SYSTEMES COMPLEXES

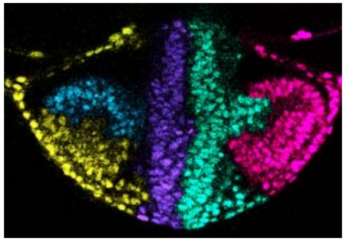
9ème rencontres de la fédération "Dynamique des Systèmes Complexes" de l'Université Joseph Fourier - Grenoble I

Heterogeneous collective motion or *moving* pattern formation?

The exemplary status of multicellular morphogenesis at the border between “informed” physics and “physical” computation

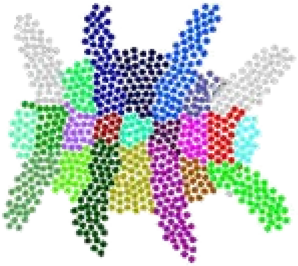
René Doursat

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



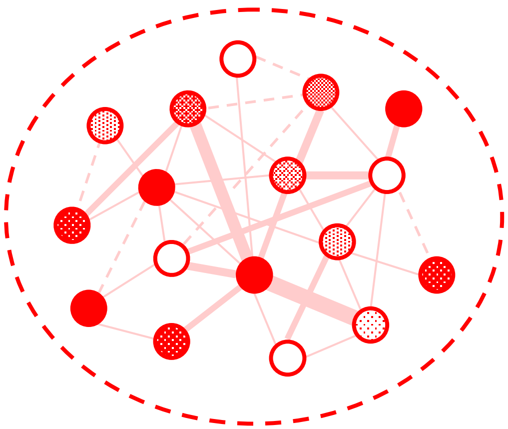
ISC PARIS ÎLE DE FRANCE

INSTITUT DES SYSTEMES COMPLEXES



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)

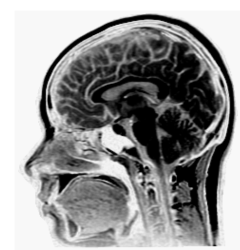
b) **emergence:** function is a bottom-up collective effect of the agents (asynchrony, balance, combinatorial creativity)

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

- Physical, biological, technological, social complex systems

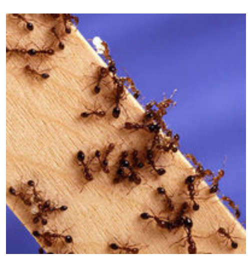
pattern formation
○ = matter

biological development
○ = cell

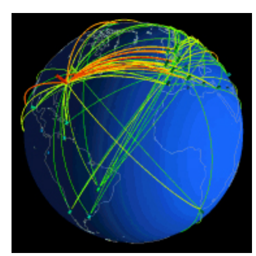


the brain & cognition
○ = neuron

insect colonies
○ = ant



Internet & Web
○ = host/page

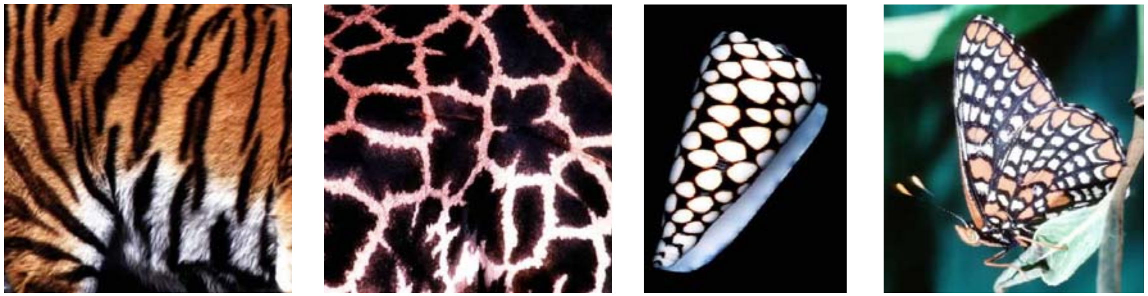


social networks
○ = person

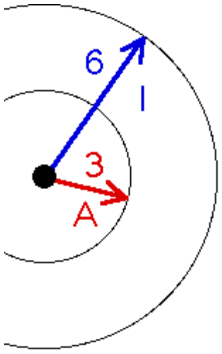
Complex Systems

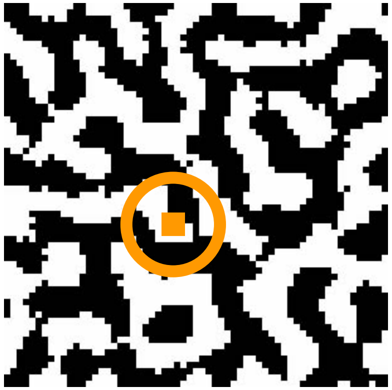
➢ Ex: Pattern formation – Animal colors

- ✓ 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)





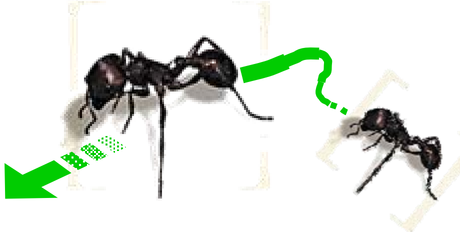
NetLogo Fur simulation

➢ Ex: Swarm intelligence – Insect colonies

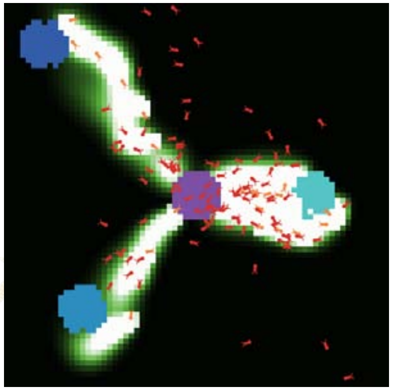
- ✓ trails form by ants that follow and reinforce each other's pheromone path

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)

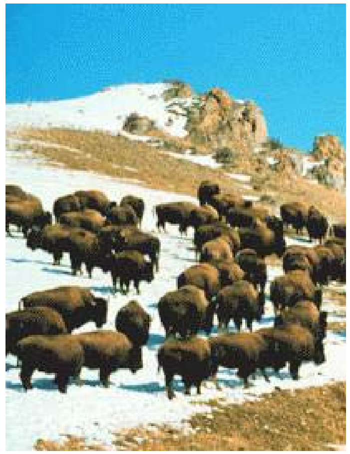


NetLogo Ants simulation

Complex Systems

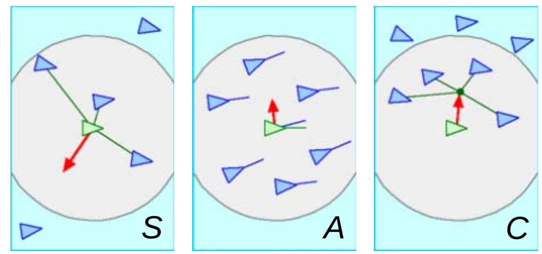
➢ Ex: Collective motion – Flocking, schooling, herding

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

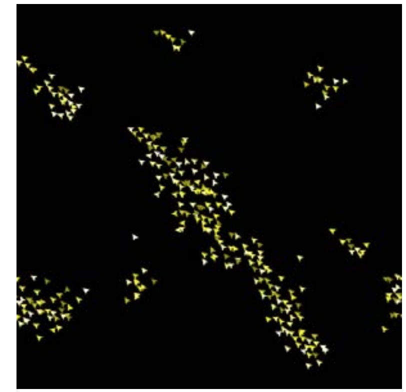


Bison herd
(Montana State University, Bozeman)

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



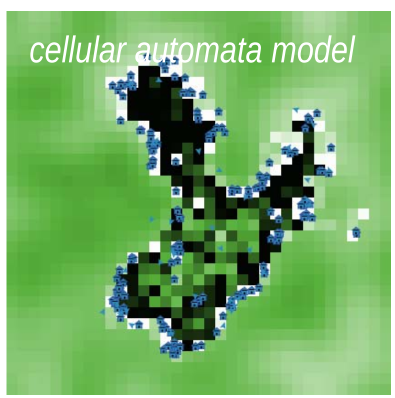
Separation, alignment and cohesion
("Boids" model, Craig Reynolds)



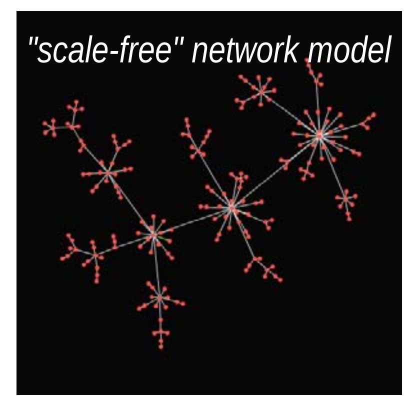
NetLogo Flocking simulation

➢ Ex: Diffusion and networks – Cities and social links

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



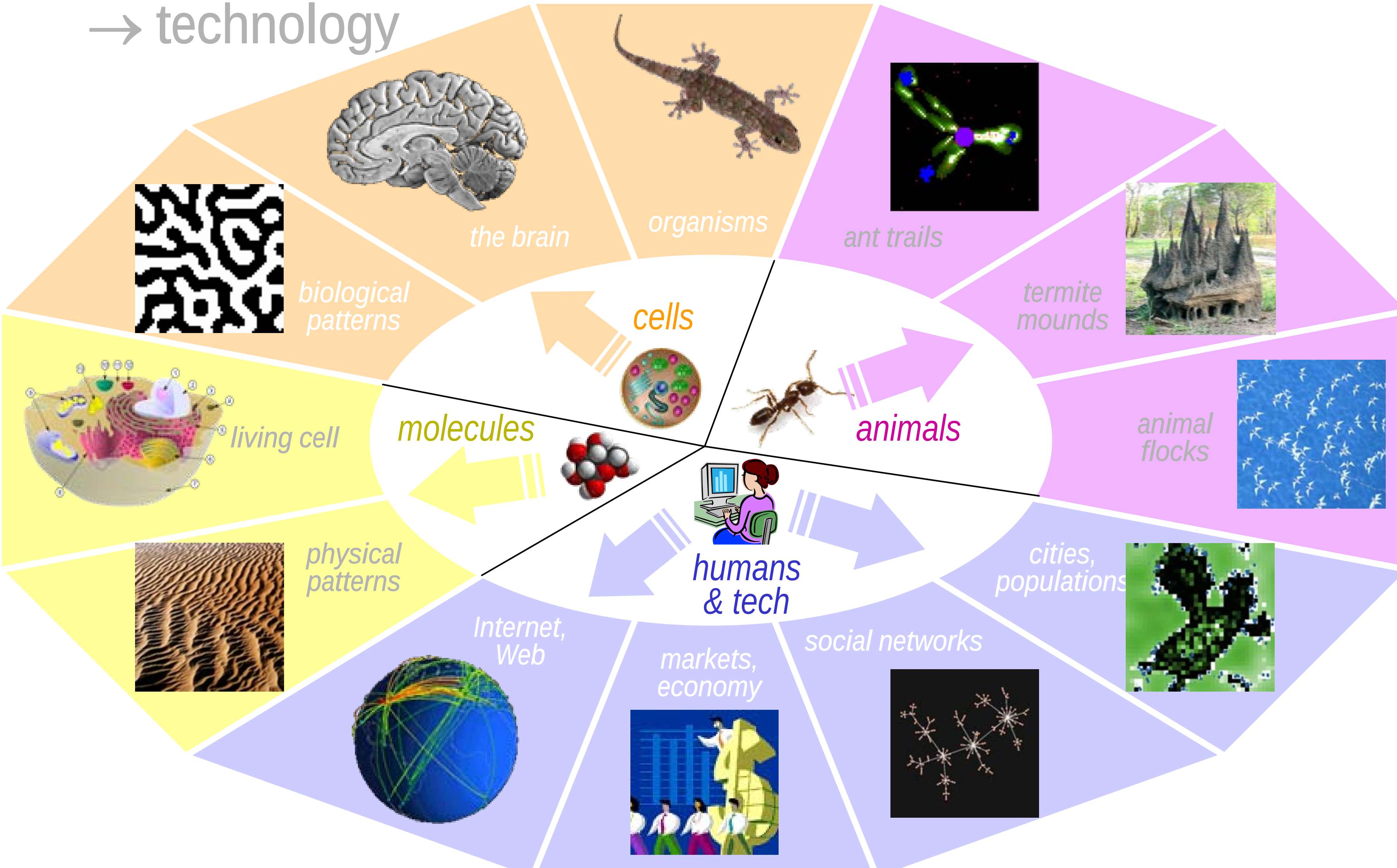
NetLogo urban sprawl simulation



NetLogo preferential attachment

Complex Systems

- All kinds of agents: molecules → cells → animals / humans → technology



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

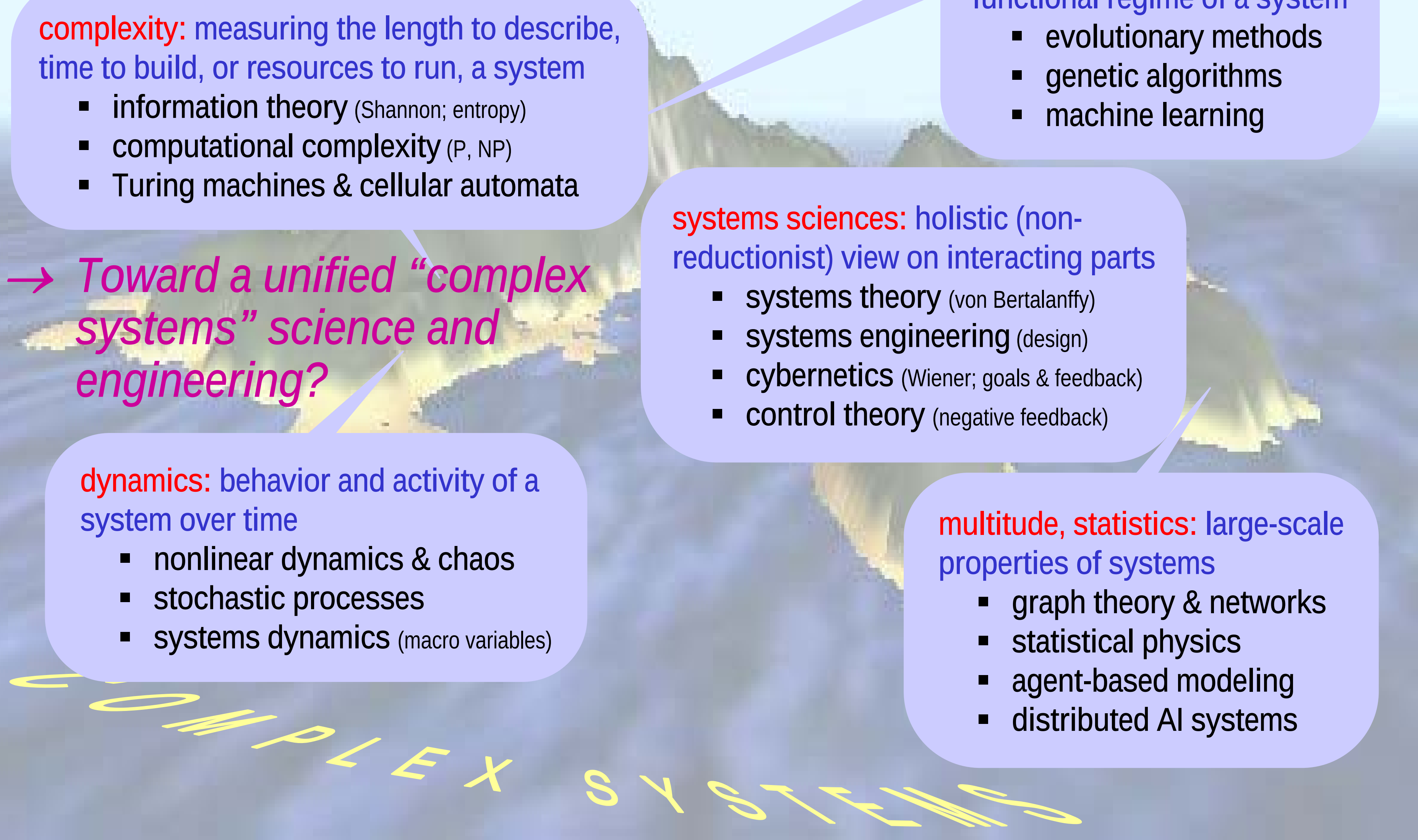
adaptation: change in typical functional regime of a system
- evolutionary methods
- genetic algorithms
- machine learning

