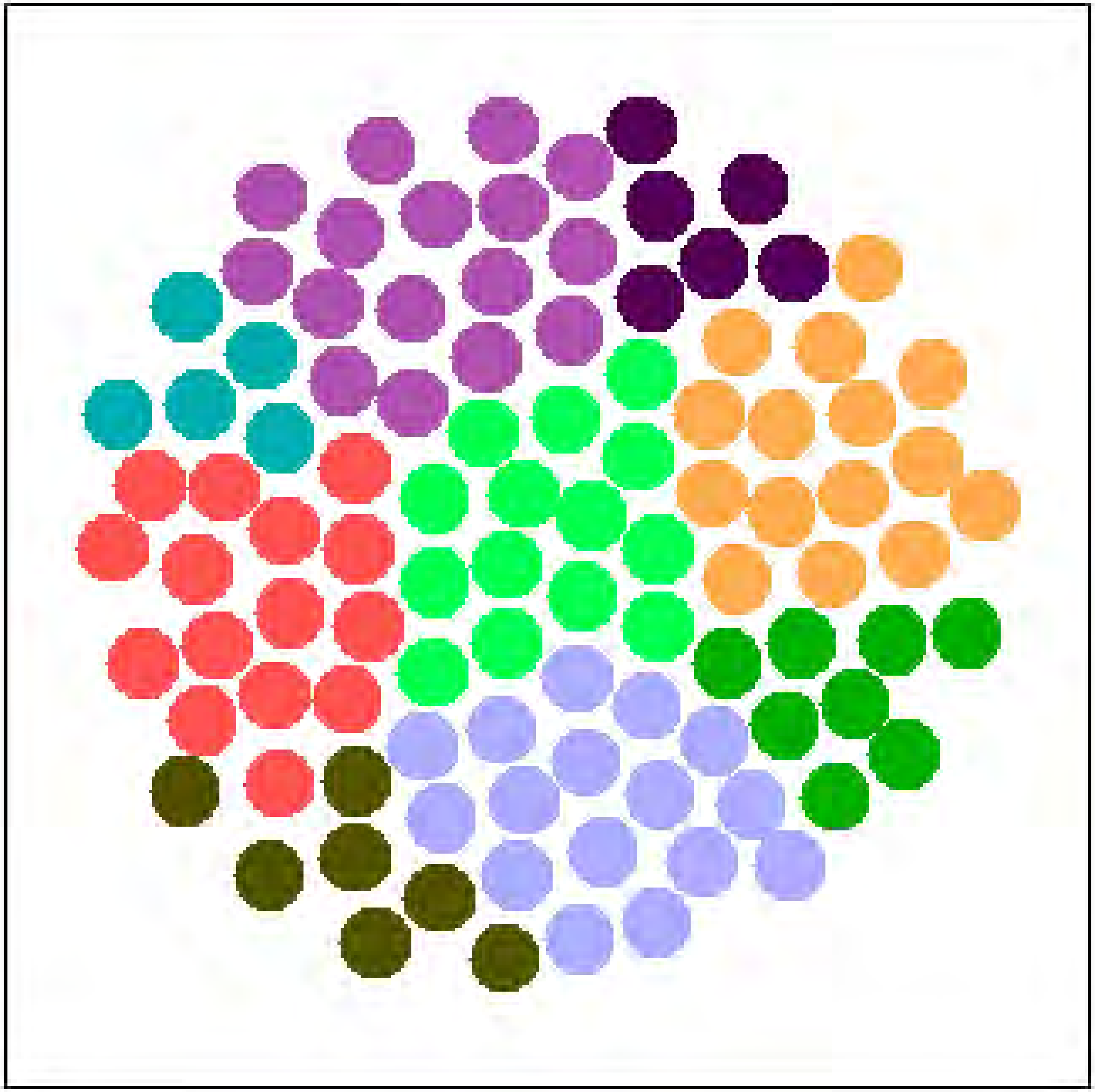
$$\Downarrow$$

$$\Delta\mathbf{r}^{c} = -\Delta\mathbf{r}^{d} = \frac{\Delta\mathbf{r}^{cd}}{2} = -\frac{k}{2\eta}\left(1 - \frac{r_0}{\left\|\mathbf{r}^{cd}\right\|}\right)\mathbf{r}^{cd}.$$

4. Morphogenetic Engineering: Devo




patt
B3
I4
I6
B4
I3
I4
I5
wki
B1
B2
B3
B4
WE X NS Y
wix,iy
GPF : {w }

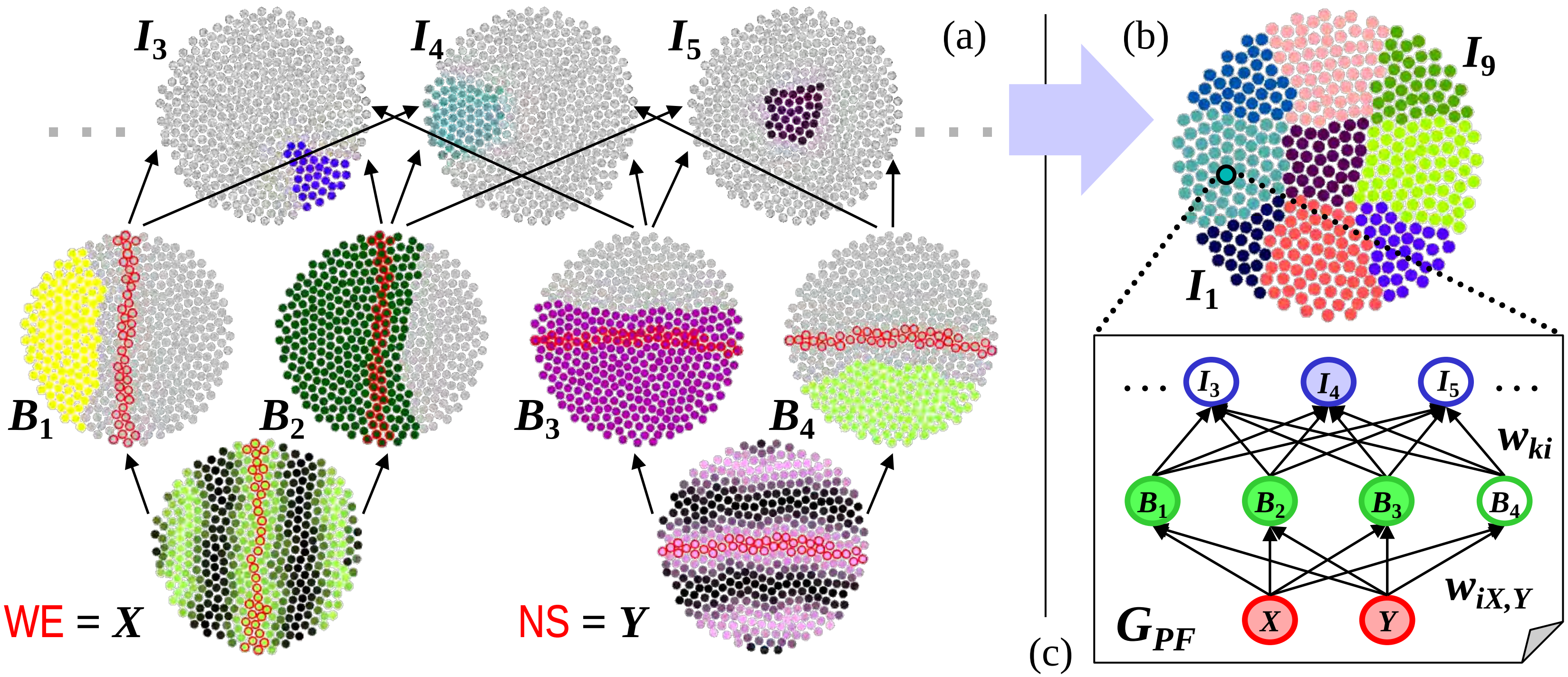


➢ Programmed patterning (patt): the hidden embryo atlas

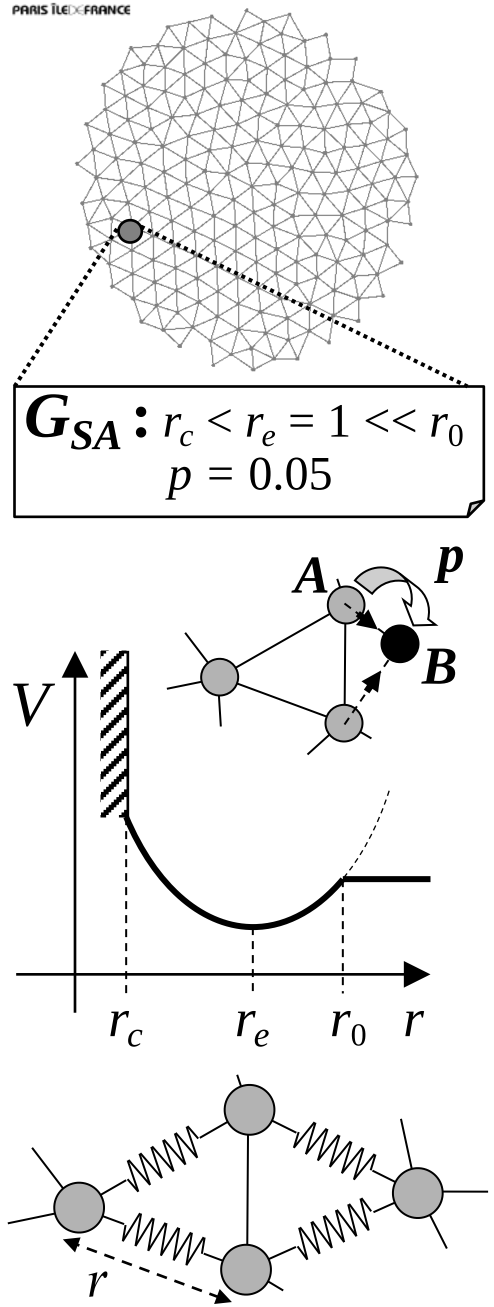
a) same swarm in different colormaps to visualize the agents' internal patterning variables X, Y, B_i and I_k (virtual *in situ hybridization*)

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

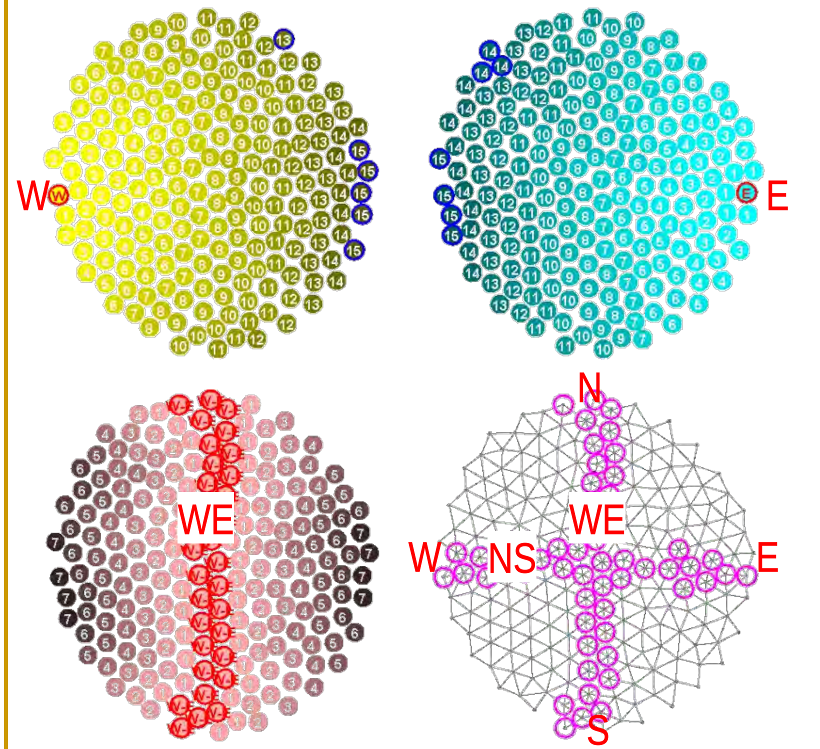
c) gene regulatory network used by each agent to calculate its expression levels, here: $B_1 = \sigma(1/3 - X)$, $B_3 = \sigma(2/3 - Y)$, $I_4 = B_1 B_3(1 - B_4)$, etc.