→ *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

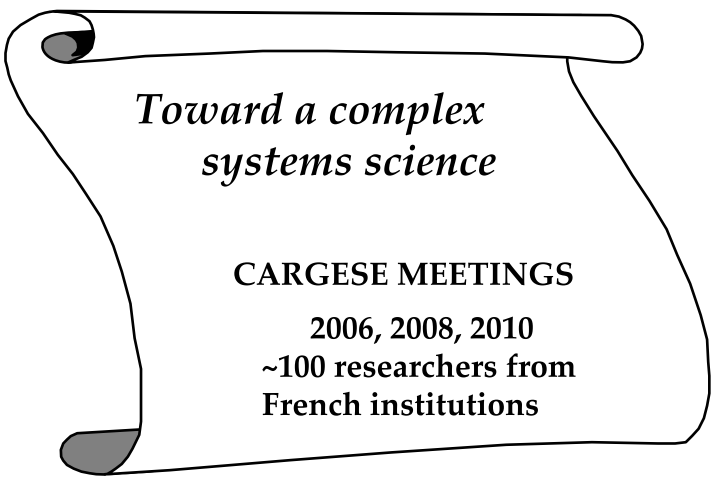
➢ French “roadmap” toward a Complex Systems Science

Big topics

- subcellular
- multicellular / development
- physiology
- indiv. & social cognition
- ecosystems
- territorial intell. & sustainability
- ubiquitous computing

Big questions

- reconstruct multiscale dynam.
- emergence & immergence
- spatiotemp. morphodynamics
- optimal control & steering
- artificial design
- fluctuations out-of-equilib.
- adaptation, learning, evolution



→ *Erasmus Mundus MSc/PhD Program in Complex Systems Science (Polytechnique, Warwick, Chalmers)*

→ *Digital University of Complex Systems (Saclay)*

Complex Systems

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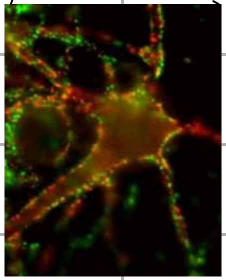
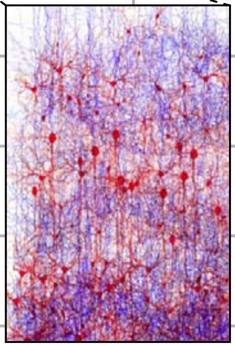
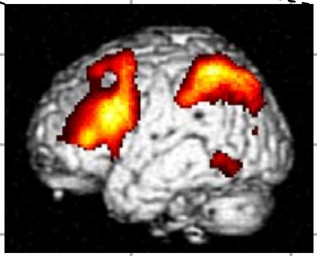
multiscale


Triller & Dahan


Blue Brain


Laufs et al.

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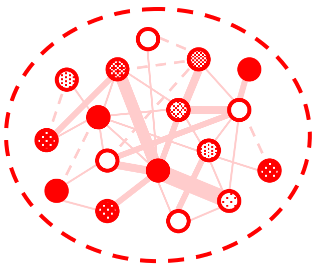
Complex Systems

➢ The challenges of complex systems (CS) research

Transfers
- among systems



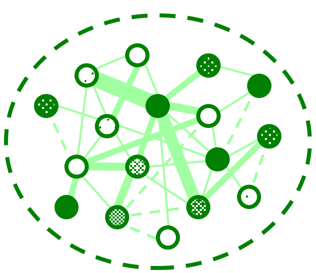
CS science: understanding & modeling "natural" CS

(spontaneously emergent, including human-made):

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

Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

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



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

(harnessed & tamed, including nature):

collective robotics, synthetic biology, energy networks

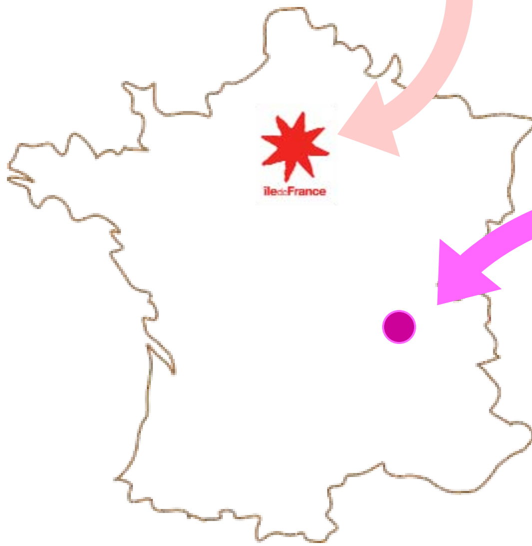
INSTITUT DES SYSTEMES COMPLEXES

Paris Ile-de-France

4th French Complex Systems Summer School, 2010

RNSC

National



IXXI

Lyon Rhône-Alpes

Reisident 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

Francesco d'Ovidio

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

nonlinear dynamics / oceanography

Francesco Ginelli

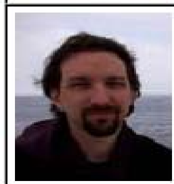
Nonequilibrium statistical mechanics (Active matter, collective motion, flockng, nonequilibrium wetting, directed percolation, long range interactions) - Dynamical system theory (Lyapunov exponents, Lyapunov vectors, synchronization, stable chaos, spatiotemporal chaos, structural stability, hyperbolicity).

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 syste

structural genomics



Taras Kowaliw

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

computational evolution / development

Telmo Menezes

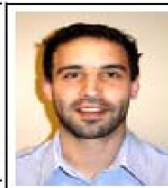
Complex network analysis and simulation - Social networks - Evolutionary search for multi-agent models, Genetic programming applied to programmable networks - Bio-inspired algorithms.

social networks

Bivas Mitra

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

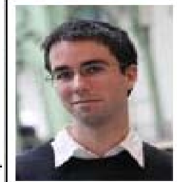
peer-to-peer networks



Romain Reuillon

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

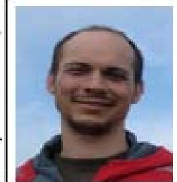
high performance computing



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

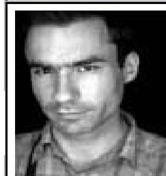
Grid Computing,Bioemergences Platform (workflow), Mophodynamics reconstruction, Images processing algorithms.

embryogenesis

David Chavalarias

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

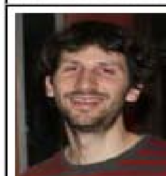
web mining / social intelligence



Srdjan Ostojic

Neuroscience théoriques - Spiking Neurons - Dynamiques Stochastic-ques.

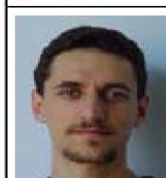
spiking neural dynamics



Andrea Perna

Morphogenesis, Collective behavior, Spatial patterns, Spatial networks.

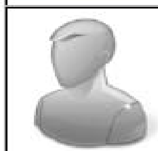
spatial networks / swarm intelligence



Fernando Peruani

Biophysique – Active Matter – Complex Networks.

active matter / complex networks

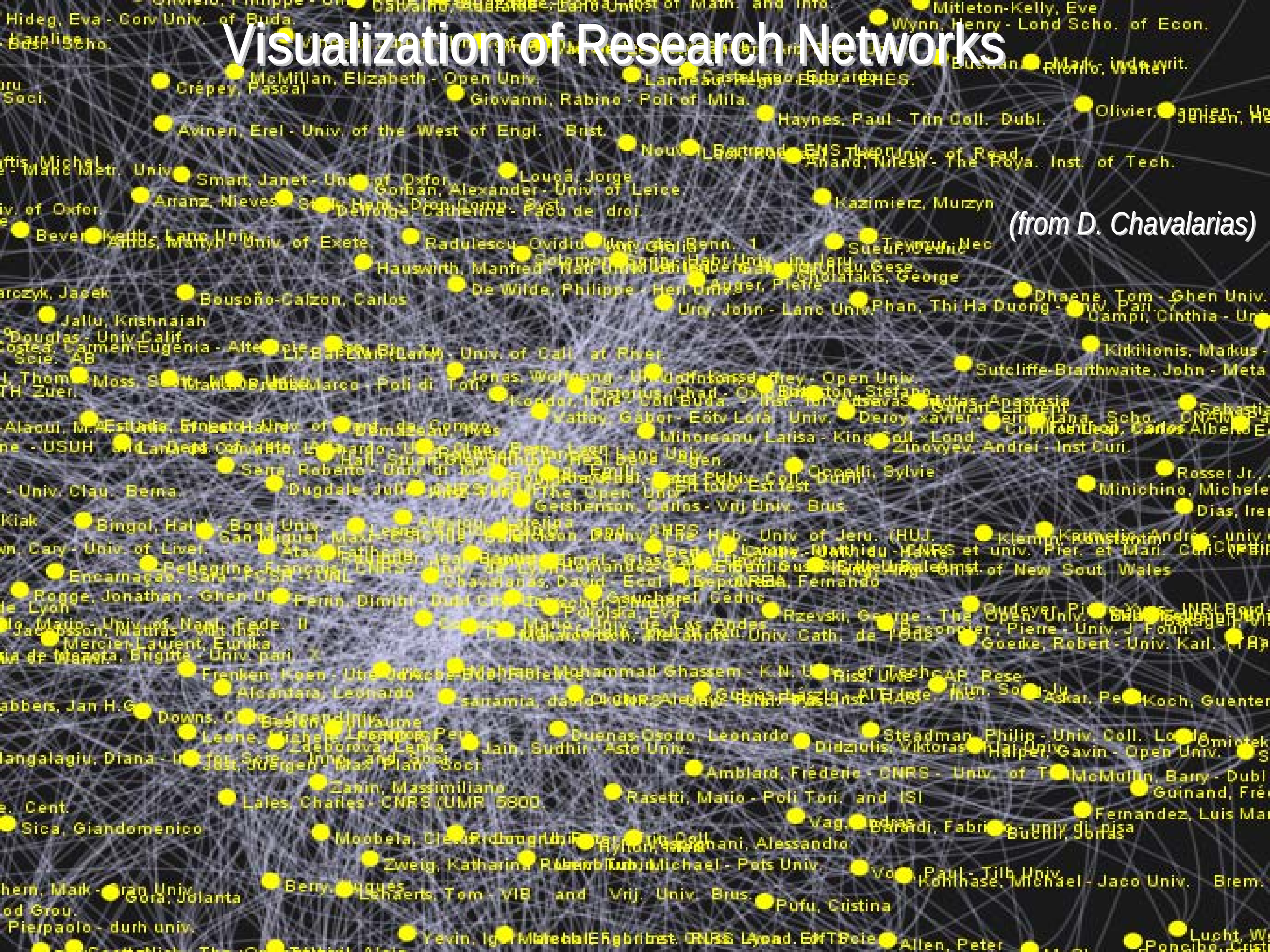


Fabien Tarissan

Informatique théorique, méthodes formelles, théorie des langages de programmation. Systèmes complexes, graphes dynamiques, modélisations des systèmes biologiques. Recherche opérationnelle, programmation mathématique, problèmes inverses.

theoretical computer science

Visualization of Research Networks



(from D. Chavalarias)

The self-made puzzle of embryogenesis

1. Self-organized *and* structured systems

2. A two-side challenge: heterogeneous motion / moving patterns

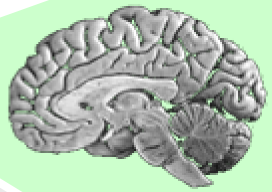
3. Artificial Multi-Agent Embryogenesis

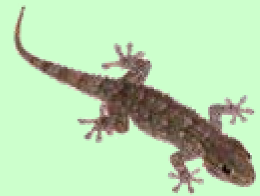
4. Artificial Evo-Devo & Future Work

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.:

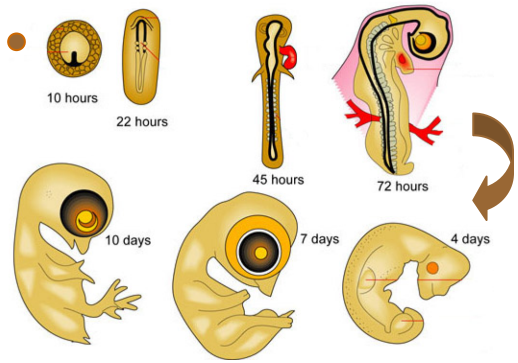
✓ a non-trivial, sophisticated morphology

- *hierarchical* (multi-scale): regions, parts, details
- *modular*: reuse of parts, quasi-repetition
- *heterogeneous*: differentiation, division of labor

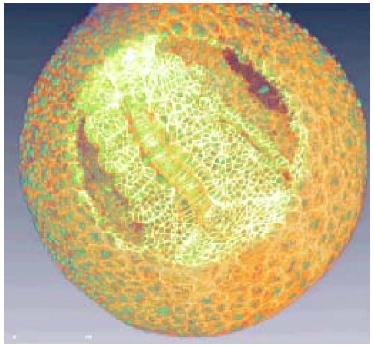
✓ *random* at agent level, *reproducible* at system level

Architecture Without Architects

Ex: Morphogenesis – Biological development



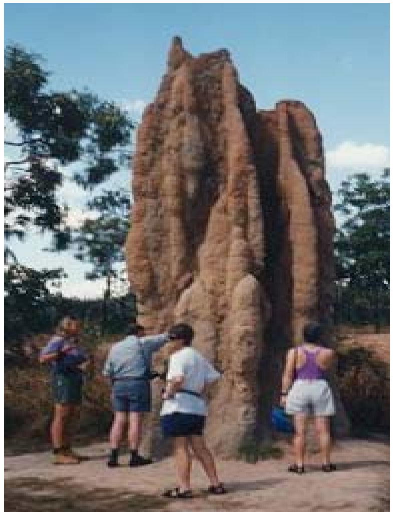
www.infovisual.info



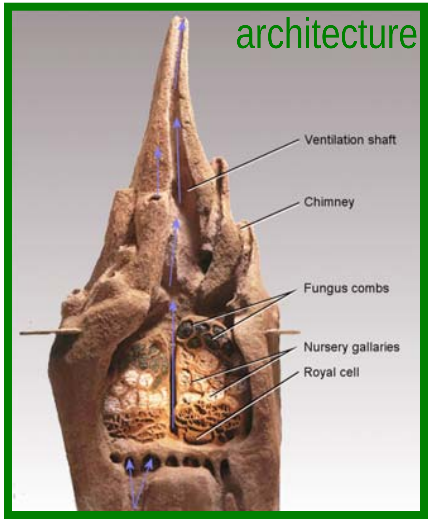
Nadine Peyriéras, Paul Bourgine et al. (Embryomics & BioEmergences)