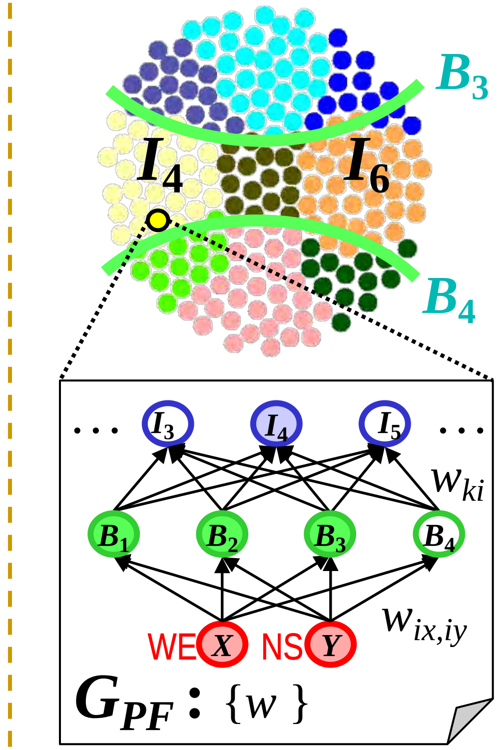
div

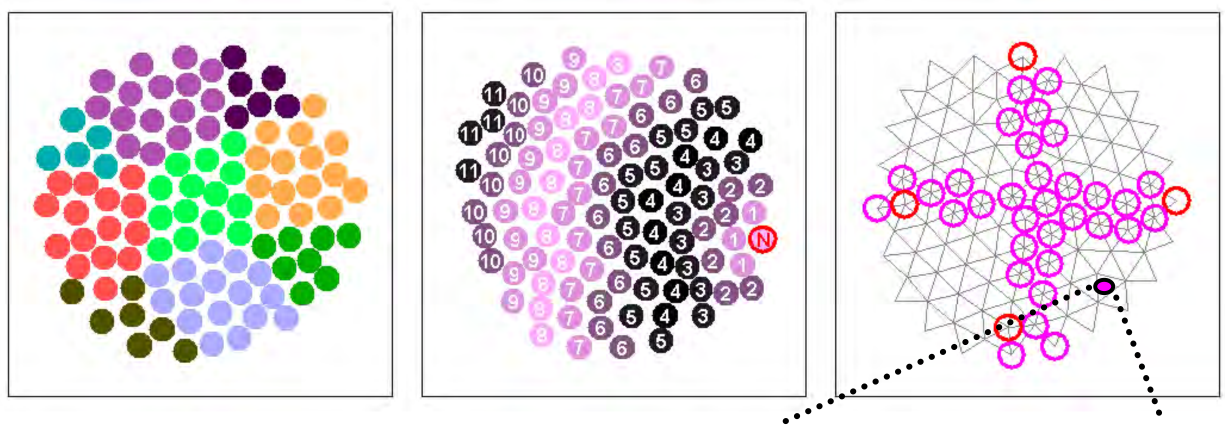


grad



patt





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

Doursat (2008)
ALIFE XI

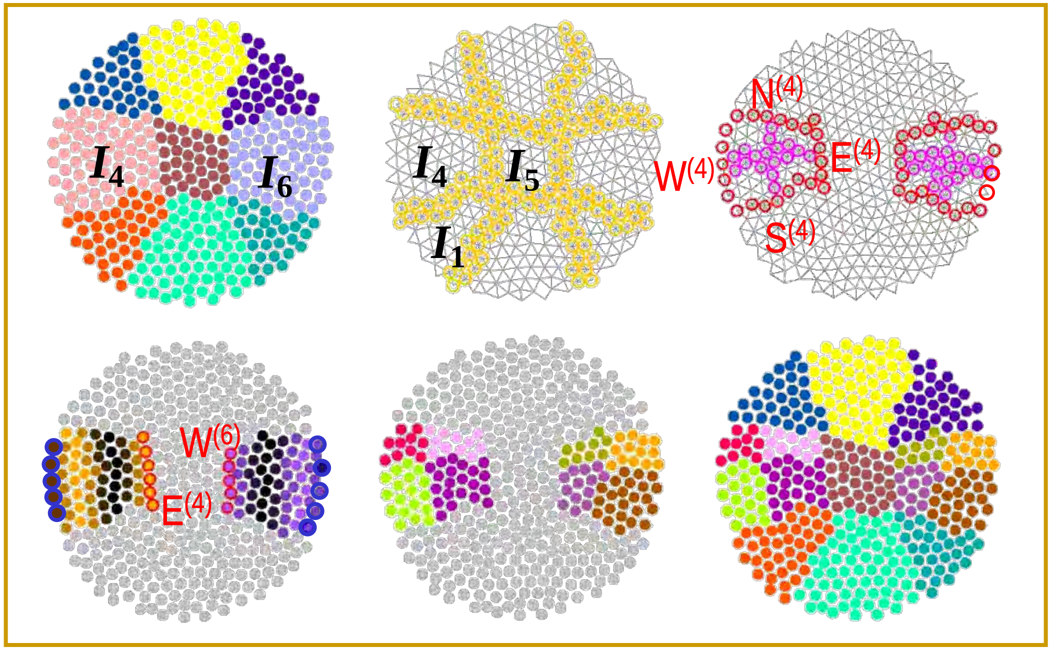
➢ Morphological refinement by iterative growth

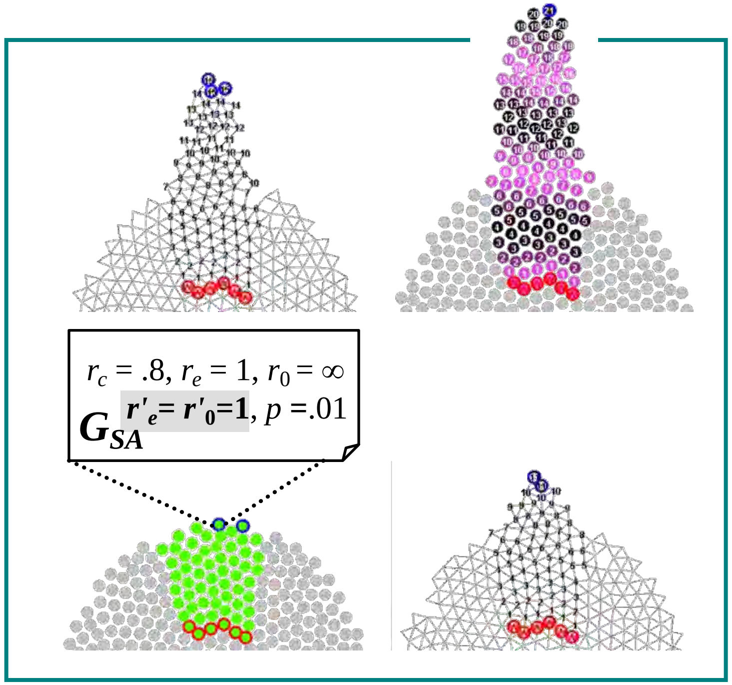
- ✓ details are not created in one shot, but gradually added. . .

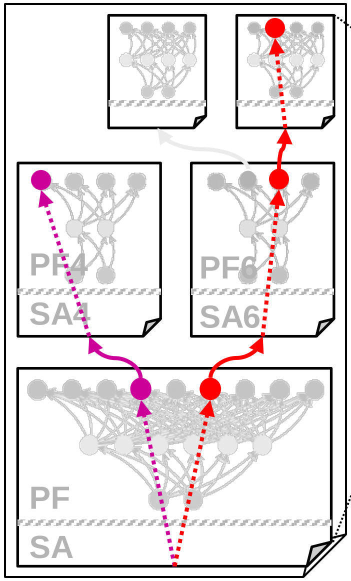
- ✓ . . . while, at the same time, the canvas grows

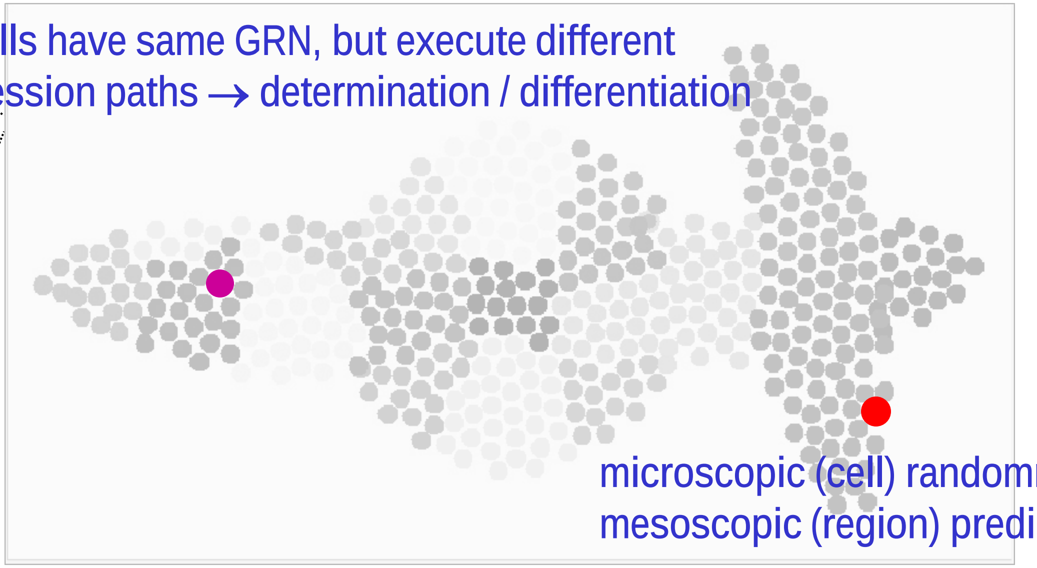
from Coen, E. (2000)
The Art of Genes, pp131-135

4. Morphogenetic Engineering: Devo









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

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

Doursat (2008)
ALIFE XI

4. Morphogenetic Engineering: Devo

- Derivative projects

ME: Devo-Evo

ME: Devo-MecaGen

ME: Devo-Bots

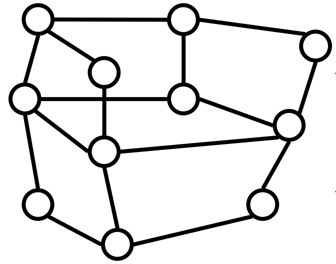
ME: Devo-SynBioTIC

ME: ProgNet-Ecstasy

ME: ProgNet

- The missing link of the Modern Synthesis...

more or less direct representation

≈ () ≈

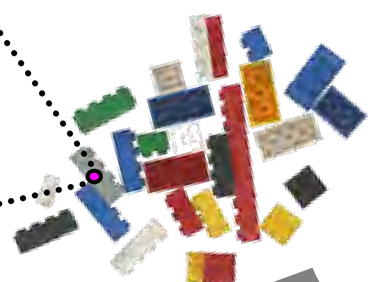
macroscopic, emergent level

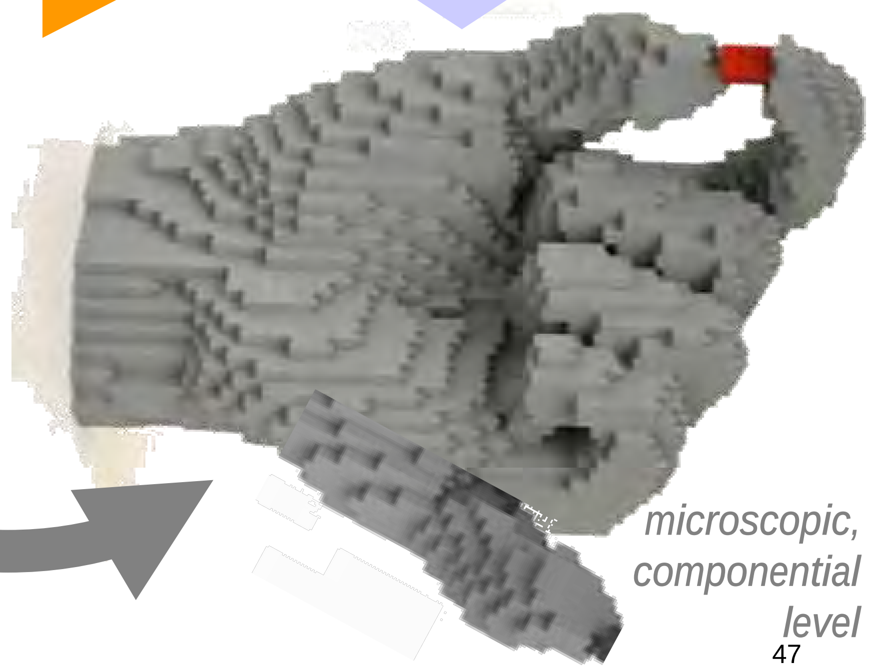
Genotype

“Transformation”?