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

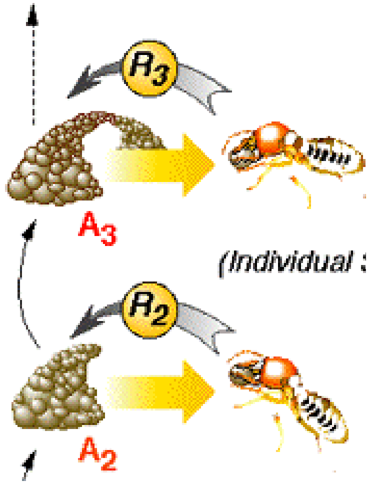
Ex: Swarm intelligence – Termite mounds



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

Systems that are self-organized and architectured

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

Peugeot Picasso

free self-organization

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

architecture

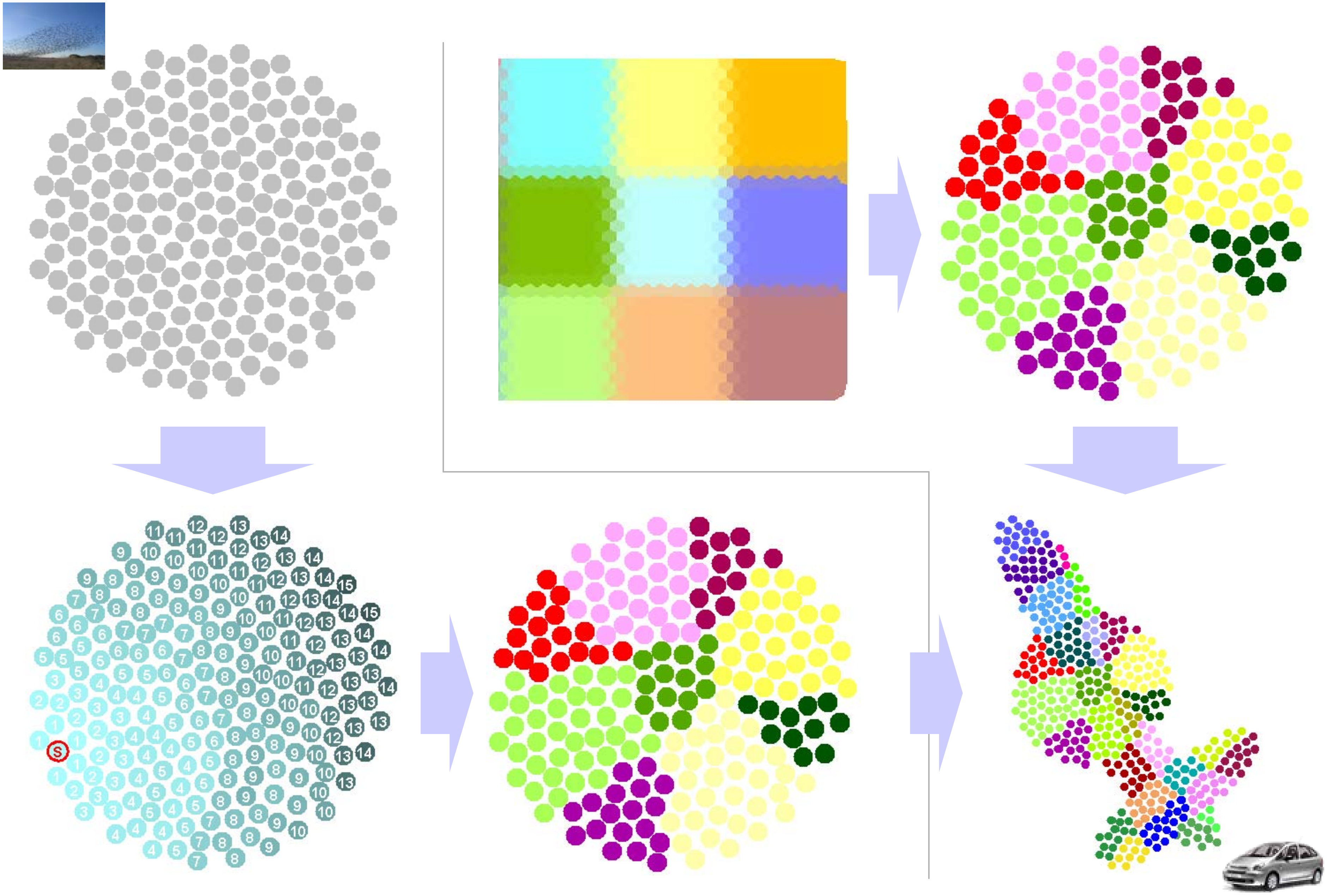
components differentiate

decompose the system

Peugeot Picasso

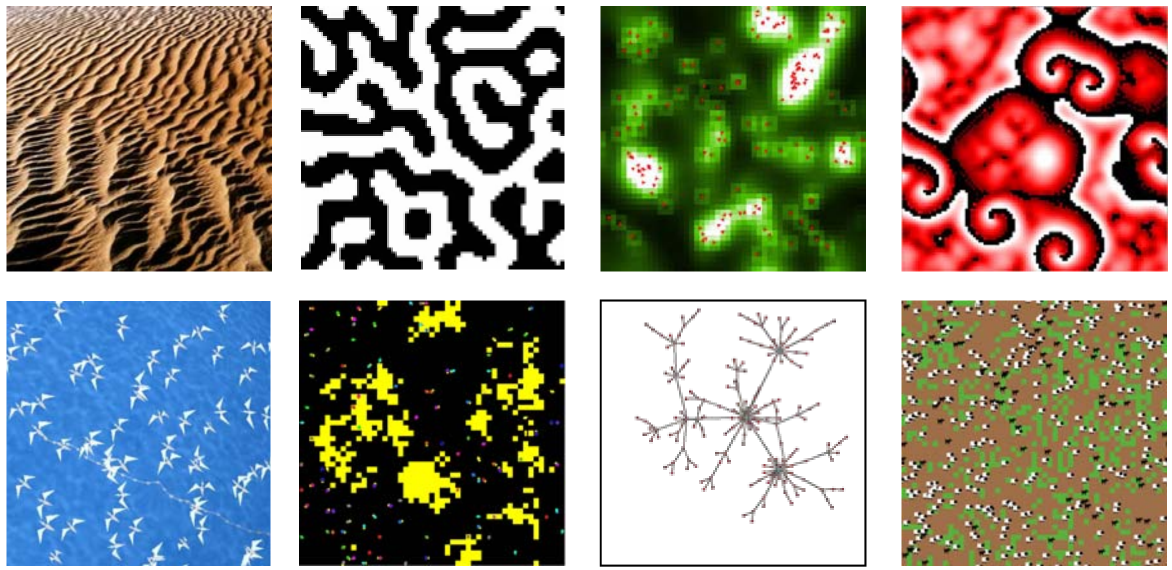
self-organized architecture / architectured self-organization

Heterogeneous collective motion / *moving* pattern formation



Statistical (self-similar) systems

- Many agents, simple rules, “complex” emergent behavior
  - → *diversity of* ***patterning*** *(spots, stripes) and/or* ***motion*** *(swarms, clusters, flocks), complex networks, etc.,* ***but......***

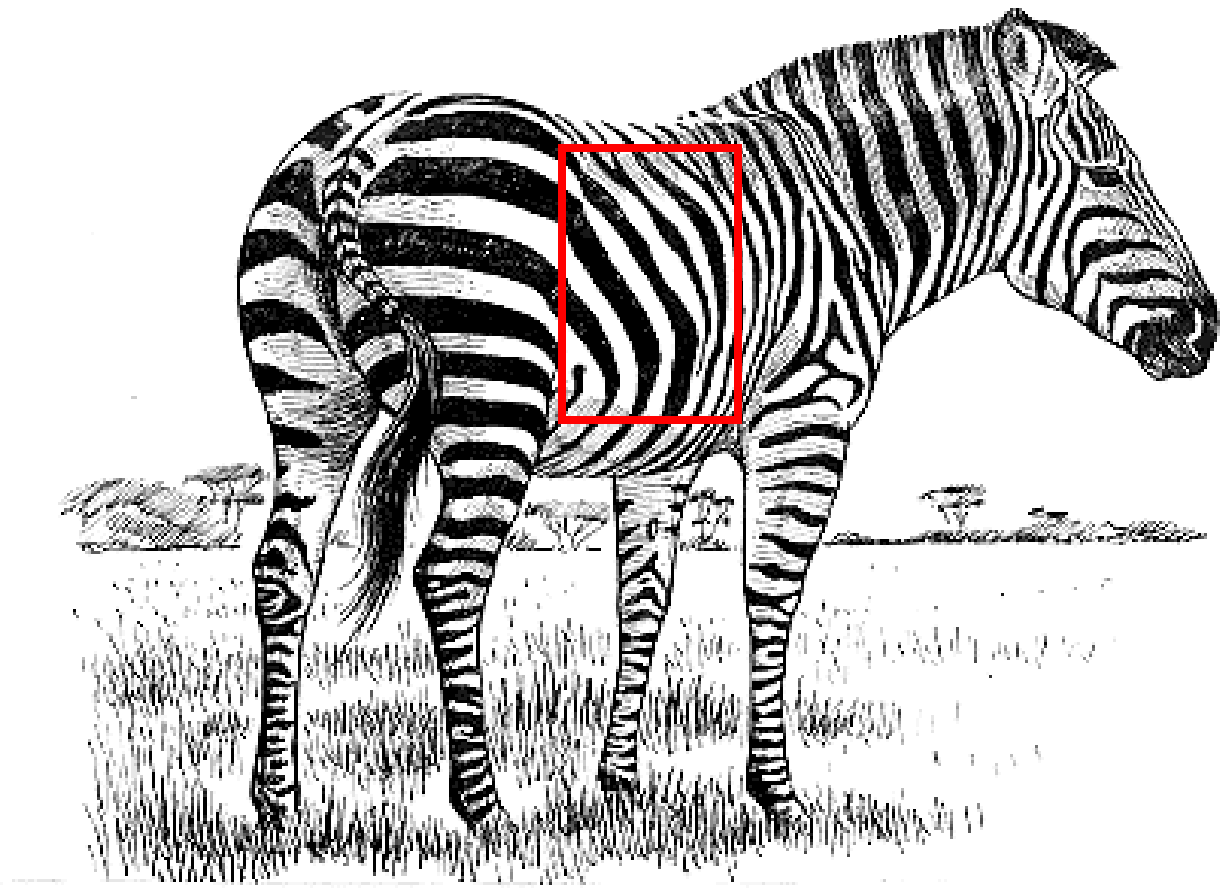


- ✓ often like “textures”: repetitive, statistically ***uniform***, information-poor
- ✓ spontaneous order arising from amplification of ***random*** fluctuations
- ✓ ***unpredictable*** number and position of mesoscopic entities (spots, groups)

→ ***“missing” ingredient: heterogeneity of the units***

Morphological (self-dissimilar) systems

compositional systems: pattern formation ≠ morphogenesis



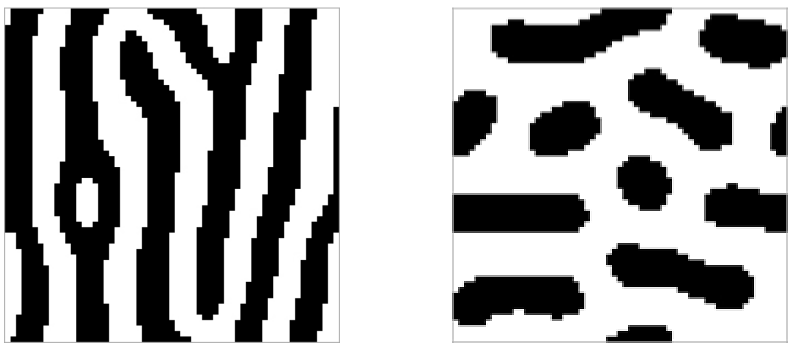
"I have the stripes, but where is the zebra?" OR

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

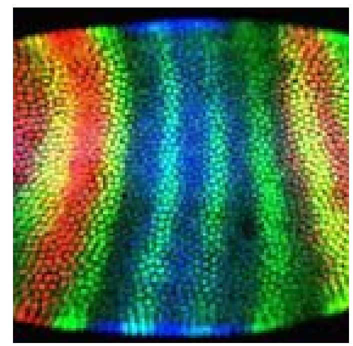
—attributed to A. Turing, after his 1952 paper on morphogenesis

Statistical vs. morphological systems

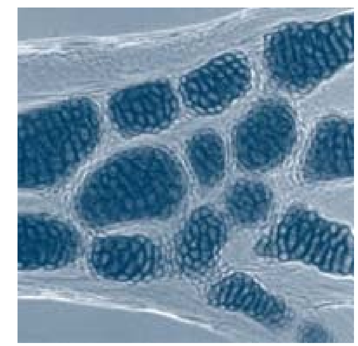
- Physical pattern formation is “free” –
  Biological (multicellular) pattern formation is “guided”



reaction-diffusion
with NetLogo



fruit fly embryo
Sean Caroll, U of Wisconsin



larval axolotl limb condensations
Gerd B. Müller

$\neq$

Fig. 8.2.

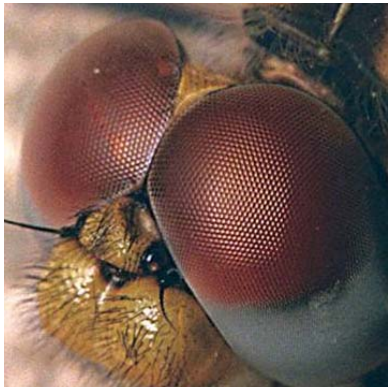
Statistical vs. morphological systems

➢ **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

From “statistical” to “morphological” CS

in inert matter / insect constructions / multicellular organisms

physical
pattern formation

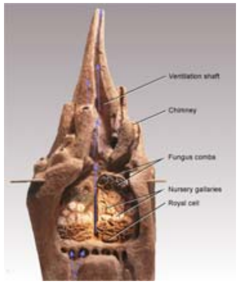
grains of sand + air

more intrinsic, sophisticated architecture

ant trail

network of ant trails

ant nest

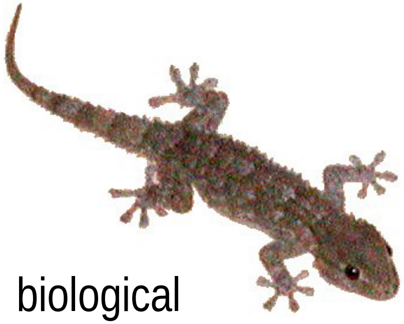


termite mound

social insect
constructions

insects

new inspiration



biological
morphogenesis

cells

The self-made puzzle of embryogenesis

1. Self-organized and structured systems
2. A two-side challenge: heterogeneous motion / moving patterns
3. Artificial Multi-Agent Embryogenesis
4. Artificial Evo-Devo & Future Work

Overview of embryogenesis

➢ An abstract computational approach to development

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

➢ Broad principles

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

\+ *coupling* between shapes and colors

➢ Multi-agent models

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

Embryogenesis couples assembly and patterning

➢ Sculpture → forms

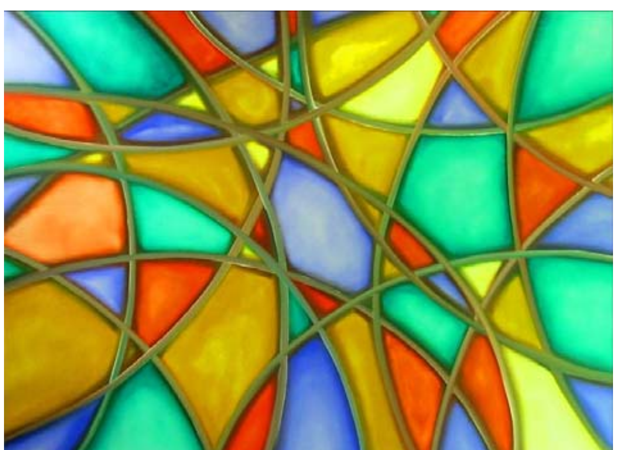
Ádám Szabó, *The chicken or the egg* (2005)
http://www.szaboadam.hu

“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”

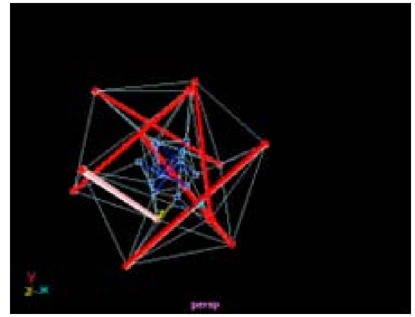
✓ new color regions appear (domains of genetic expression) triggered by deformations

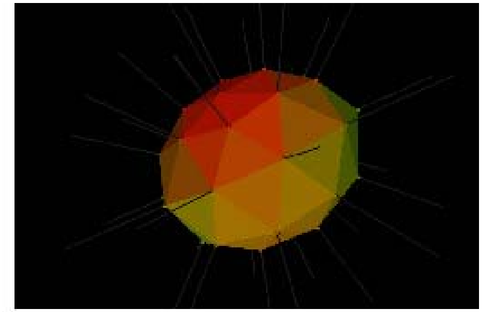
Embryogenesis couples mechanics and regulation