Phenotype

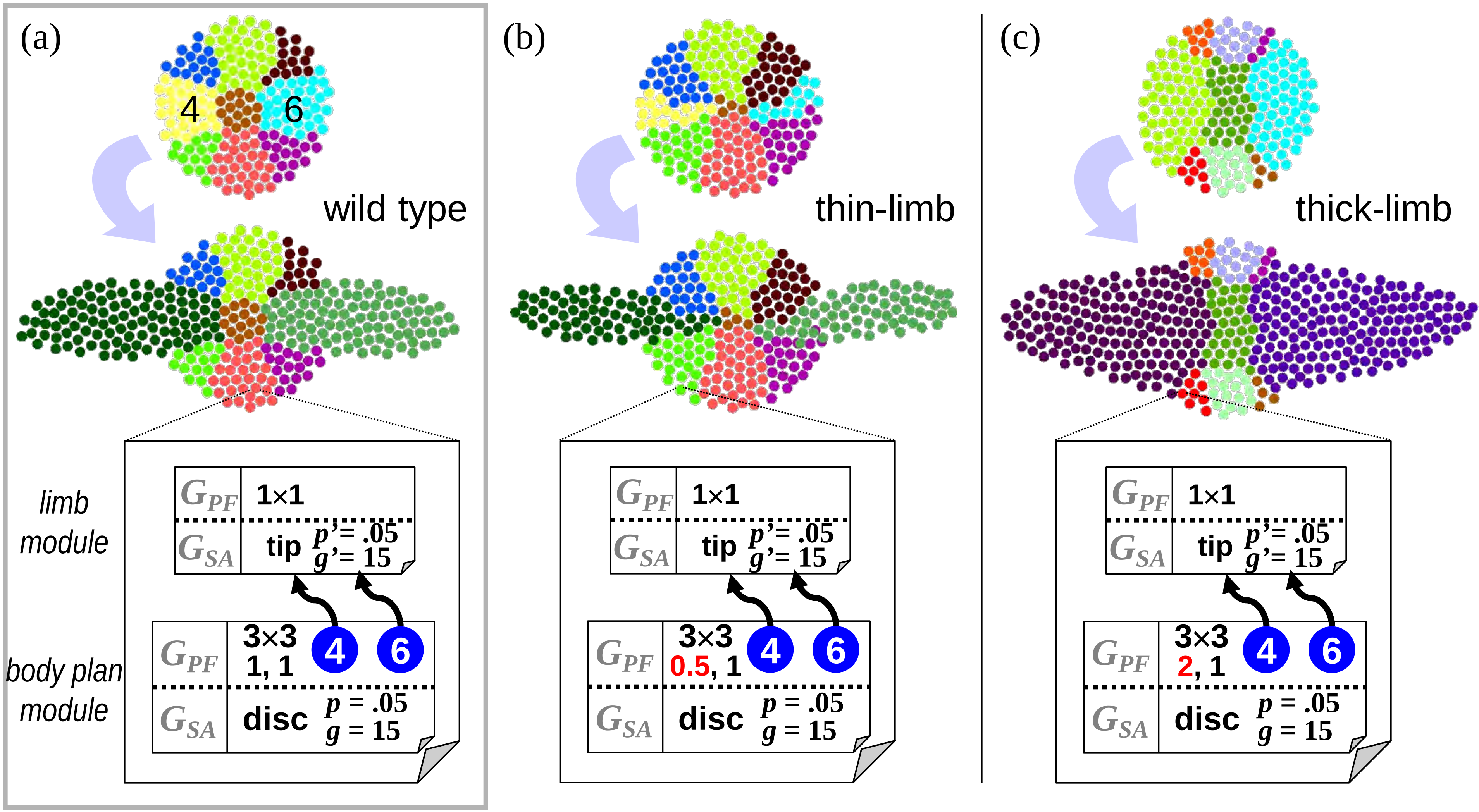
generic elementary rules of **self-assembly**





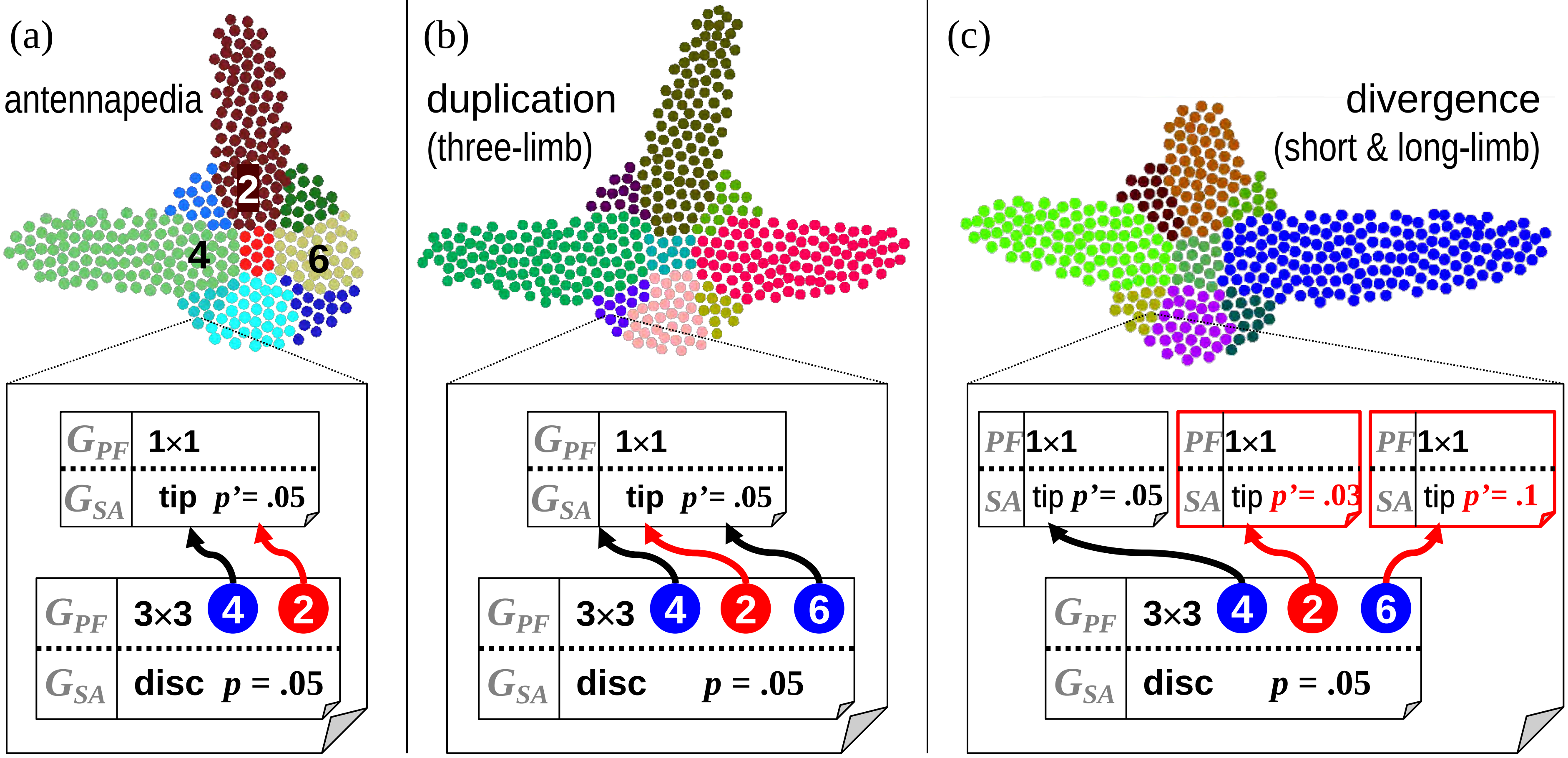
microscopic, componential level

- Quantitative mutations: limb thickness



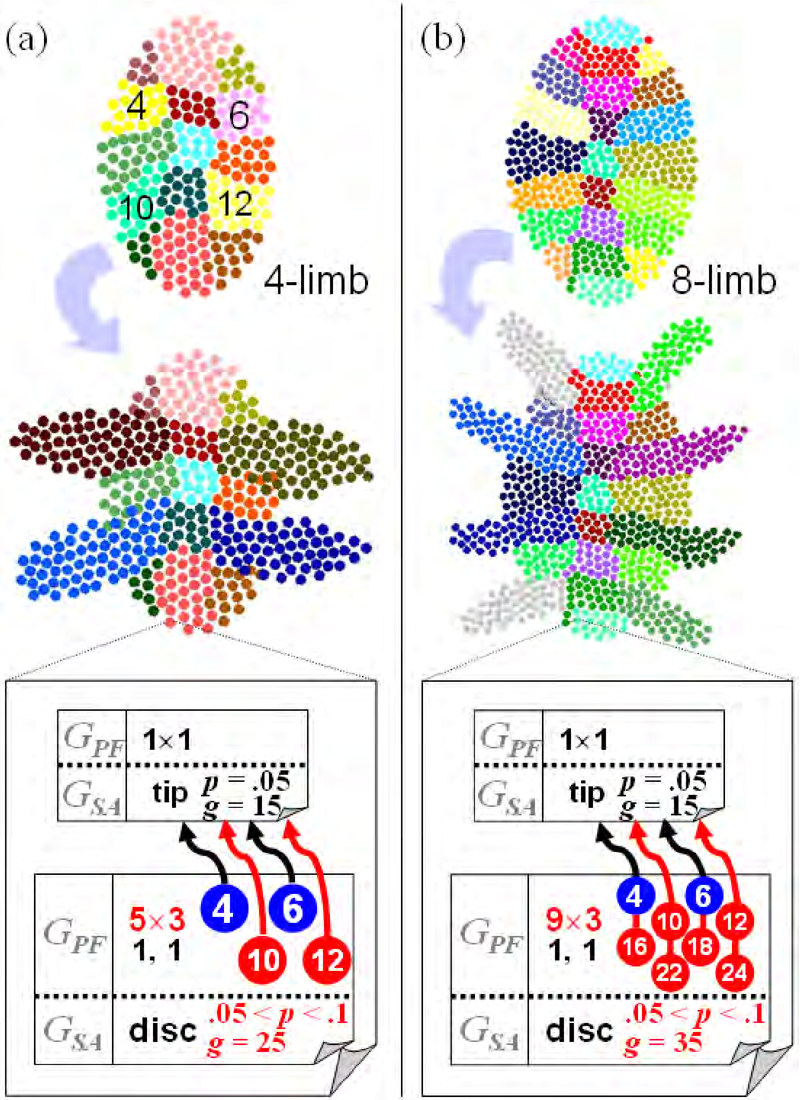
➢ Qualitative mutations: limb position and differentiation

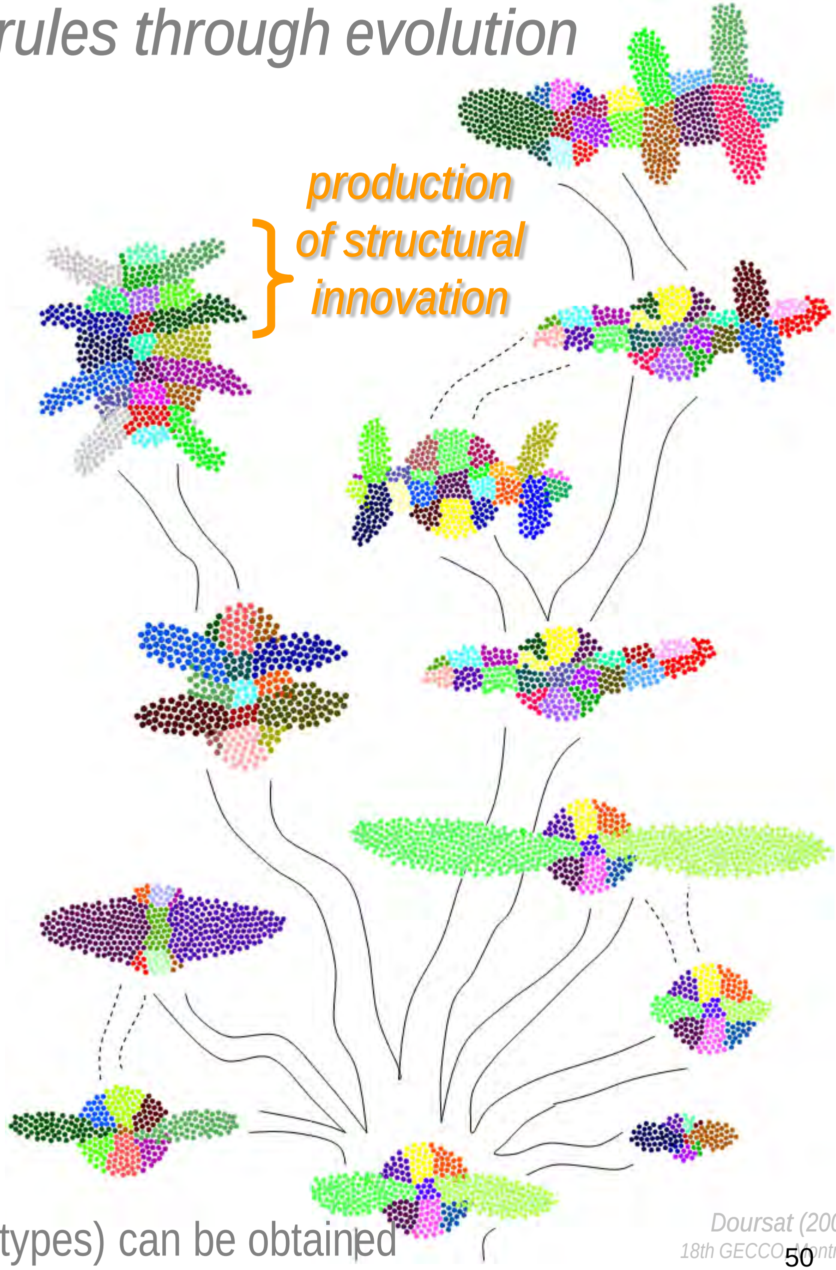
antennapedia | *homology* by *duplication* | *divergence* of the homology



4. Morphogenetic Engineering: Devo-Evo

Changing the agents' self-architecting rules through evolution



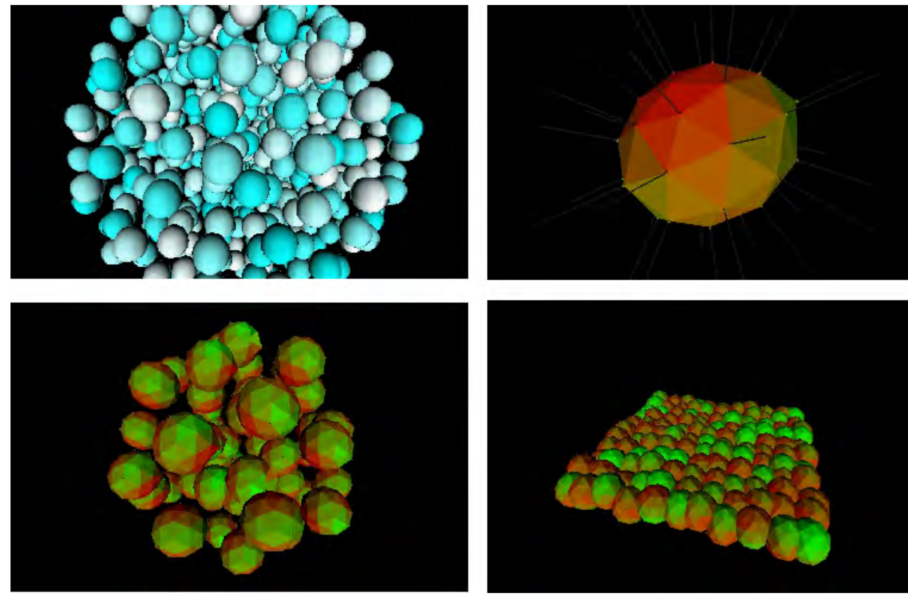


by tinkering with the genotype, new architectures (phenotypes) can be obtained

Doursat (2009)
18th GECCO, Montreal

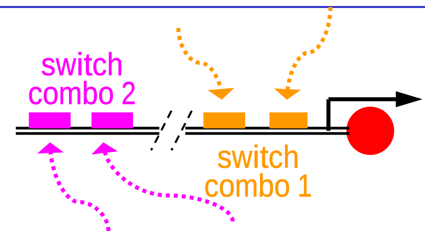
4. Morphogenetic Engineering: Devo-MecaGen

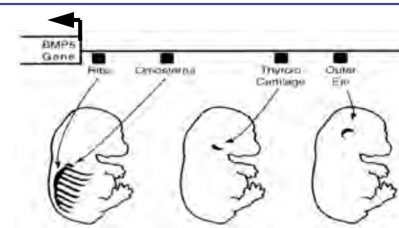
- ➢ More accurate mechanics
  - ✓ 3-D
  - ✓ individual cell shapes
  - ✓ collective motion, migration
  - ✓ adhesion



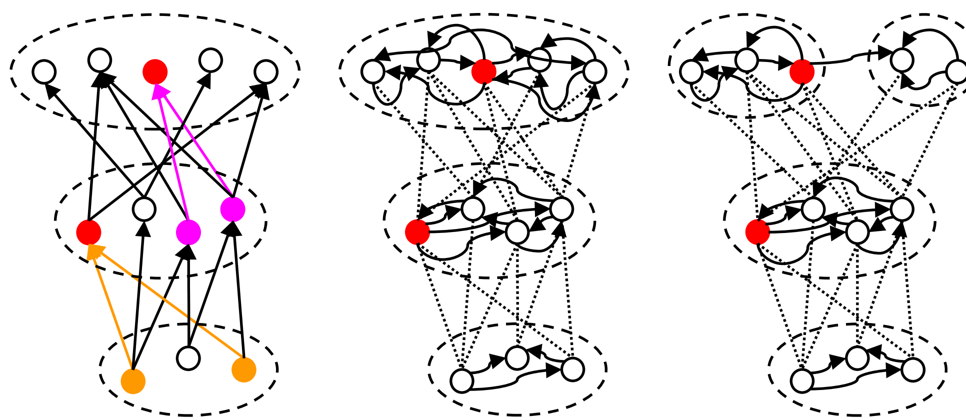
(Delille, Doursat, Peyrieras)

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





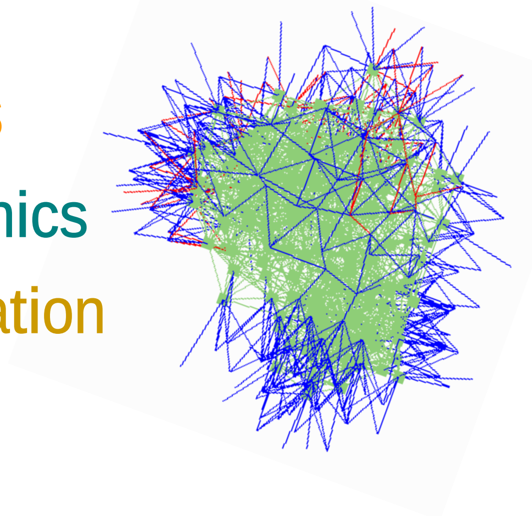
after David Kingsley, in Carroll, S. B. (2005) *Endless Forms Most Beautiful*, p125

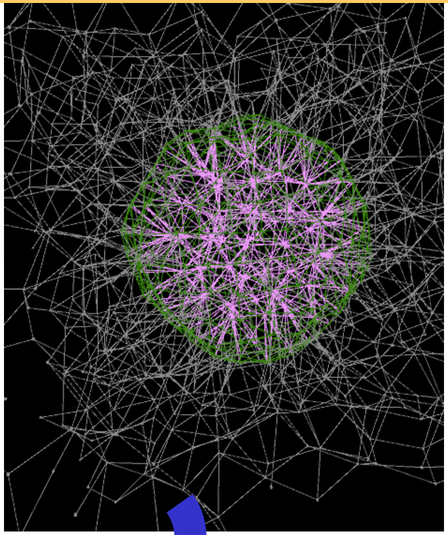


4. Morphogenetic Engineering: Devo-MecaGen

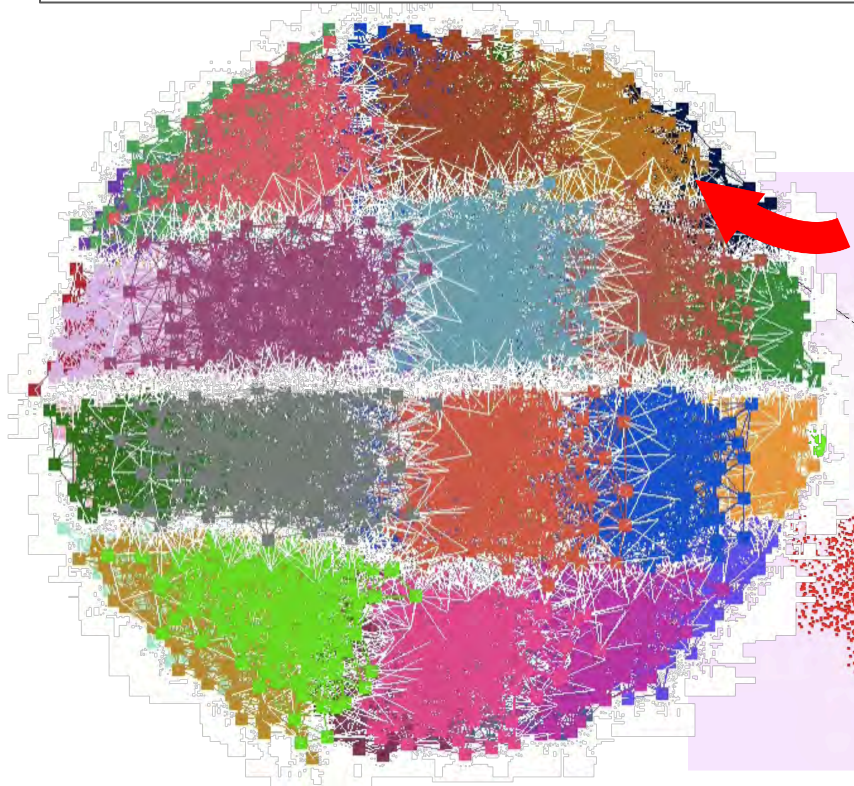
➢ Multi-agent embryogenesis

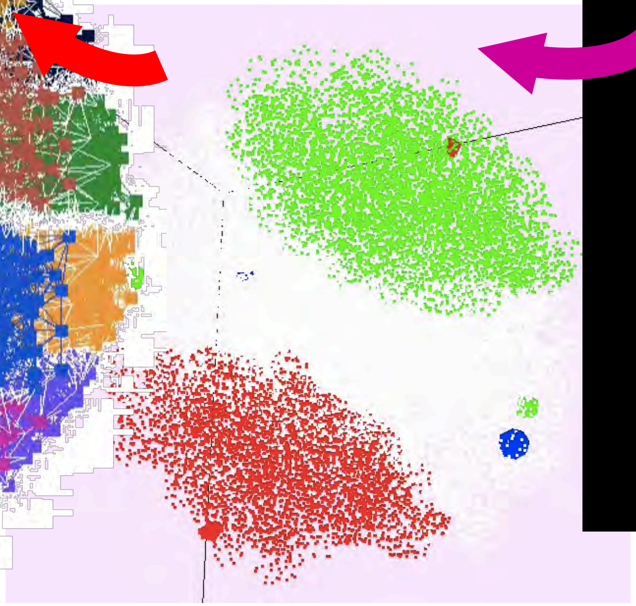
- ✓ 3D particle-based mechanics
- ✓ kinetic-based gene regulation



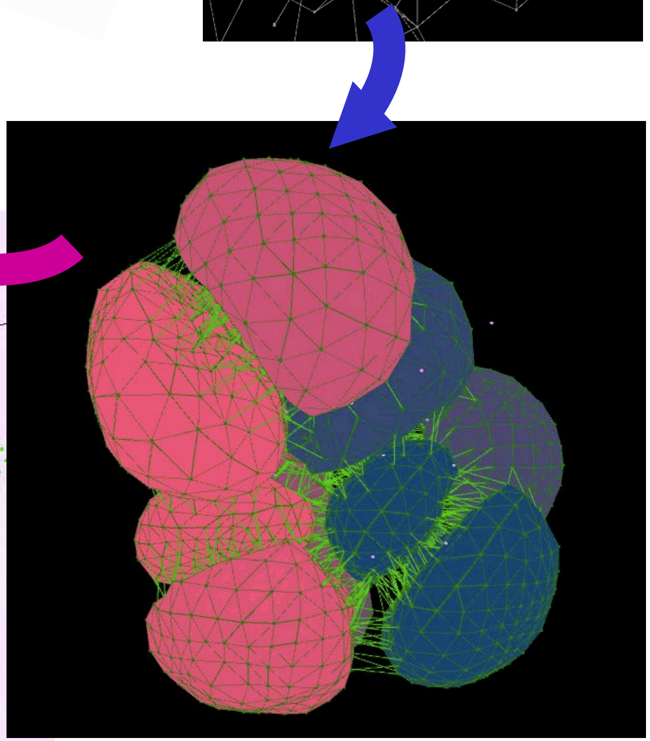


PhD student: **Julien Delile** (FdV, DGA), co-supervised by
- **Nadine Peyriéras**, CNRS Gif s/Yvette
- (**Stéphane Doncieux**, LIP6)