➢ Cellular mechanics

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

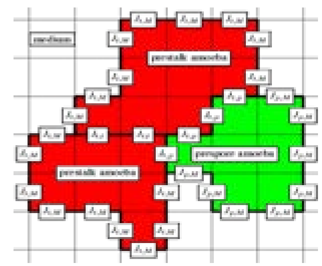
tensional integrity (Ingber)

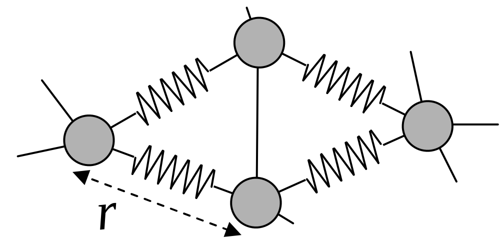




(Delile & Doursat)

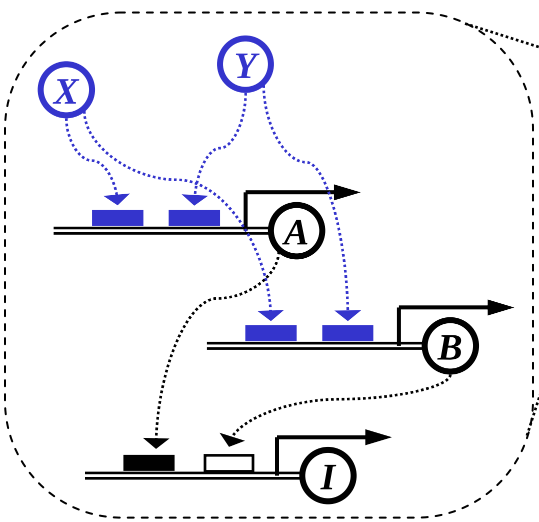
cellular Potts model (Graner, Glazier, Hogeweg)

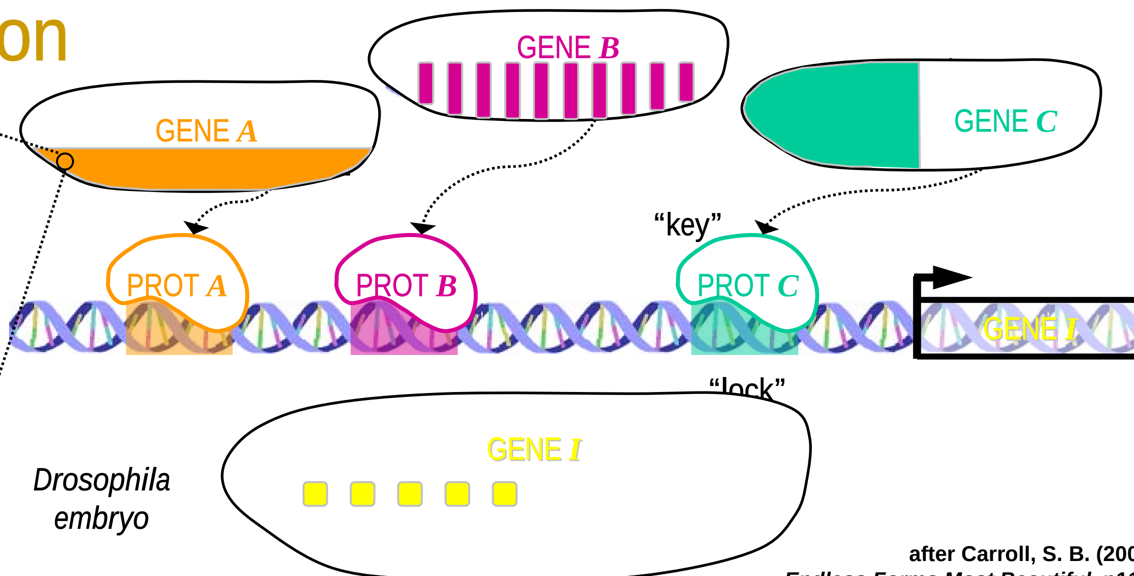




(Doursat)

➢ Genetic regulation



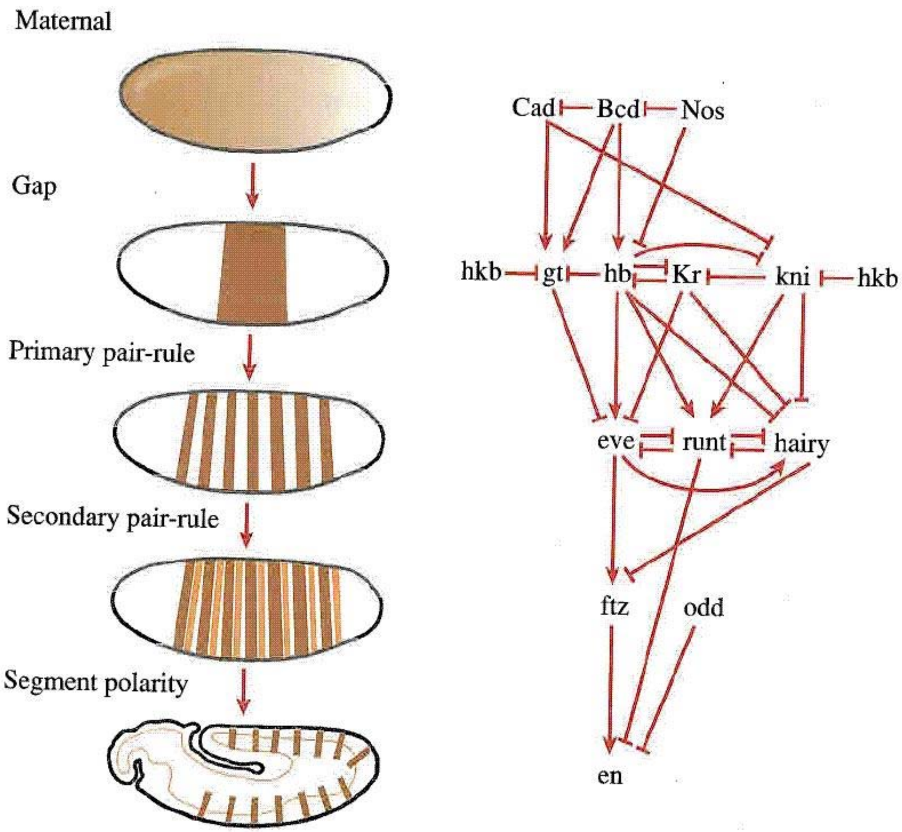


after Carroll, S. B. (2005)
Endless Forms Most Beautiful, p117

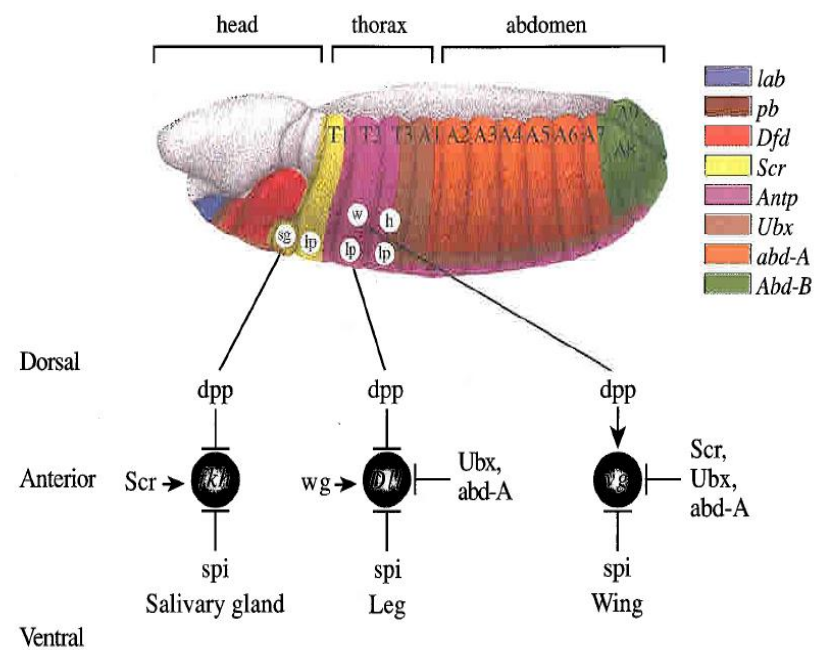
Gene regulatory pattern formation

➢ Segmentation & identity domains in *Drosophila*

- ✓ periodic A/P band patterns are controlled by a 5-tier gene regulatory hierarchy



- ✓ intersection with other axes creates organ primordia and imaginal discs (identity domains of future legs, wings, antennae, etc.)

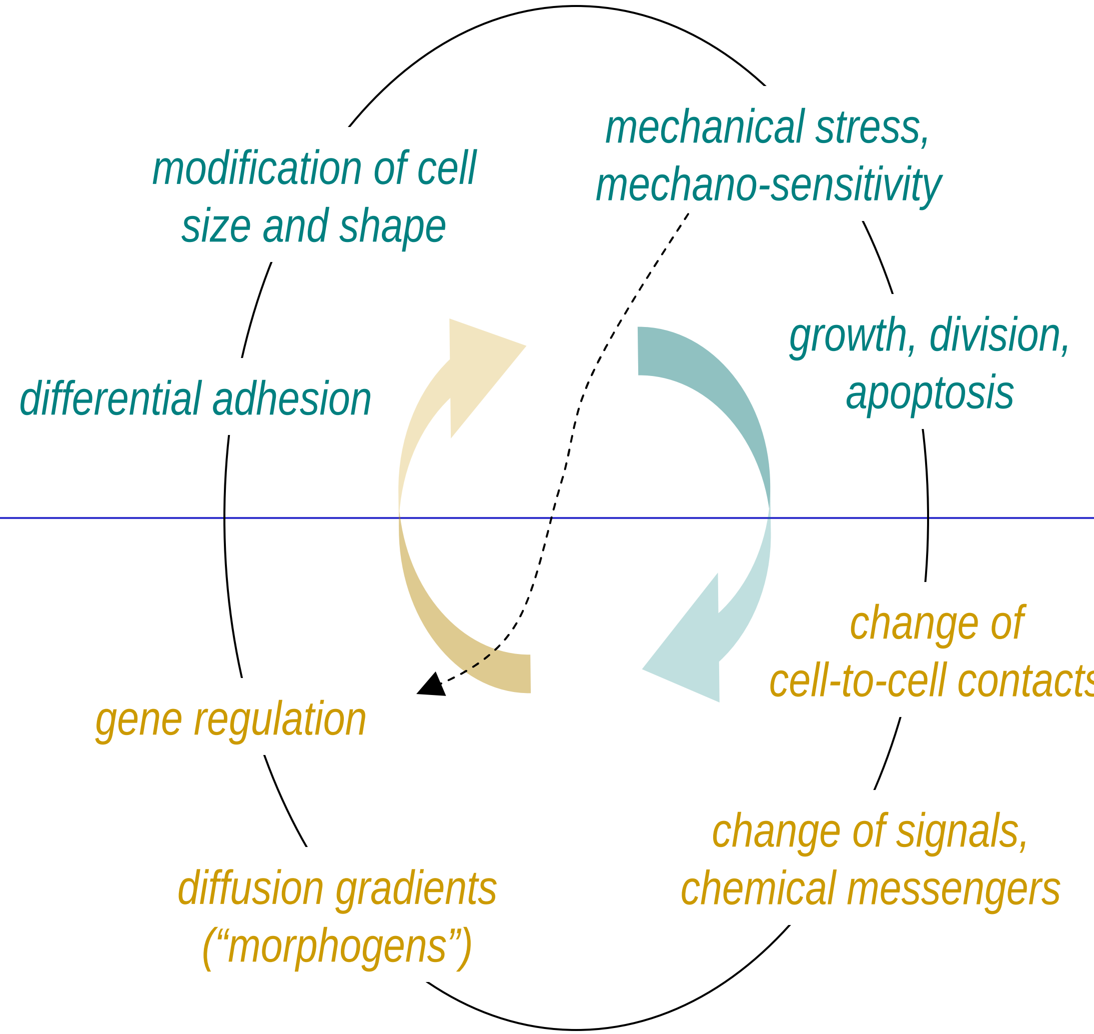


from Carroll, S. B., et al. (2001)
From DNA to Diversity, p63

Embryogenesis couples mechanics and regulation

- Cellular mechanics

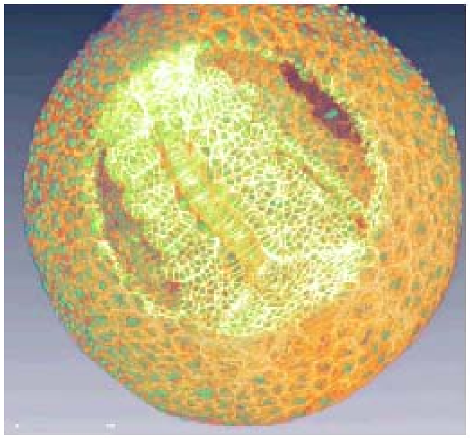
- Genetic regulation



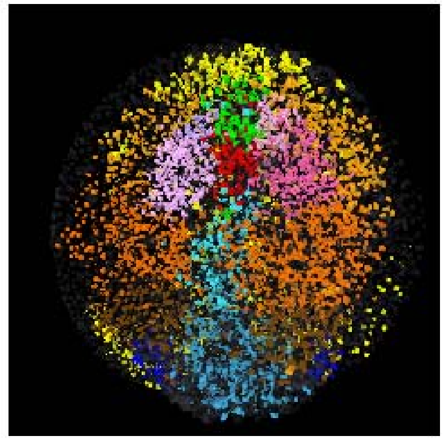
Embryogenesis couples motion and patterns

➢ Collective motion regionalized into patterns

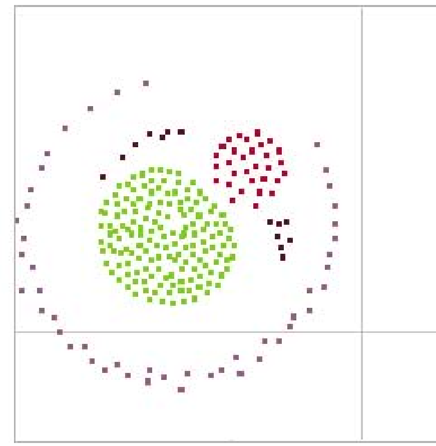
Nadine Peyriéras, Paul Bourgine, Thierry Savy, Benoît Lombardot, Emmanuel Faure et al.
Embryomics & BioEmergences



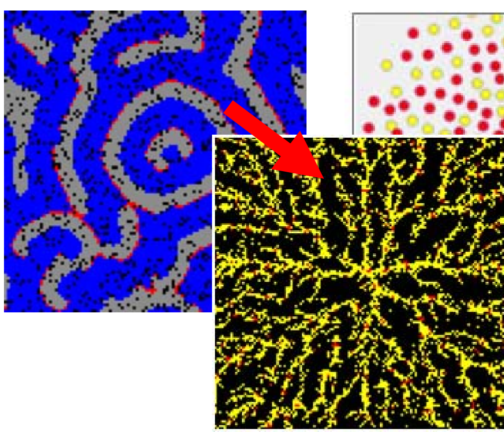
zebrafish



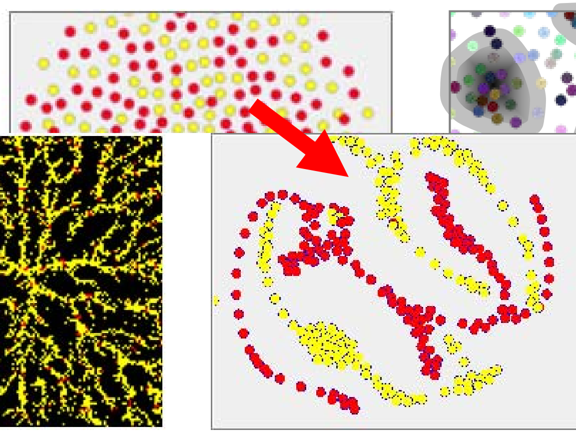
Hiroki Sayama (Swarm Chemistry)
http://bingweb.binghamton.edu/~sayama/SwarmChemistry/

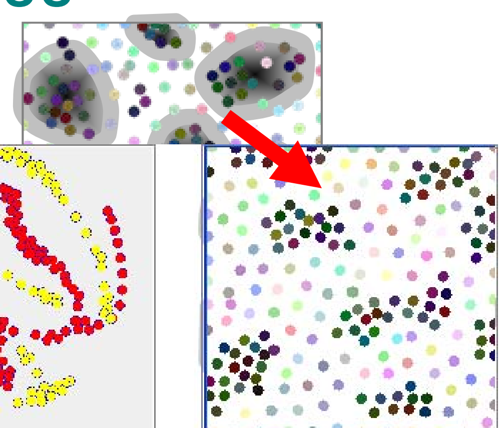


➢ Pattern formation that triggers motion

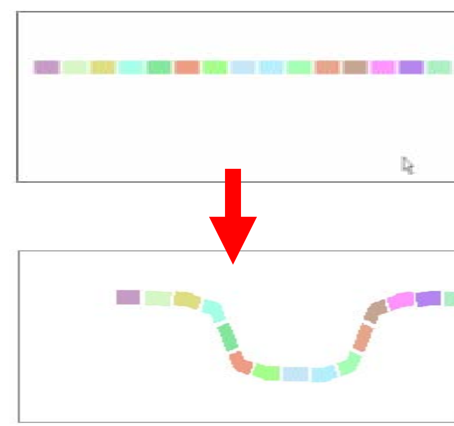


http://zool33.uni-graz.at/schmickl





Doursat



The self-made puzzle of embryogenesis

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Why multi-agent modeling?