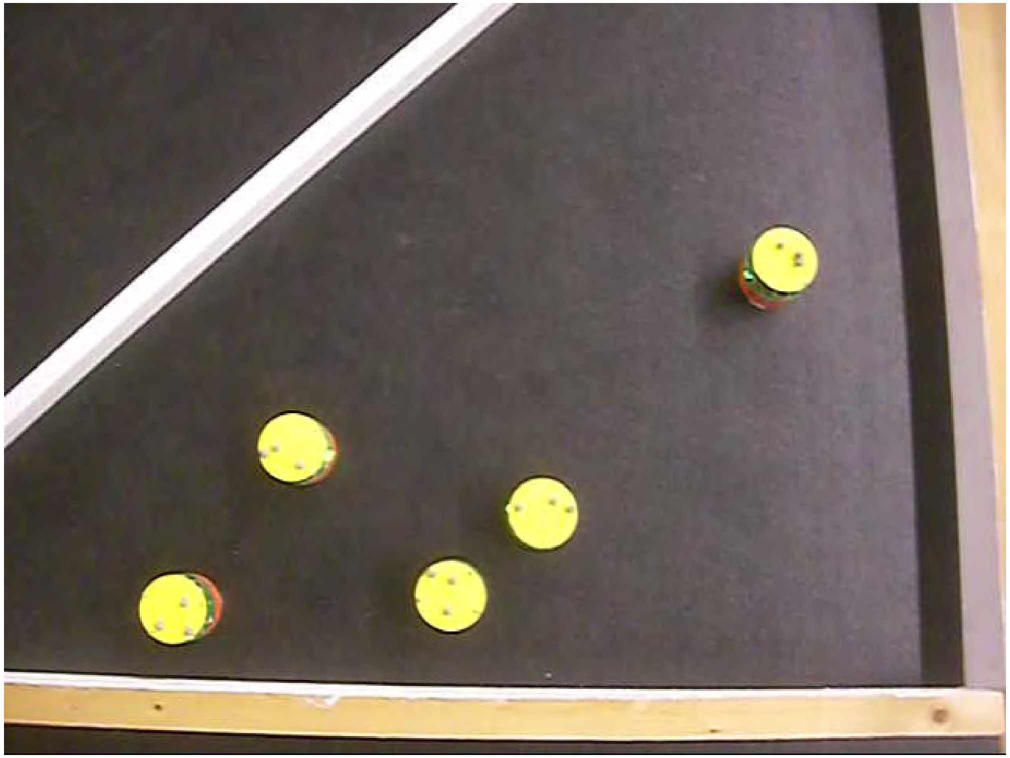
simulations by
Julien Delile

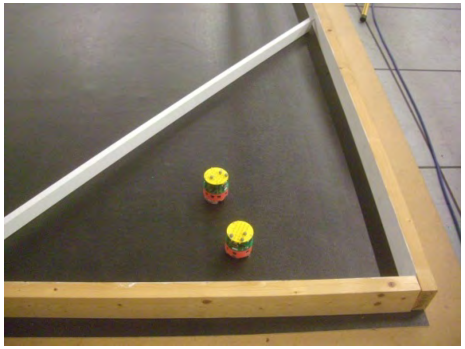


4. Morphogenetic Engineering: Devo-Bots

- Morphogenetic swarm robotics: toward structured robot flocking
  - ✓ using "e-pucks"

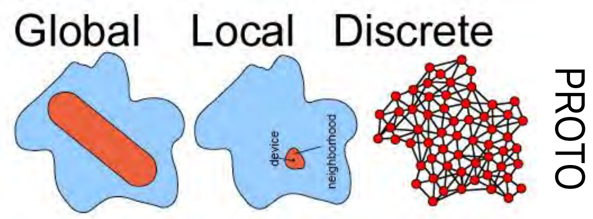
Current collaboration with
- **Alan Winfield**, Bristol Robotics Lab, UWE
- **Wenguo Liu**, Bristol Robotics Lab, UWE





➢ Synthetic Biological SysTems: from DesIgn to Compilation

ANR Project with (among others)
- **Jean-Louis Giavitto**, ex-IBISC, Evry
- **Oliver Michel**, **A. Spicher**, LACL, Creteil
- **Franck Delaplace**, Evry ... et al.



- ex: spatial computing languages: PROTO (Beal) and MGS (Giavitto)

La prise en compte du spatial

[Même] si pour l'instant la biologie synthétique se focalise sur la « programmation d'une seule bactérie », le développement de biosystèmes un tant soit peu complexe reposera sur le fonctionnement intégré de colonies bactériennes et donc sur la prise en compte d'interactions spatiales au sein d'une population de cellules différenciées. [...]

La maîtrise des interactions spatiales ouvre la voie à une ingénierie du développement [biologique], ce qui permet de rêver à des applications qui vont bien au-delà de la conception de la cellule comme « usine chimique ».

Projet SynBioTIC, 2010

➢ Engineering Complex Socio-Technical Adaptive SYstems

Submitted FET-ICT Open Project with
- **Jeremy Pitt**, Imperial College, London
- **Andrzej Nowak**, U Warsaw
- **Mihaela Ulieru**, Canada Research Chair

The ECSTASY project is about the science of socio-technical combinatorics underpinning the ICT for engineering such scenarios.

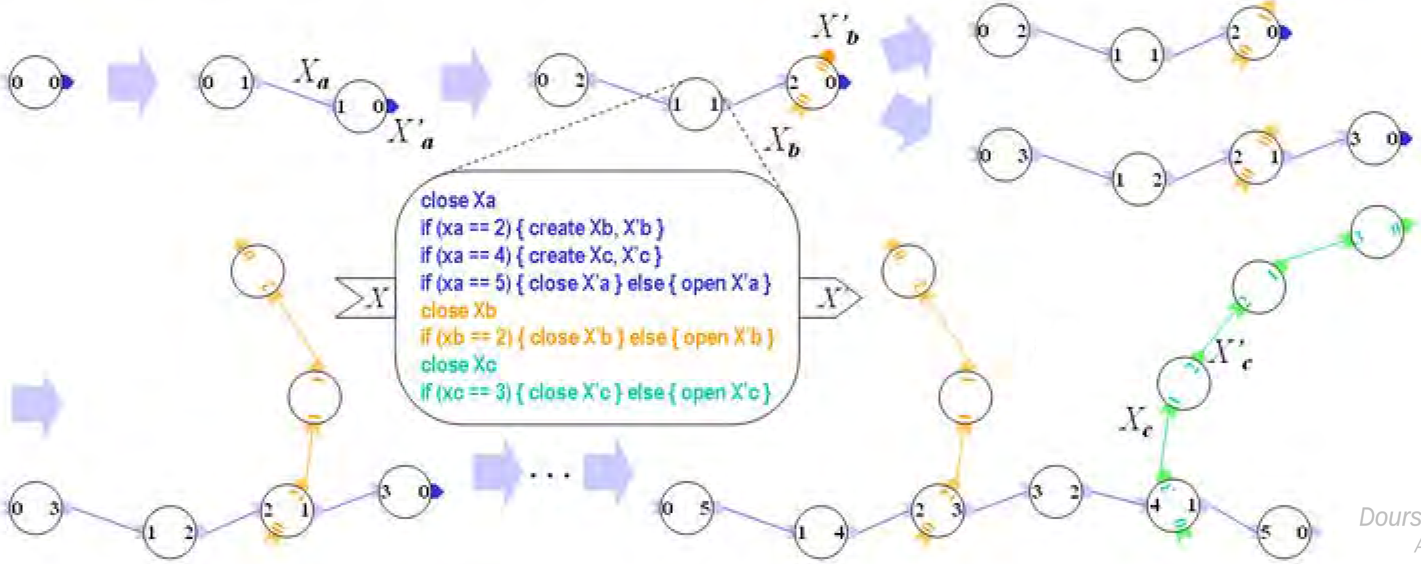
We define socio-technical combinatorics as the study of the potentially infinite number of discrete and reconfigurable physical, behavioural and organisational structures which characterise socio-technical systems comprising humans, sensors, and agents.

It is also the study of how these structures interact with each other and their environment – how they assemble, evolve, dis-assemble, and re-assemble, and how they can be engineered.

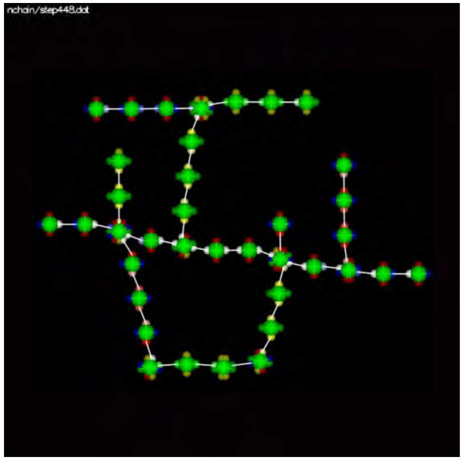
Projet ECSTASY, 2011

4. Morphogenetic Engineering: ProgNet

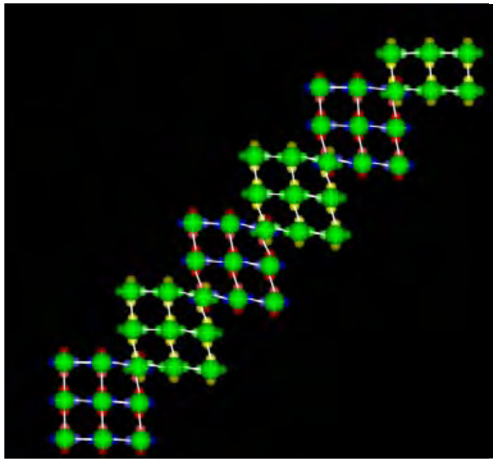
Generalizing morphogenesis to self-building networks by programmable attachment of nodes



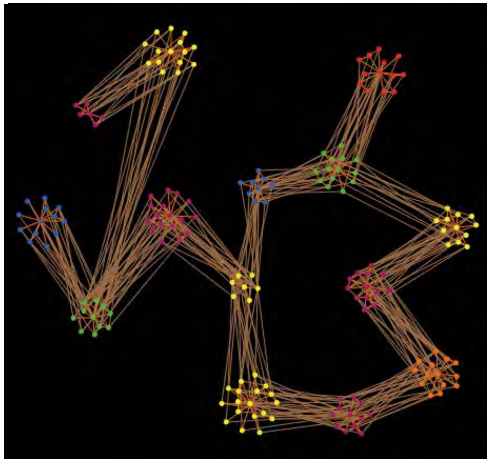
Doursat & Ulieru (2008)
Autonomics 2008, Turin



single-node composite branching

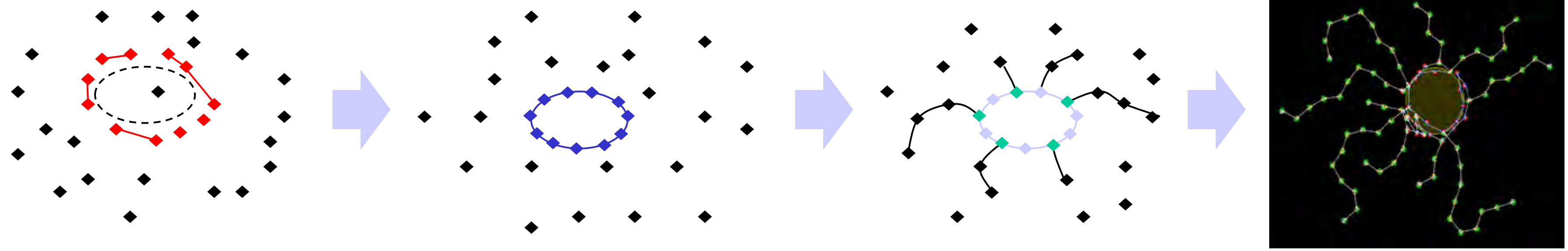


iterative lattice pile-up



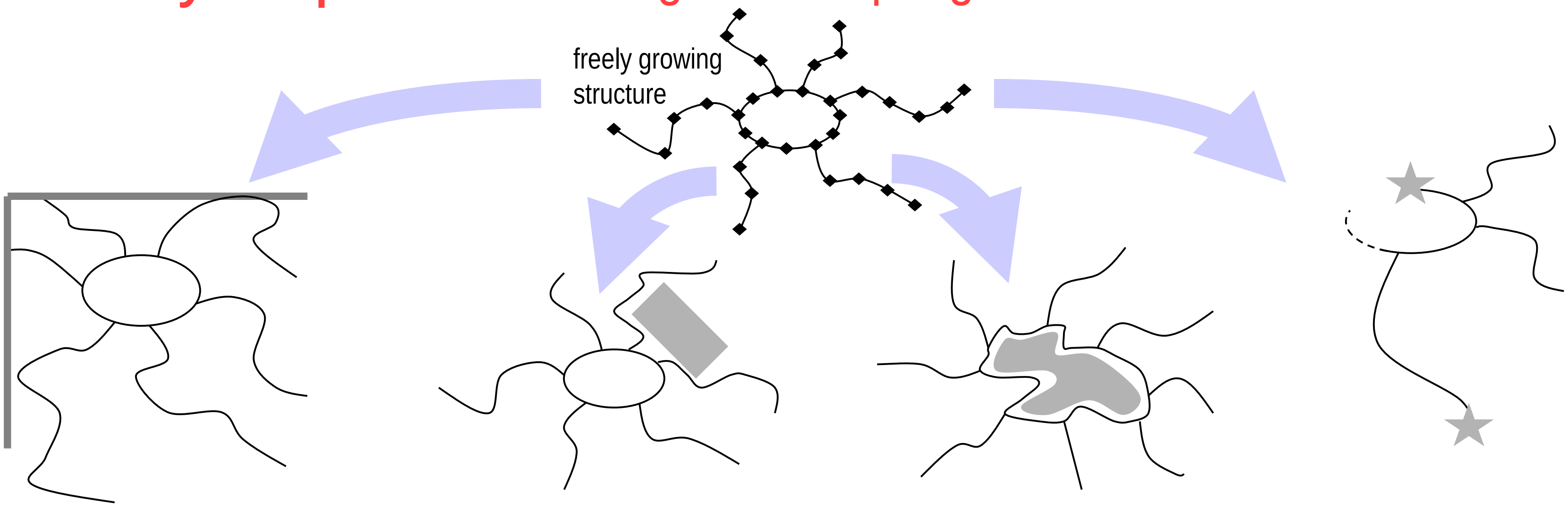
clustered composite branching

Development: growing an intrinsic architecture

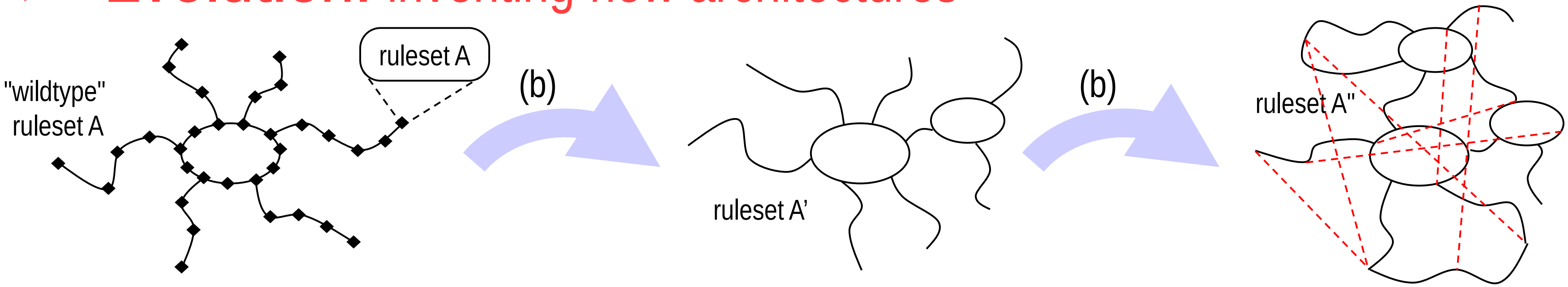


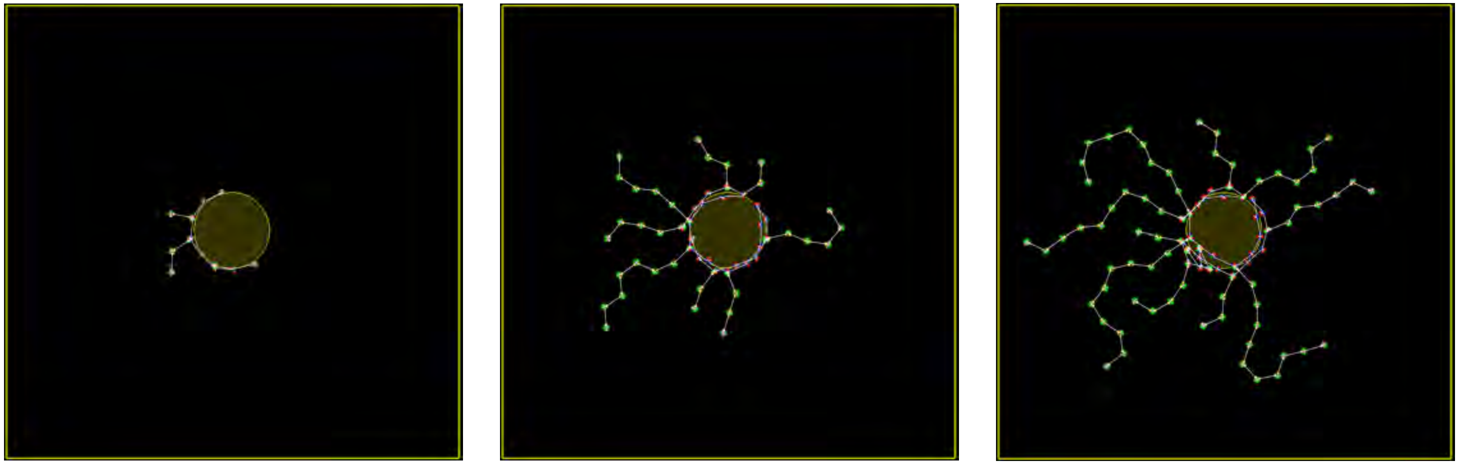
Ulieru & Doursat (2010) ACM TAAS
simulation by Adam MacDonald, UNB