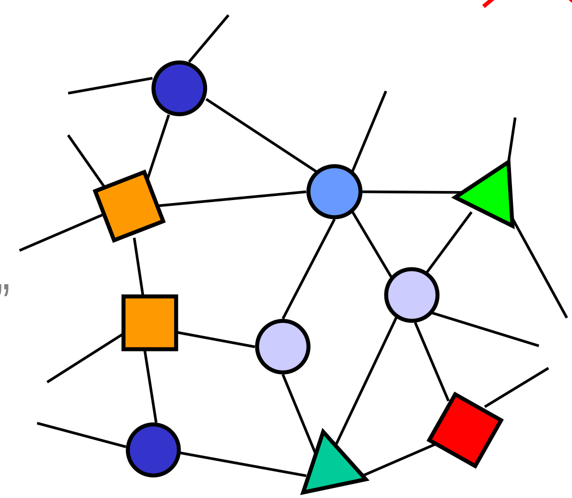
- Equations and laws can be hard or impossible to find...
  - ✓ *"The study of non-linear physics is like the study of non-elephant biology."* —Stanislaw Ulam
    - the physical world is a fundamentally *non-linear* and *out-of-equilibrium* process
    - focusing on linear approximations and stable points is missing the big picture in most cases
  - ✓ let's push this quip: *"The study of non-analytical complex systems is like the study of non-elephant biology."* —??
    - complex systems have their own "elephant" species, too: dynamical systems that can be described by diff. eqs or statistical laws
    - many real-world complex systems do not obey neat macroscopic laws

Why multi-agent modeling?

➢ Equations and laws can be hard or impossible to find in...

morphogenesis

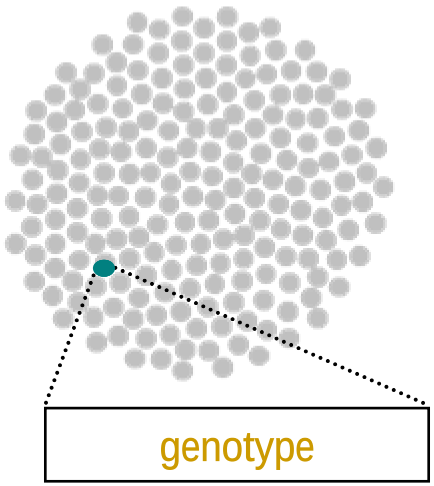
- ✓ systems that *no macroscopic quantity* suffices to explain ~~(ODE)~~
  - no law of “concentration”, “pressure”, etc.
  - even if global metrics can be found, they rarely obey a given equation or law
- ✓ systems that require a *non-Cartesian* decomposition of space ~~(PDE)~~
  - network of irregularly placed or mobile *agents*
- ✓ systems that contain *heterogeneity*
  - segmentation into different *types of agents*
  - at a fine grain, this would require a “patchwork” of regional equations
- ✓ systems that are dynamically *adaptive*
  - the topology and strength of the interactions depend on the short-term activity of the agents and long-term “fitness” of the system in its environment



Different approaches and families of models

➢ Biological, bio-inspired or artificial models

- ✓ focused on spatial differentiation patterns (little or no motion)
  - reaction-diffusion (PDEs, cellular automata)
  - gene networks (Boolean or concentrations) on a fixed lattice
  - “amorphous computing”
- ✓ focused on motion (little or no patterning)
  - Cellular Potts Model (on predefined cell types)
  - aggregation, self-assembly
  - collective motion, flocking, cellular sorting



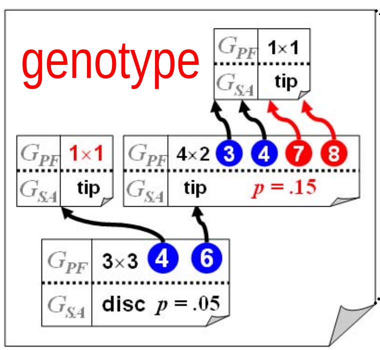
a combination that is still rare ; but see Hogeweg / Salazar-Ciudad / Mjolsness..

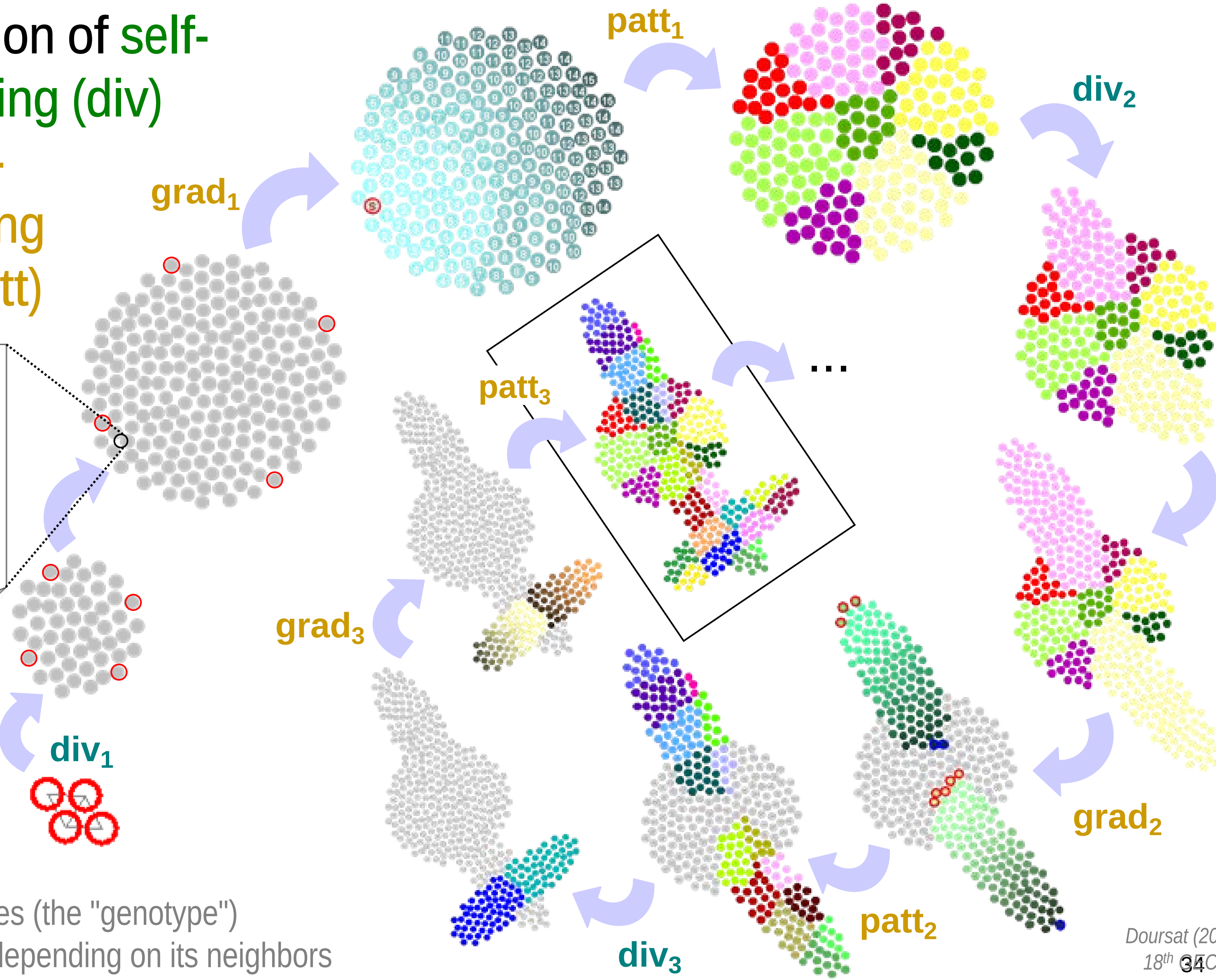
- ✓ at different scales
  - macroscopic models (densities, differential geometry) → no individual information
  - mesoscopic models (cellular centers, Potts) → no membrane geometry or nuclei
  - microscopic models (elastic polyedra, drop models) → cellular deformations

Artificial Embryogenesis

Capturing the essence of embryogenesis in an Artificial Life agent model

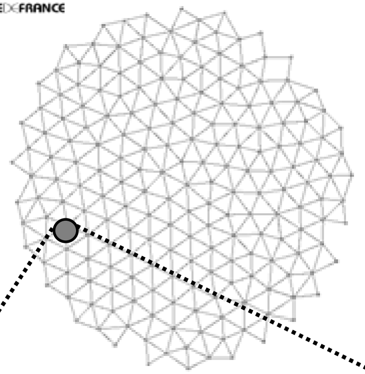
- Alternation of self-positioning (div) and self-identifying (grad/patt)





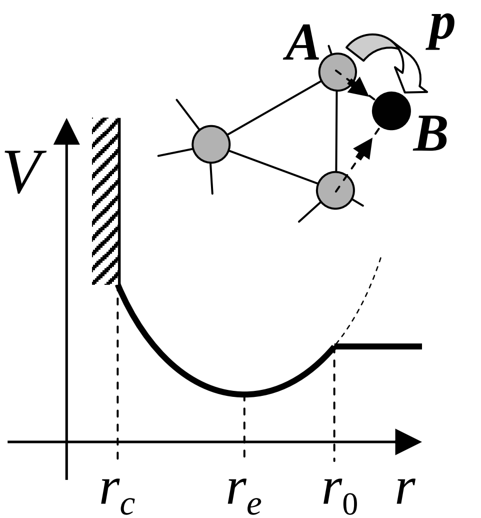
each agent
follows the same set
of self-architecting rules (the "genotype")
but reacts differently depending on its neighbors