➢ Polymorphism: reacting and adapting to the environment

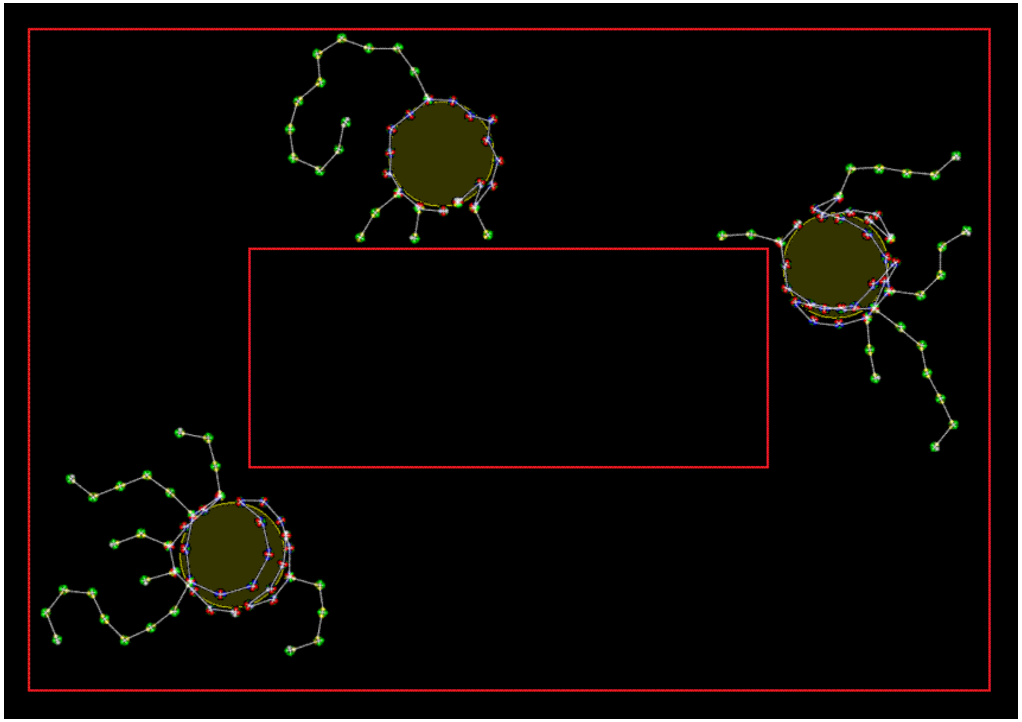


➢ Evolution: inventing new architectures



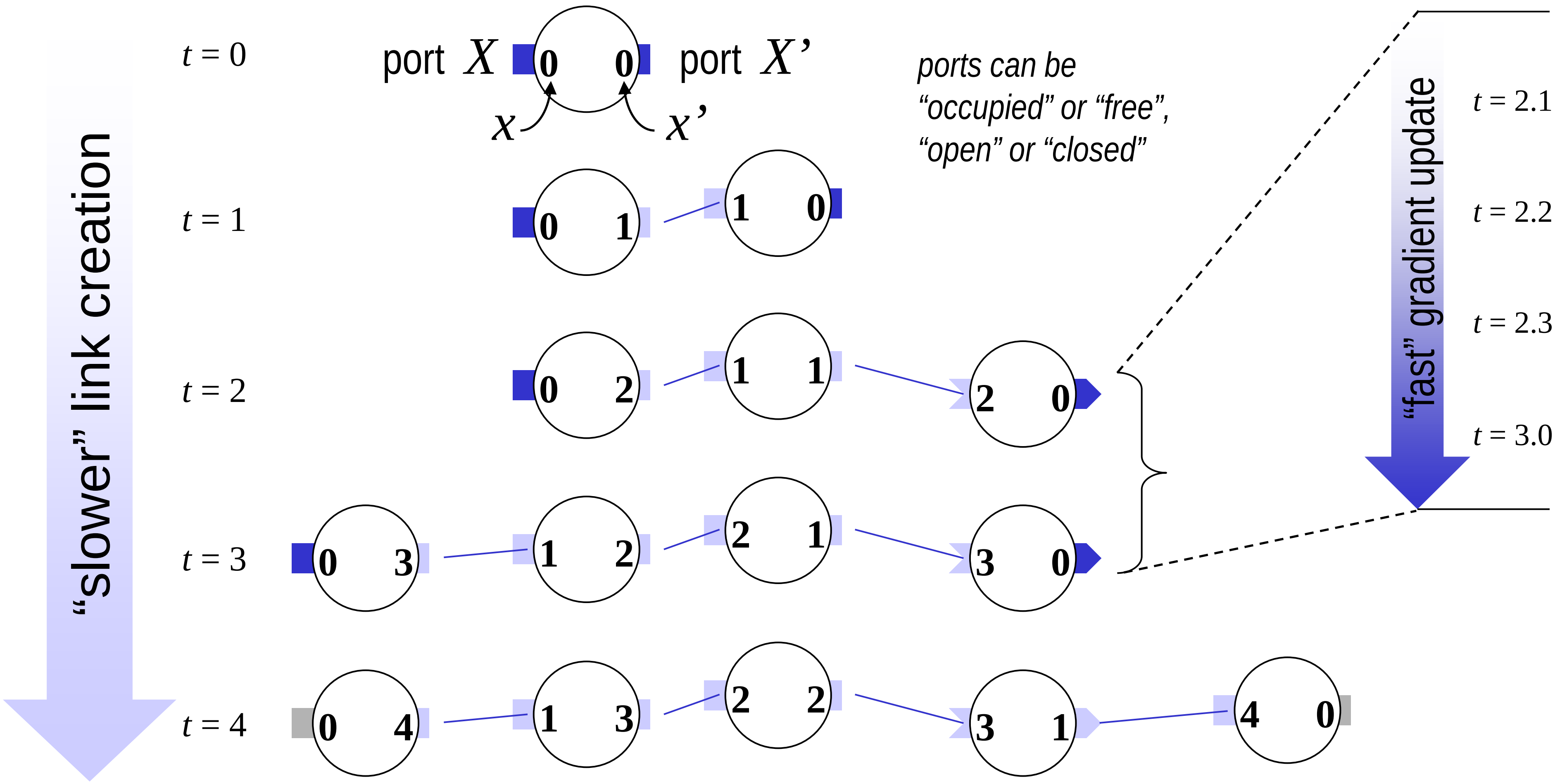


Order influenced (not imposed) by the environment



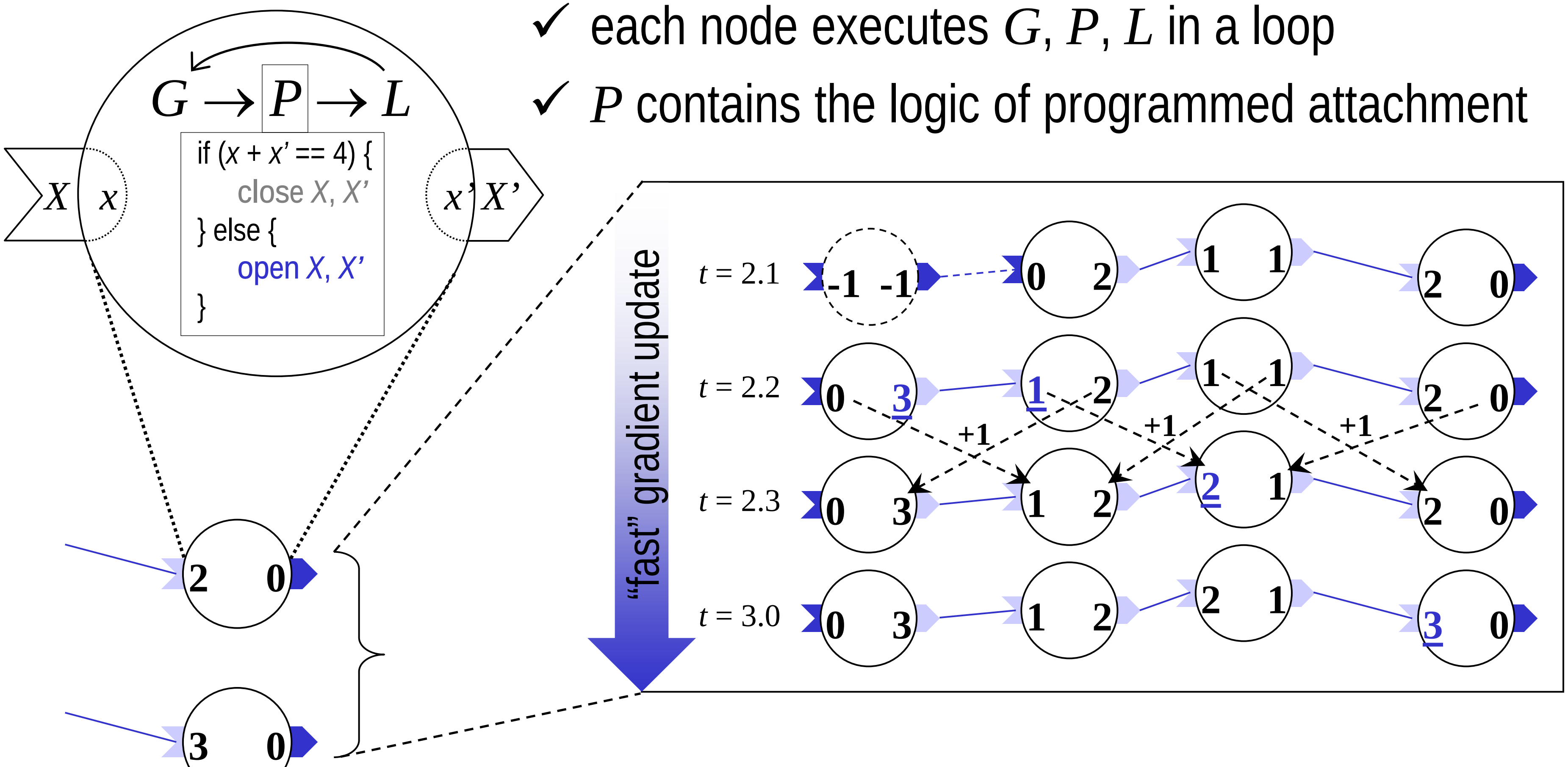
Simple chaining

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



➢ Simple chaining

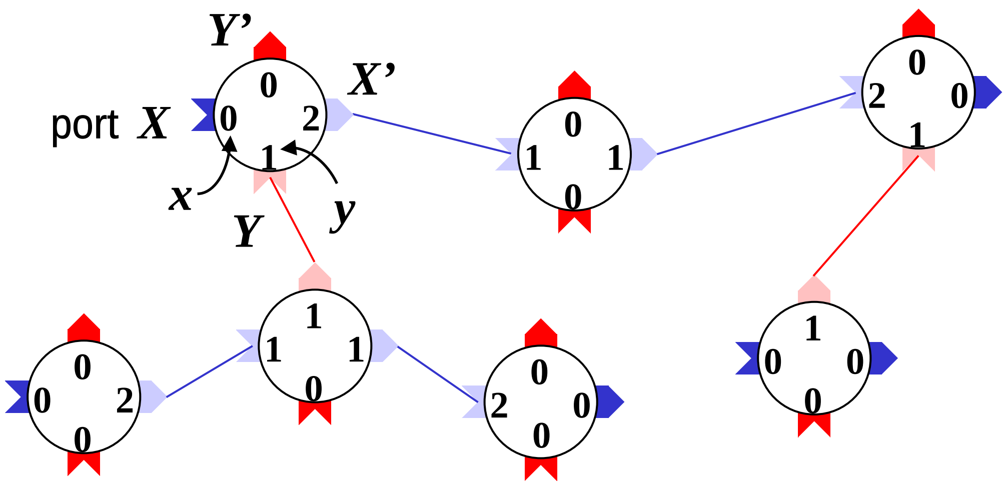
- ✓ port management (P) relies on gradient update (G)
- ✓ each node executes G, P, L in a loop
- ✓ P contains the logic of programmed attachment



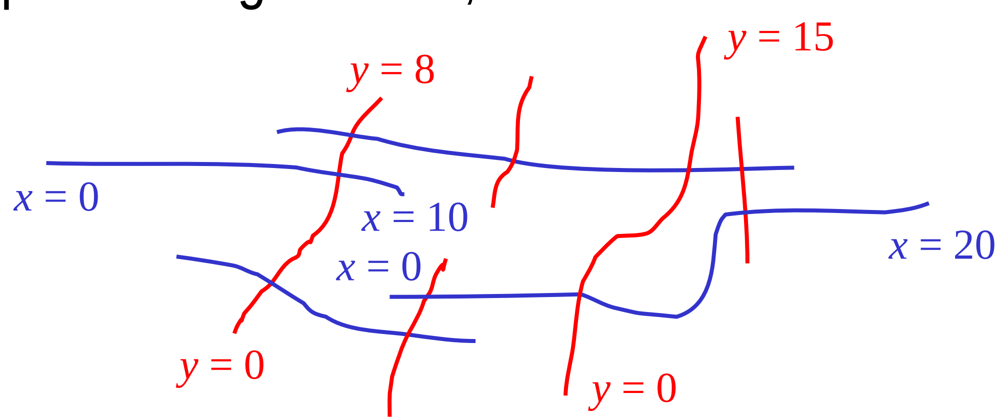
4. Morphogenetic Engineering: ProgNet

➢ Lattice formation by guided attachment

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

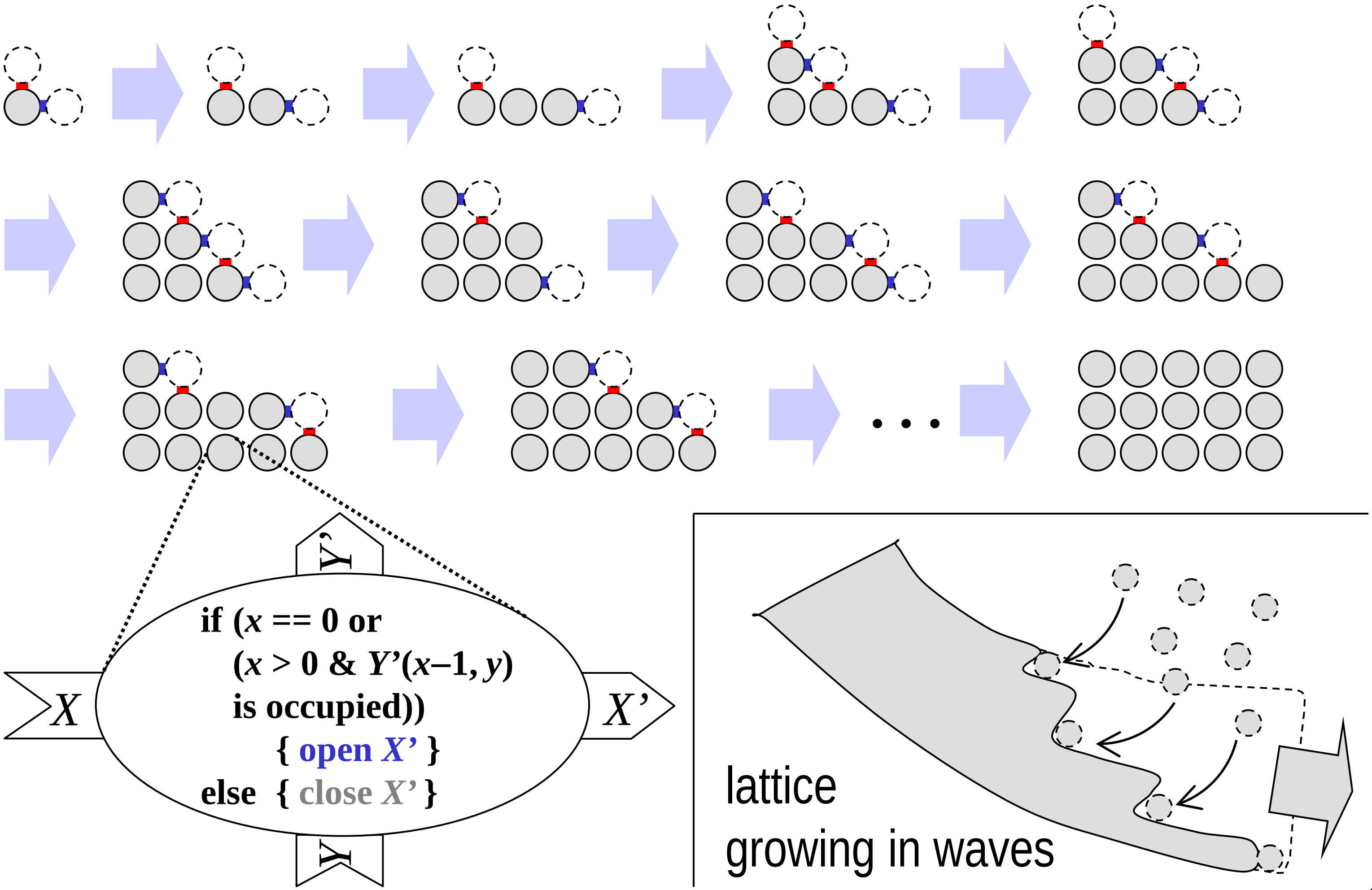


- ✓ without port management *P*, chains form and intersect randomly



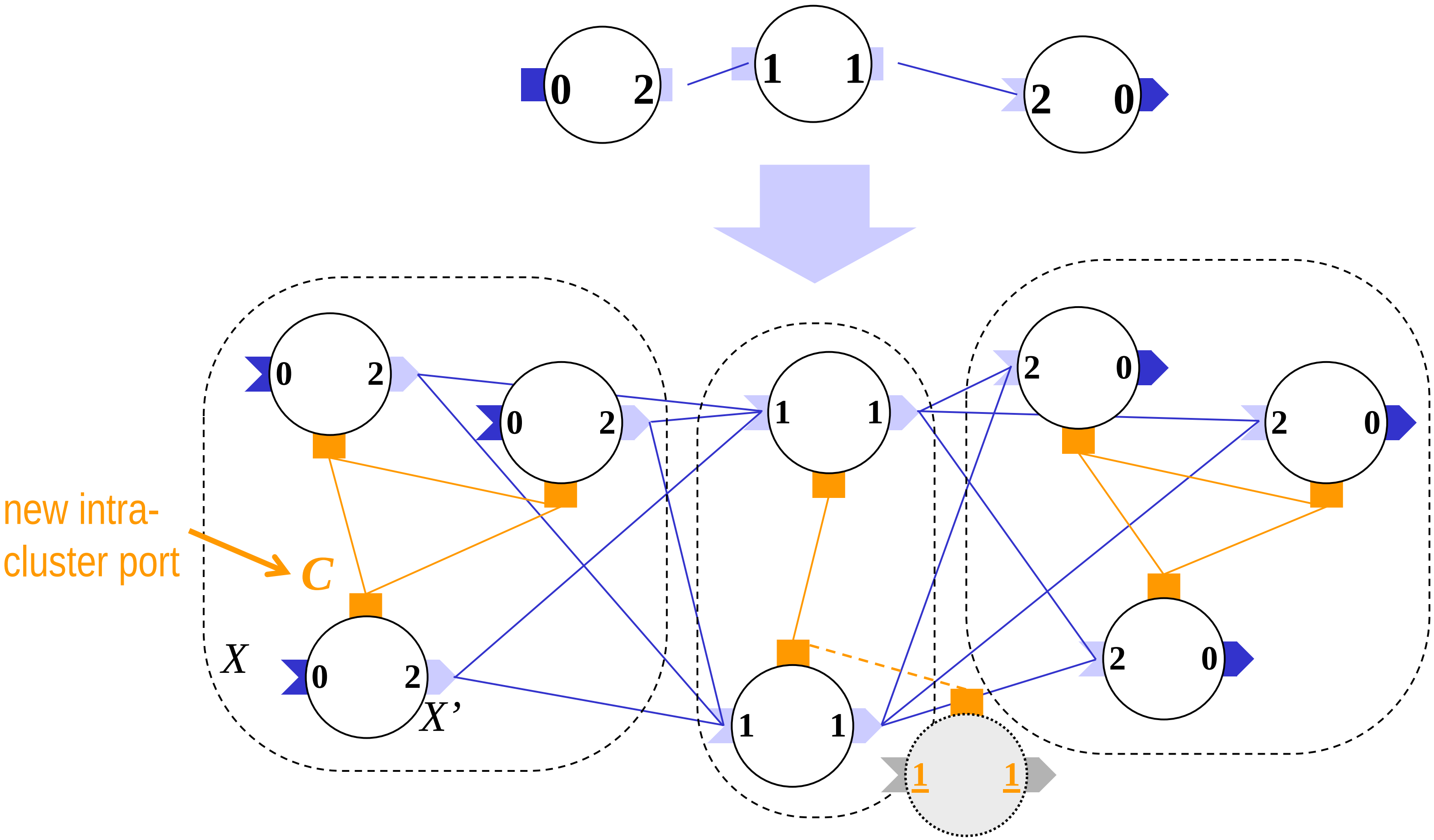
➢ Lattice formation by guided attachment

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



Cluster chains and lattices

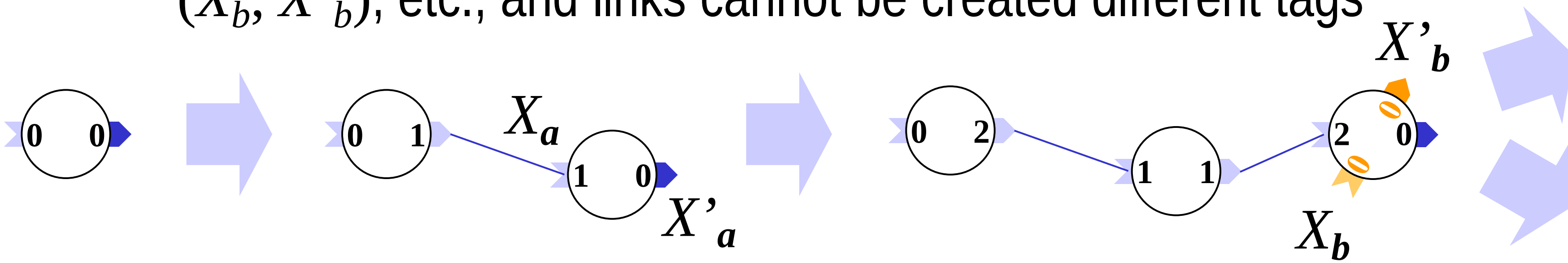
- ✓ several nodes per location: reintroducing randomness but only within the constraints of a specific structure

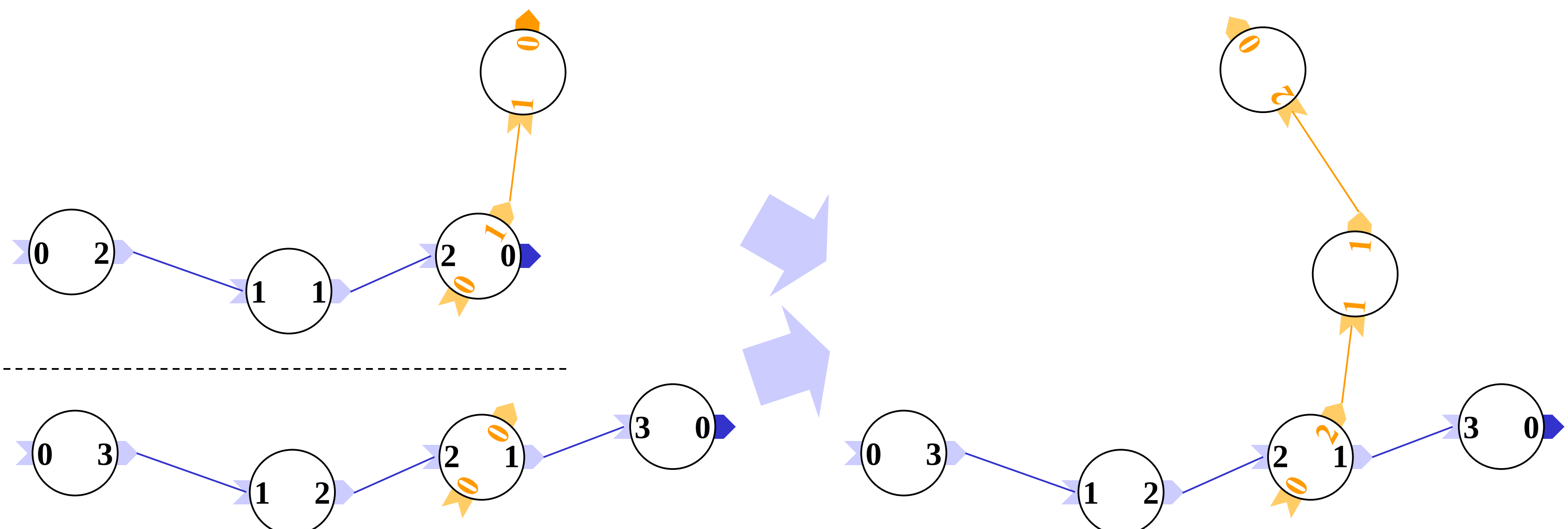


4. Morphogenetic Engineering: ProgNet

➢ Modular structures by local gradients

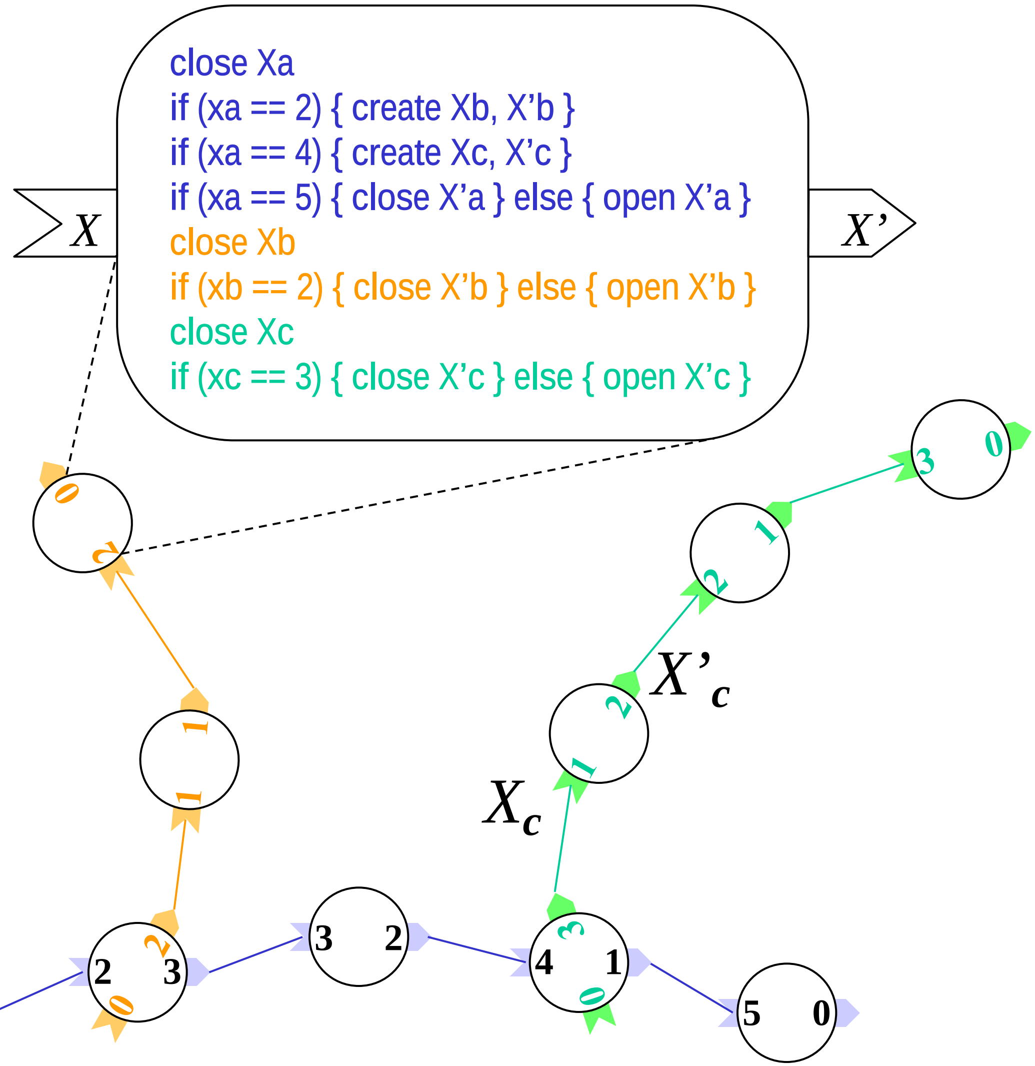
- ✓ modeled here by different coordinate systems, (X_a, X'_a), (X_b, X'_b), etc., and links cannot be created different tags





Modular structures by local gradients

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



. . .

Summary: ME is about programming the agents of emergence

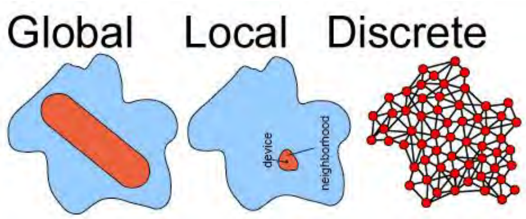
a) Giving agents self-identifying and self-positioning abilities
- ✓ agents possess the same set of rules but execute different subsets depending on their position = "differentiation" in cells, "stigmergy" in insects

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.

Summary: ME is about programming the agents of emergence

- ✓ 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*

4. Morphogenetic Engineering (ME)

1st "Morphogenetic Engineering" Workshop, ISC,Paris 2009

http://iscpif.fr/MEW2009

2nd "Morphogenetic Engineering" Session, ANTS 2010, Brussels

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

3rd "Morphogenetic Engineering" Workshop, ECAL 2011, Paris

http://ecal11.org/workshops#mew

"Morphogenetic Engineering" Book, 2011, Springer

R. Doursat, H. Sayama & O. Michel, eds.

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. Morphogenetic Engineering

From cells and insects to robots and networks

5. A New World of CS Computation

Or how to exploit and organize spontaneity

11th ECAL, Paris 2011

20th Anniversary Edition: "Back to the Origins of Alife"

Cité Universitaire Internationale, Paris, August 8-12, 2011

Organizing committee: Hugues Bersini, Paul Bourgine, René Doursat (chairs) – Tom Lenaerts, Mario Giacobini, Marco Dorigo

Overview and Spirit

- Refocusing on complex biological systems
  - first ECAL conferences centered on theoretical biology and the physics of complex systems
  - today, Alife can take more inspiration from new developments at the intersection between computer science and complex biological systems
- Expanding the topics of Alife
  - multiscale pattern-forming morphodynamics
  - autopoiesis & robustness
  - capacity to self-repair
  - cognitive capacities
  - co-adaptation at all levels, including ecology
  - etc.

Keynote Speakers (tentative)

- Eric Wieschaus: Nobel Prize in Physiology 1995
- Jean-Marie Lehn: Nobel Prize in Physics 1987
- Robert Laughlin: Nobel Prize in Physics 1998
- Jacques Demongeot: a pioneer of mathematical biology
- David Harel: UML co-inventor, *C. Elegans* computer model
- James D. Murray: FRS, *Mathematical Biology* book
- Jordan Pollack: Alife pioneer, co-founder of Evo Robotics
- Ricard Solé: theoretical biologist, complex systems
- Pier Luigi Lisi: synthetic biology

A tribute to Francisco Varela