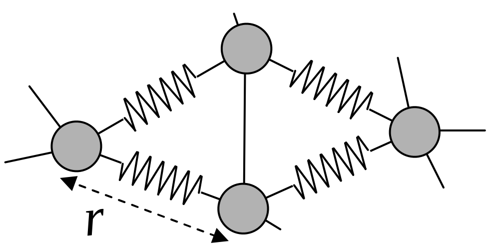
div

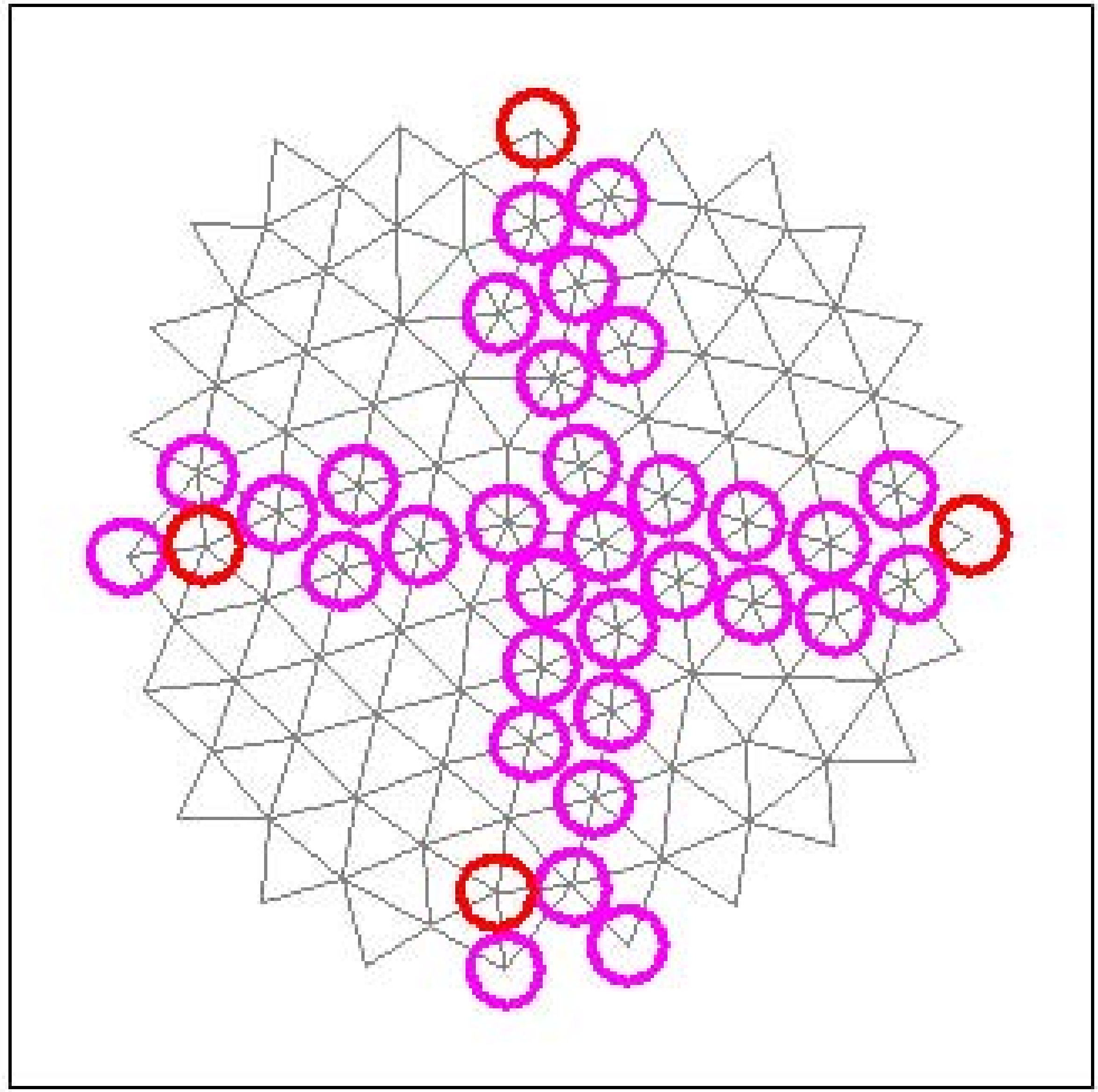


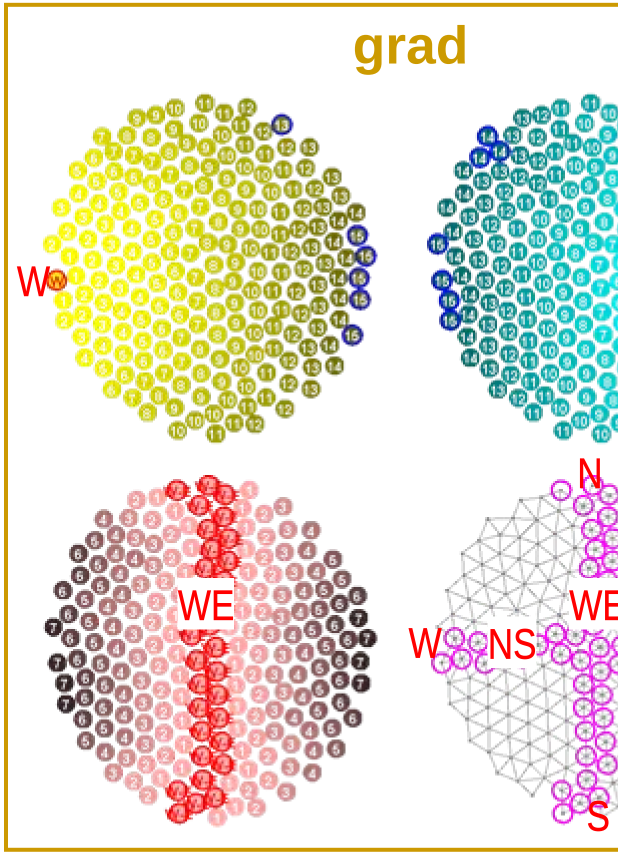
$G_{SA:}\ r_c < r_e = 1 << r_0$

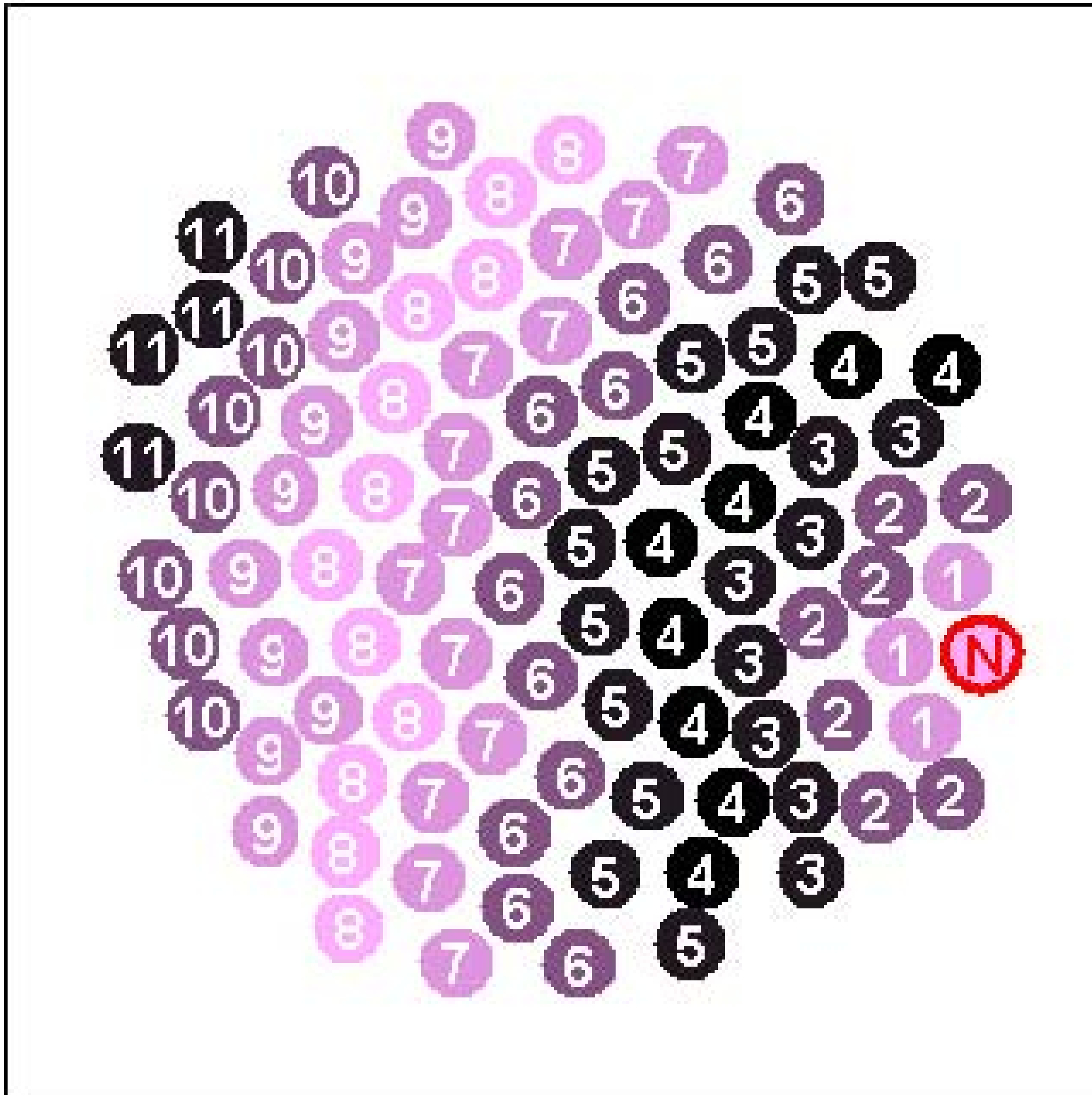
$p = 0.05$

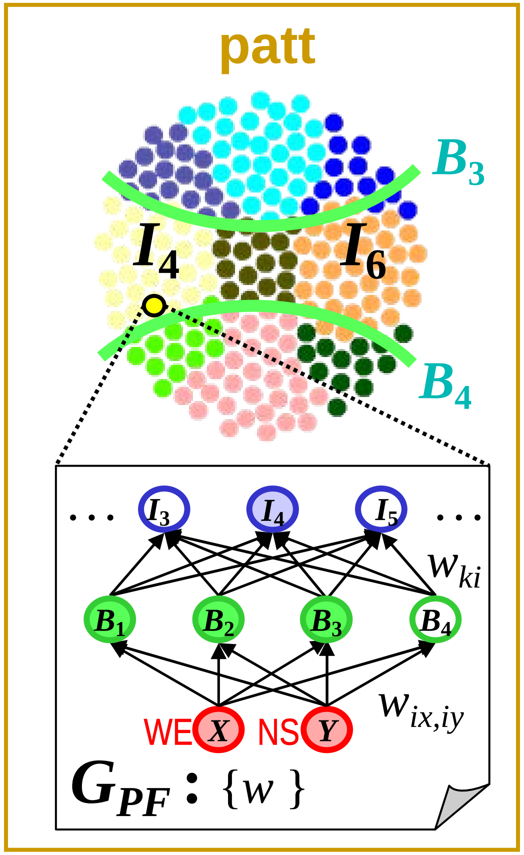




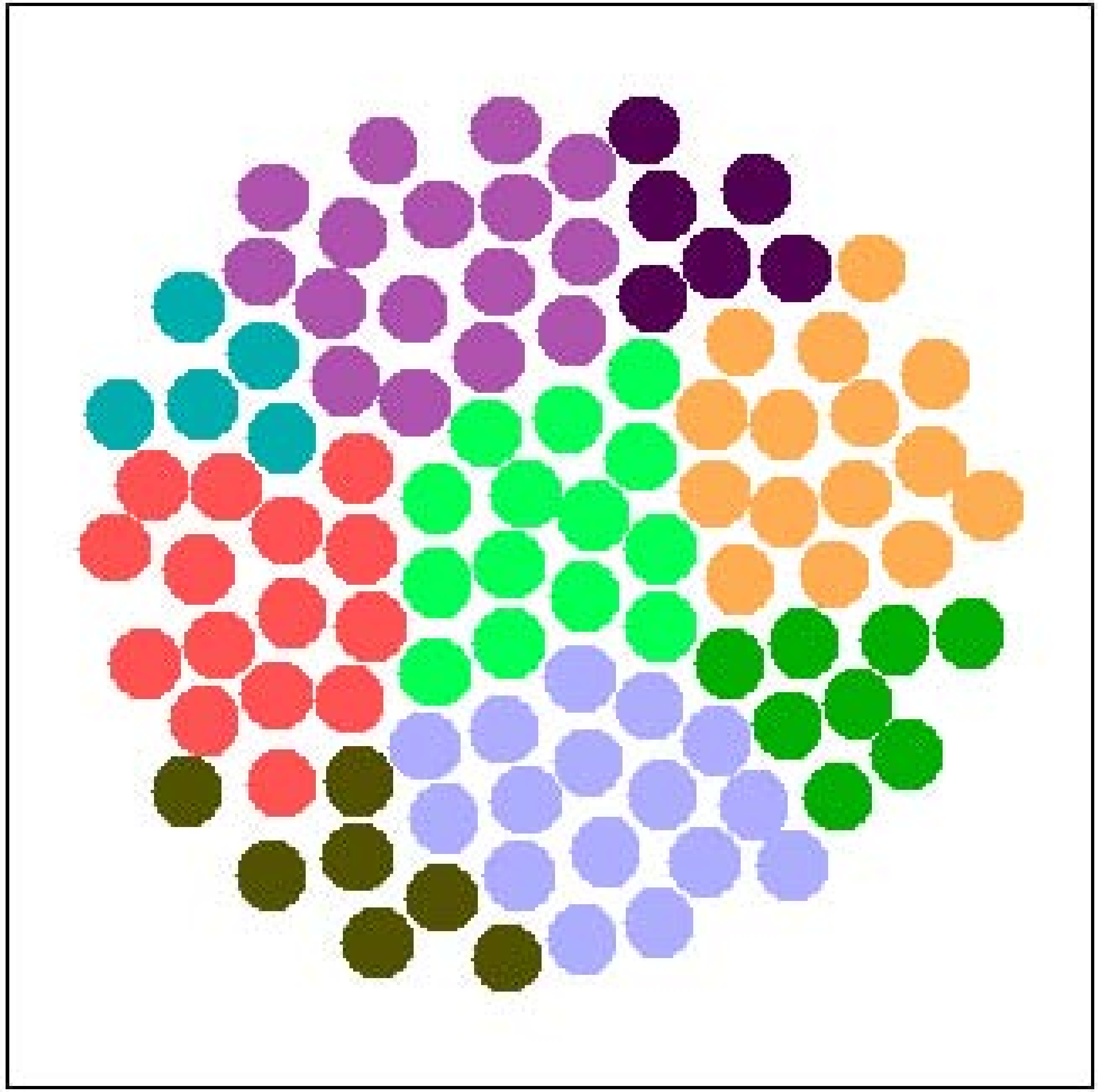


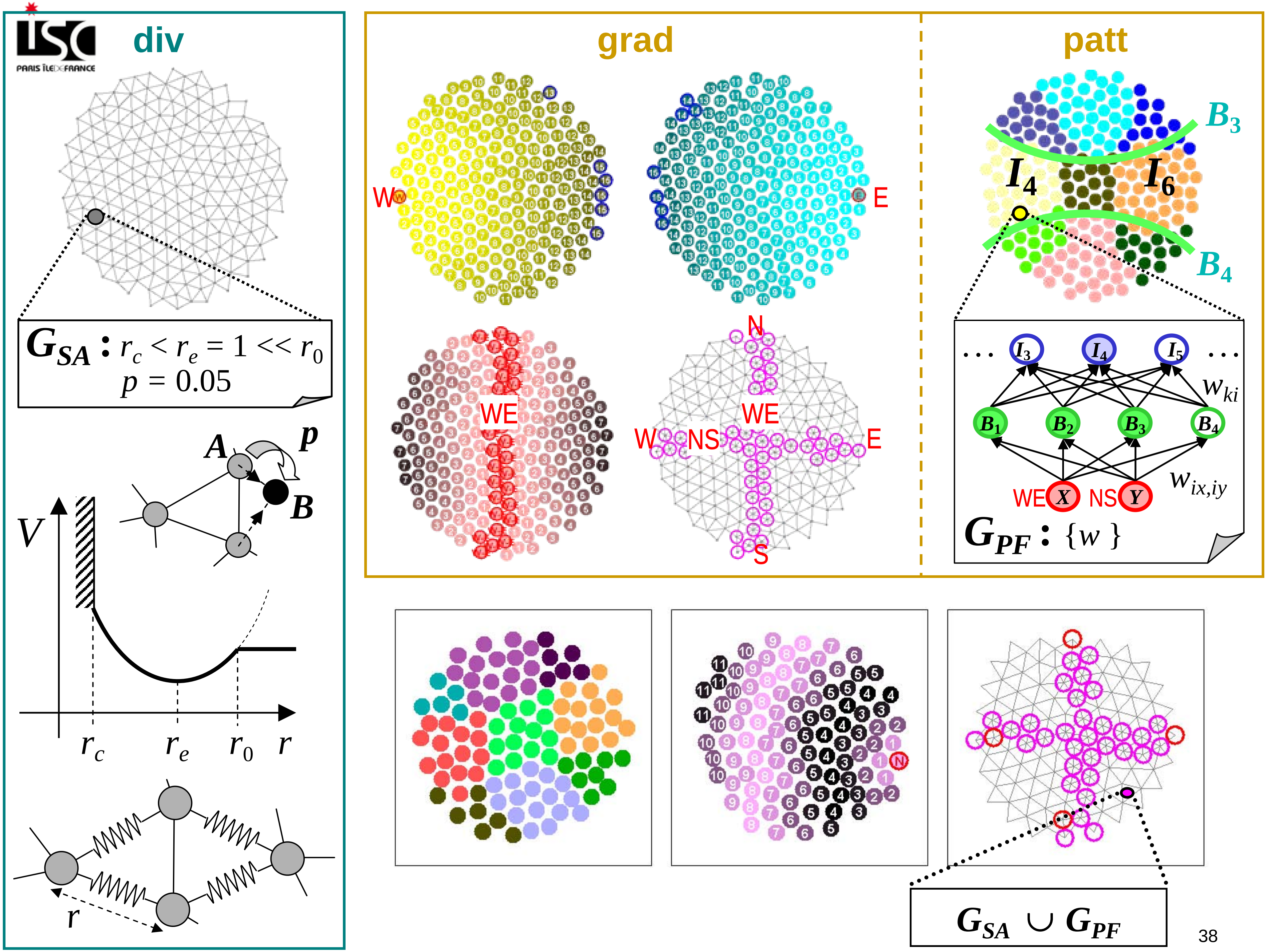

grad
W
N
WE
W
NS
WE
S


N



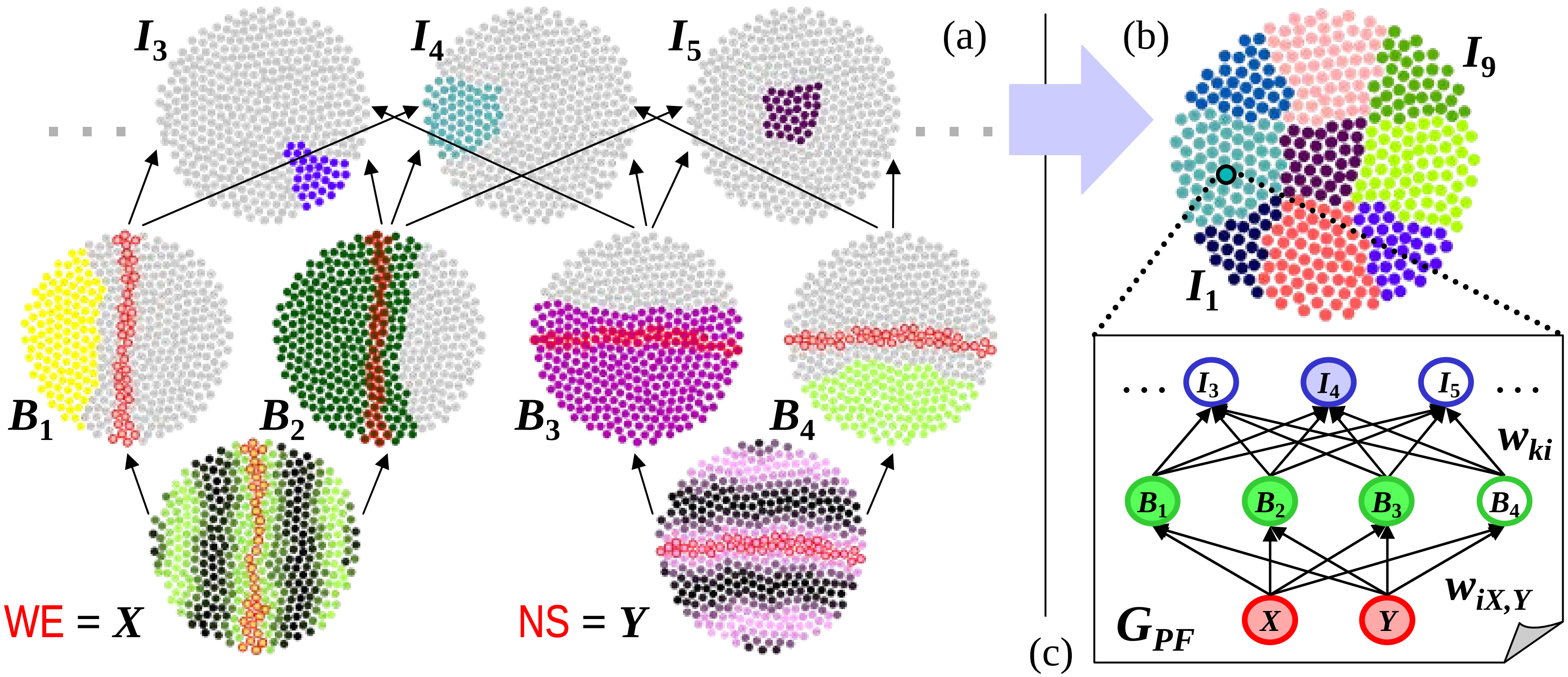
patt
B_3
I_4
I_6
B_4
I_3
I_4
I_5
w_{ki}
B_1
B_2
B_3
B_4
$w_{ix,iy}$
WE
X
NS
Y
G_{PF} : {w }




div
G_{SA} : $r_c < r_e = 1 << r_0$
$p = 0.05$
A
B
p
V
r_c
r_e
r_0
r
r
grad
W
E
WE
N
S
W
NS
WE
E
patt
B_3
B_4
I_4
I_6
I_3
I_4
I_5
B_1
B_2
B_3
B_4
w_{ki}
$w_{ix,iy}$
WE
X
NS
Y
G_{PF} : {w}
$G_{SA} \cup G_{PF}$

Artificial Embryogenesis

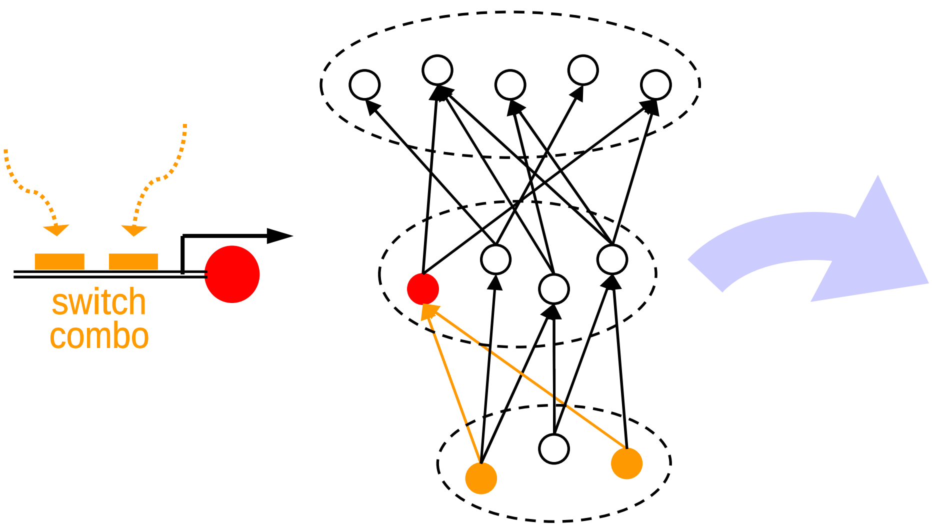
- Programmed patterning (patt): the hidden embryo atlas
  a) same swarm in different colormaps to visualize the agents' internal patterning variables X, Y, B_i and I_k (virtual *in situ hybridization)*
  b) consolidated view of all identity regions I_k for $k = 1...9$
  c) gene regulatory network used 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.

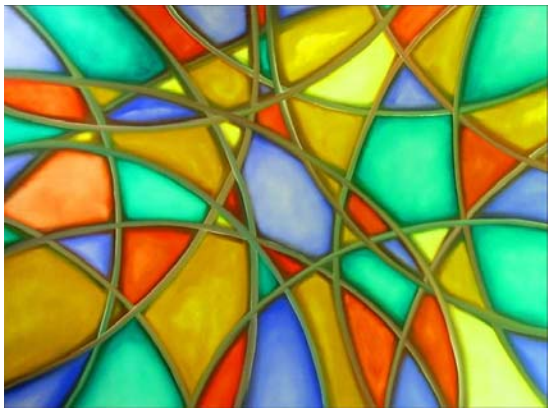


From feedforward to recurrent gene regulation

➢ Summary: simple feedforward hypothesis

- ✓ developmental genes are broadly organized in tiers, or "generations": earlier genes map the way for later genes
- ✓ gene expression propagates in a directed fashion: first, positional morphogens create domains, then domains intersect

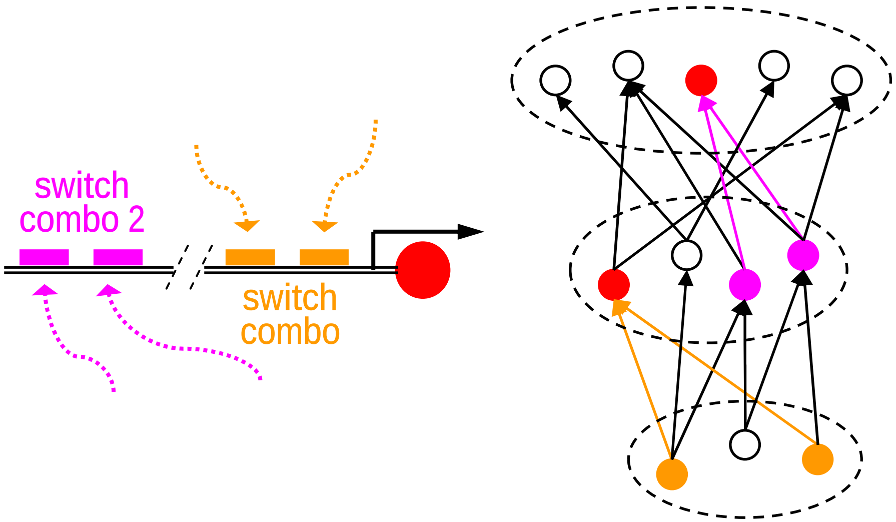


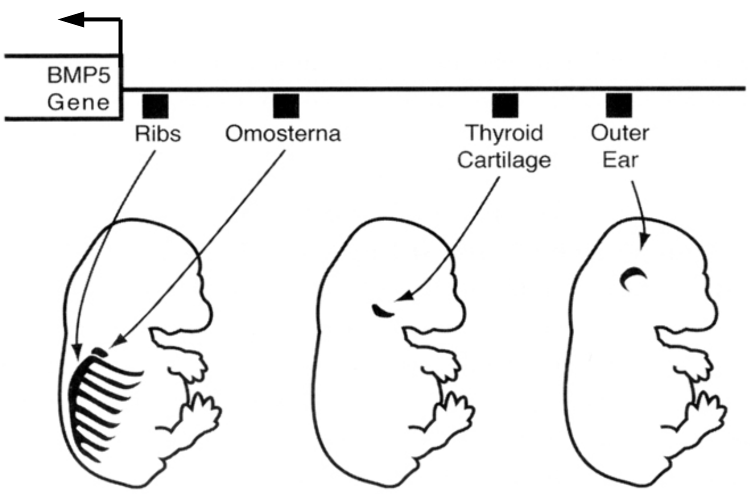


From feedforward to recurrent gene regulation

➢ Toolkit genes are often multivalent

- ✓ exception to the feedforward paradigm: “toolkit” genes that are reused at different stages and different places in the organism
- ✓ however, a toolkit gene is triggered by different switch combos, which can be represented by duplicate nodes in different tiers



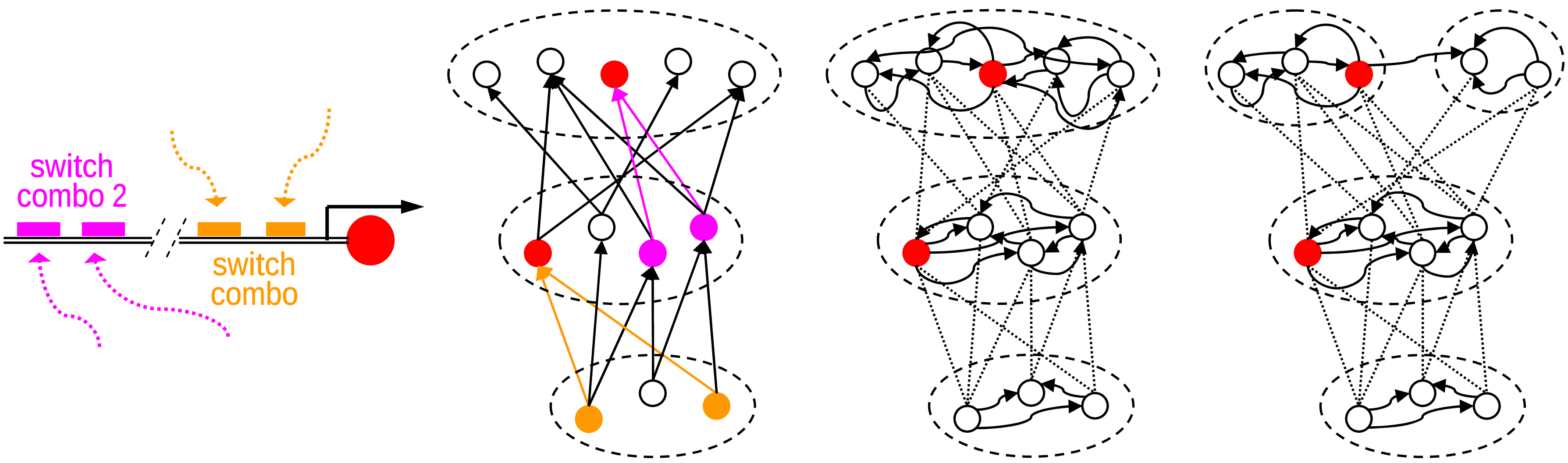


after David Kingsley, in Carroll, S. B. (2005)
Endless Forms Most Beautiful, p125

From feedforward to recurrent gene regulation

➢ More realistic variants of GRNs

- ✓ add recurrent links within tiers $\rightarrow$ domains are not established independently but influence and sharpen each other
- ✓ subdivide tiers into subnetworks $\rightarrow$ this creates **modules** that can be reused and starts a hierarchical architecture



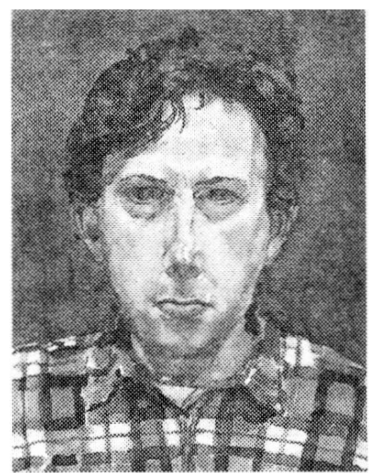
Artificial Embryogenesis

➢ Morphological refinement by iterative growth

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

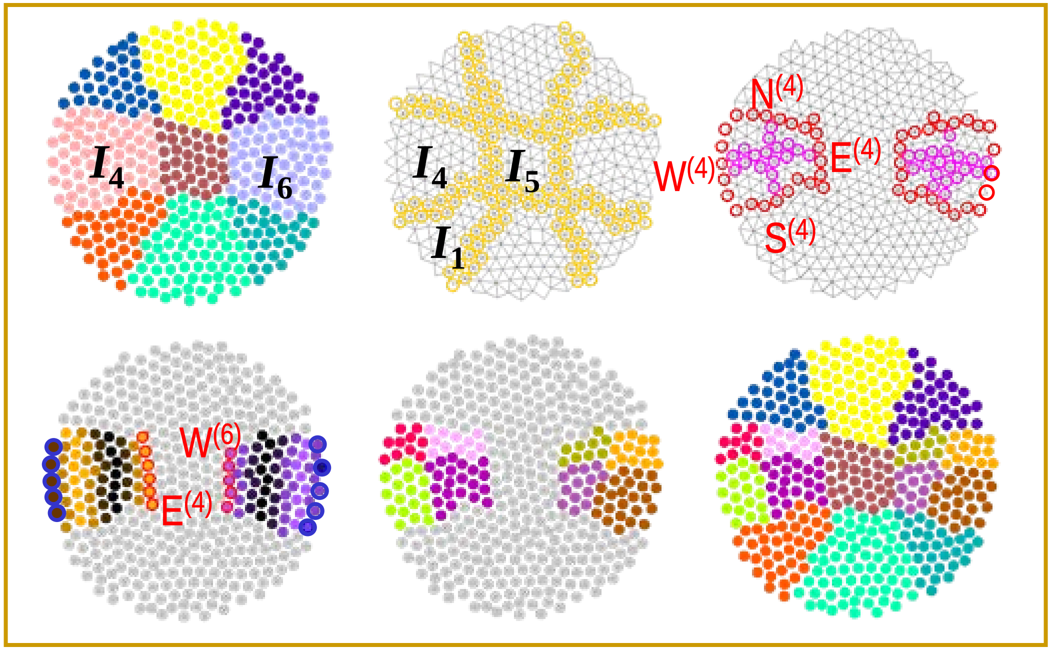
  

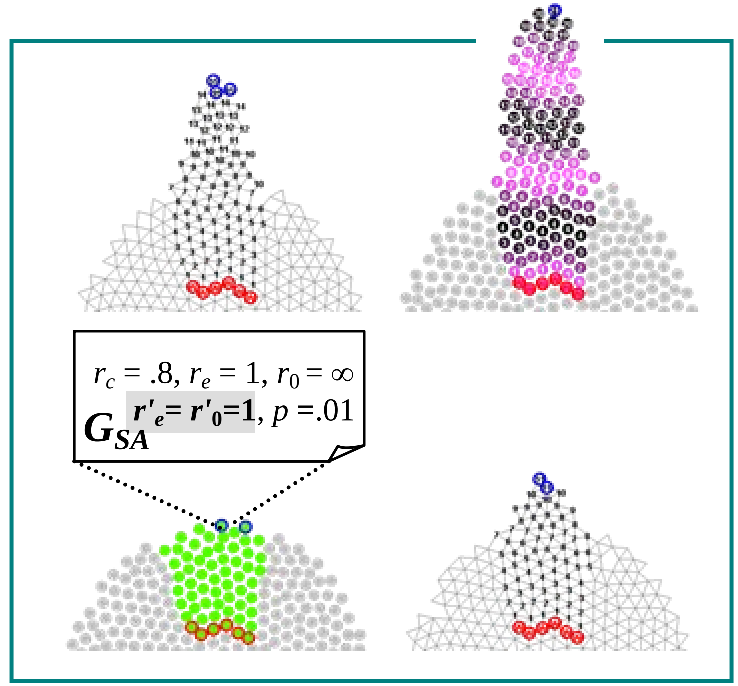
- ✓ . . . while, at the same time, the canvas grows

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

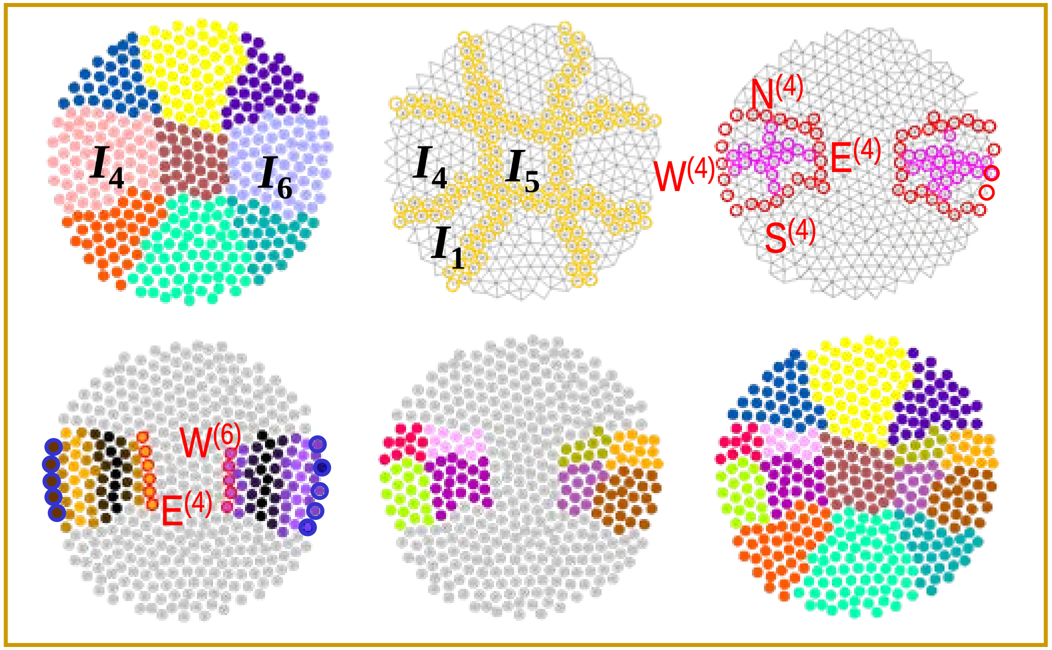
Artificial Embryogenesis

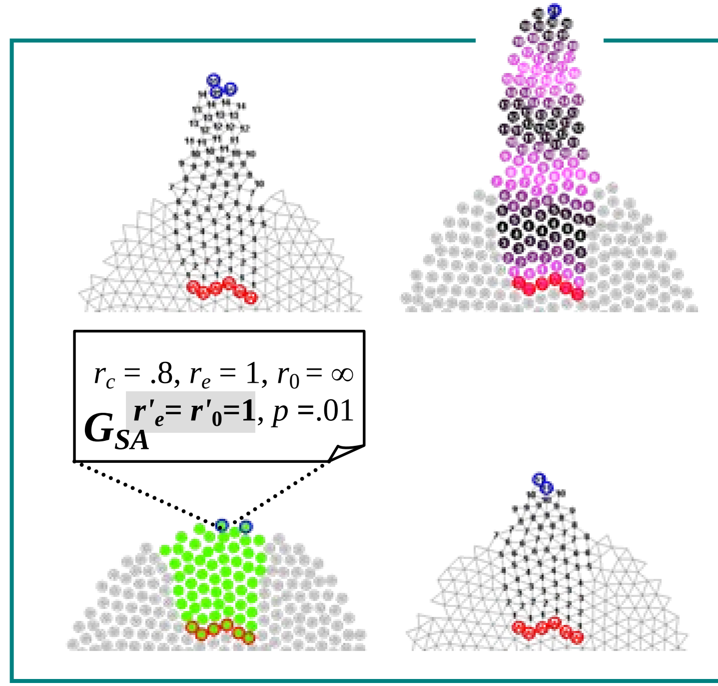


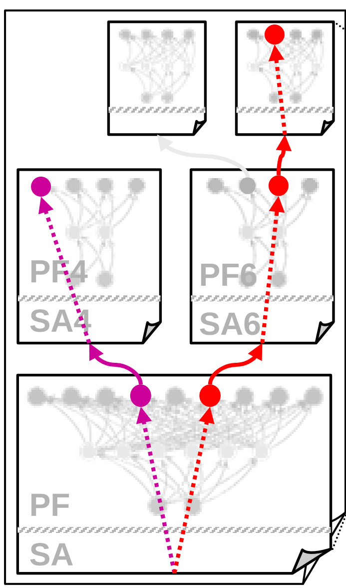


Doursat
(Alife XI, 2008)
(GECCO 2009)

Artificial Embryogenesis







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

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

Doursat (2008) ALIFE XI

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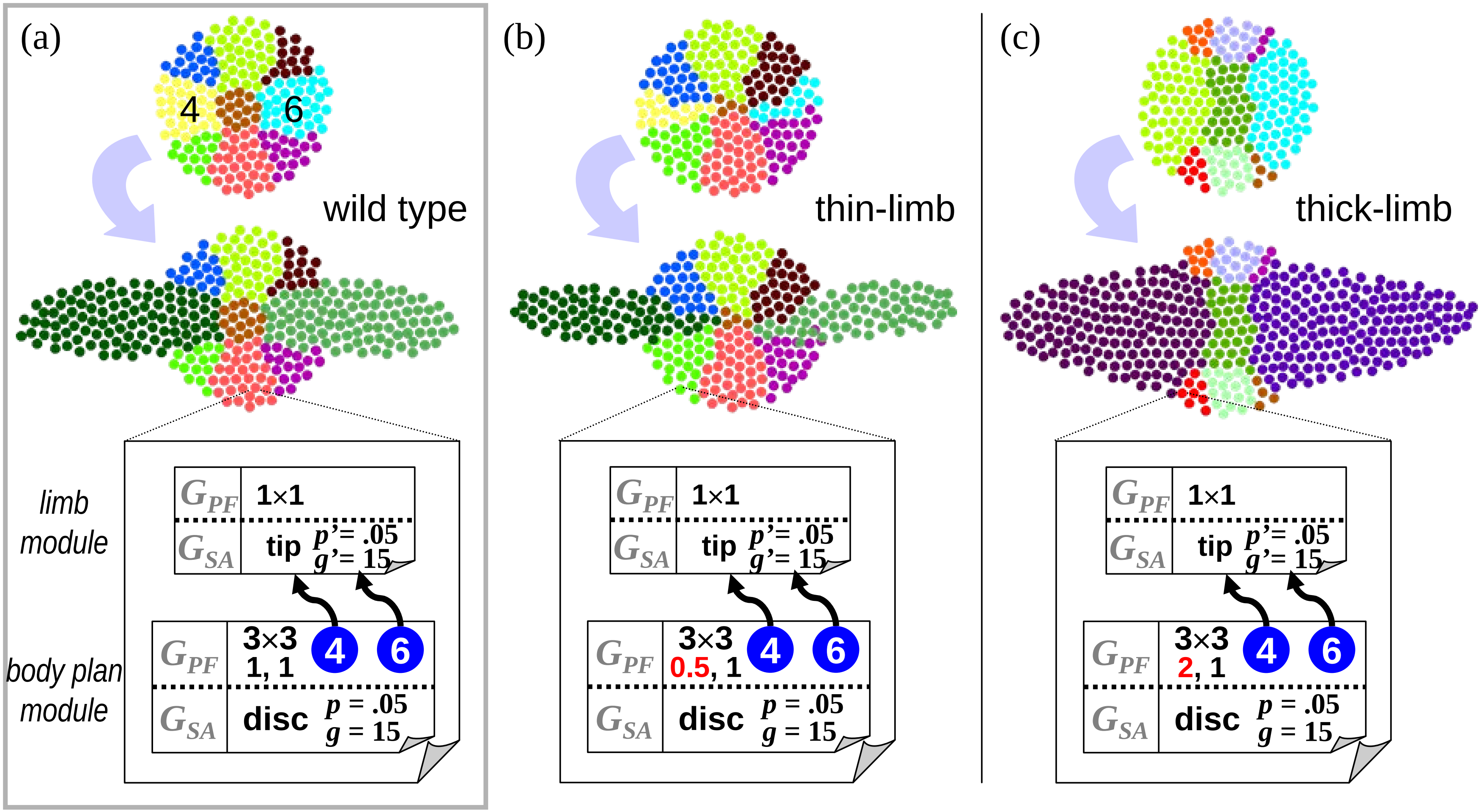
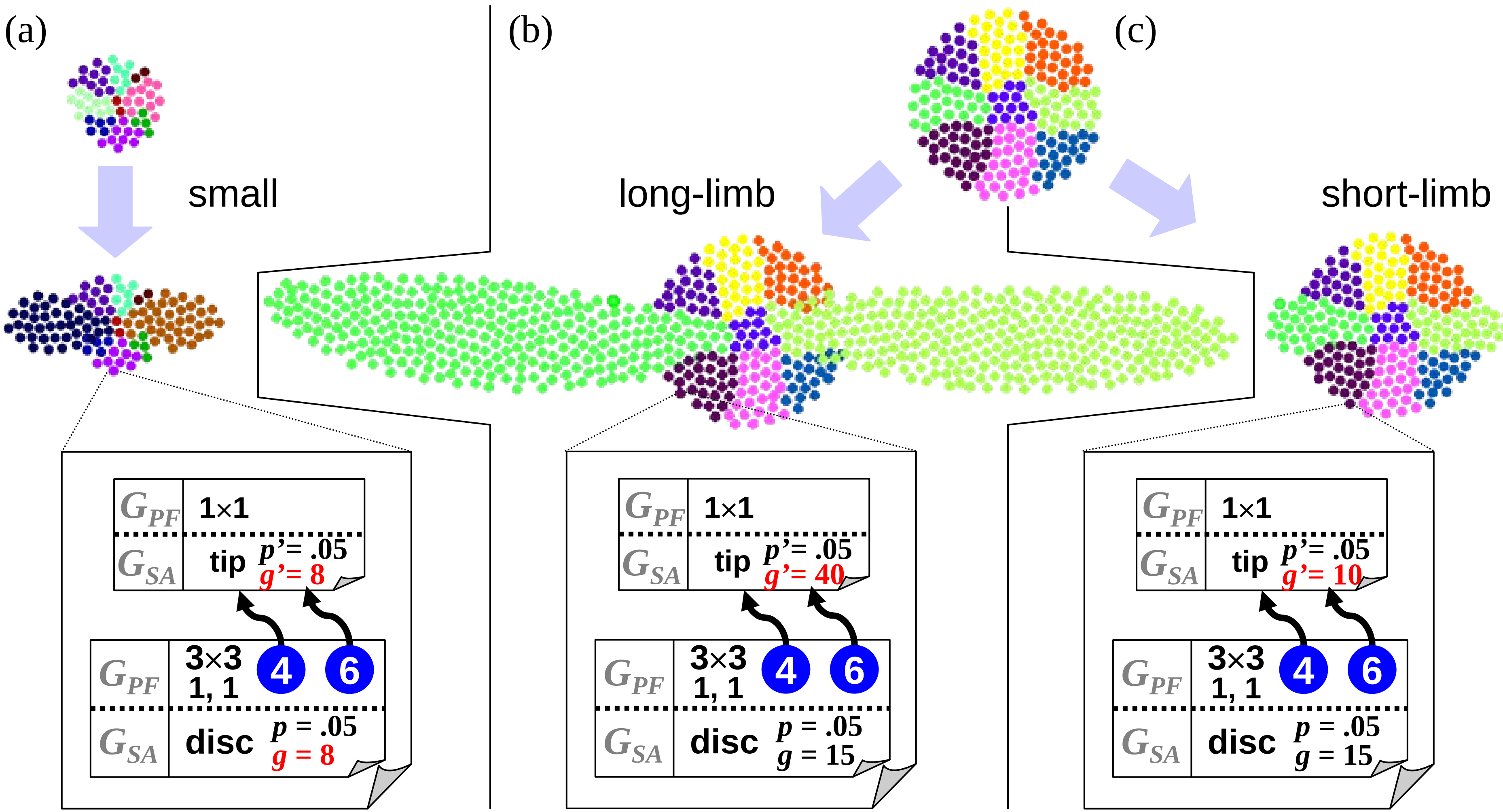
Artificial Evo-Devo

➢ Quantitative mutations: limb thickness



Artificial Evo-Devo

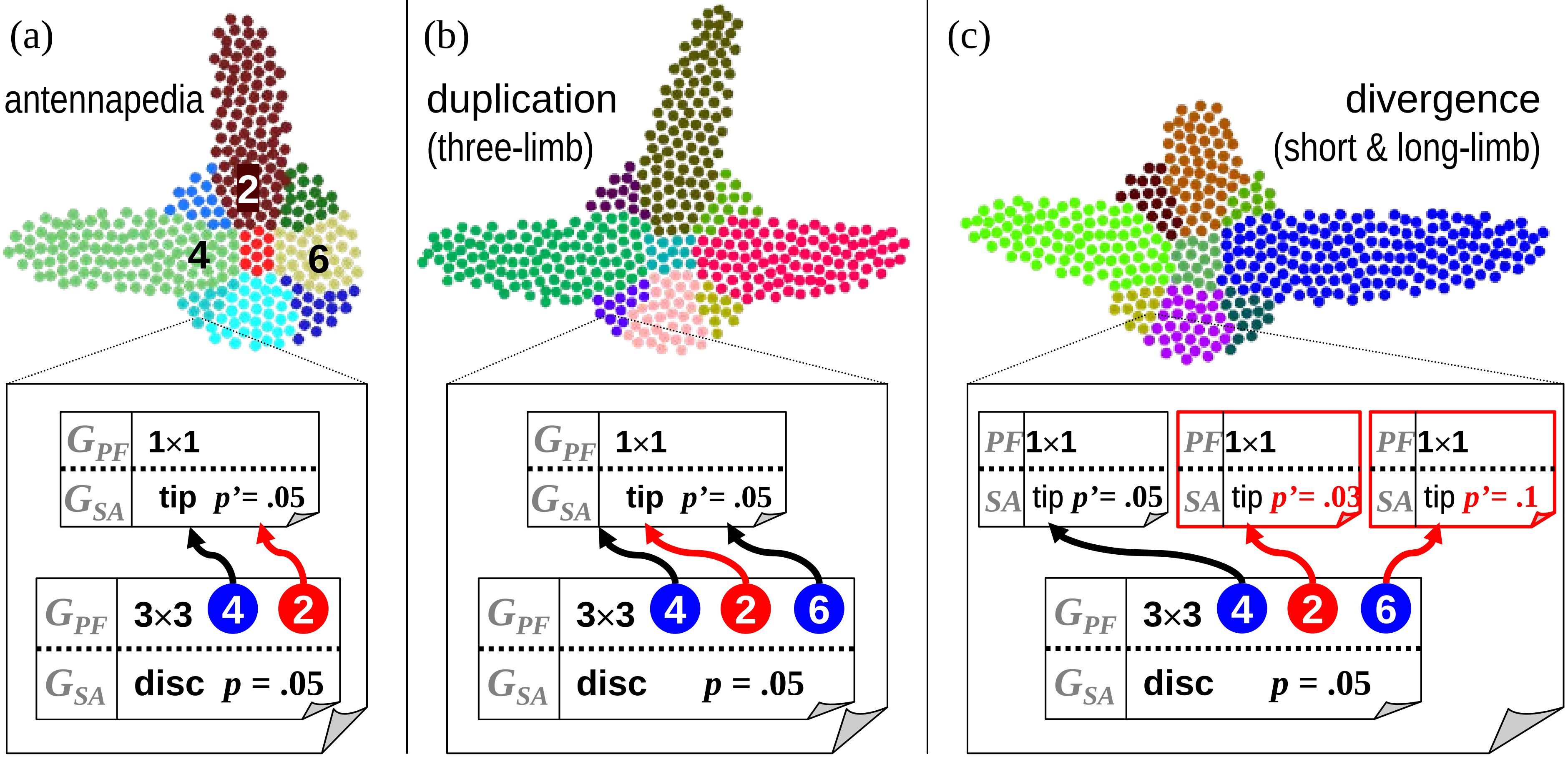
➢ Quantitative mutations: body size and limb length



Artificial Evo-Devo

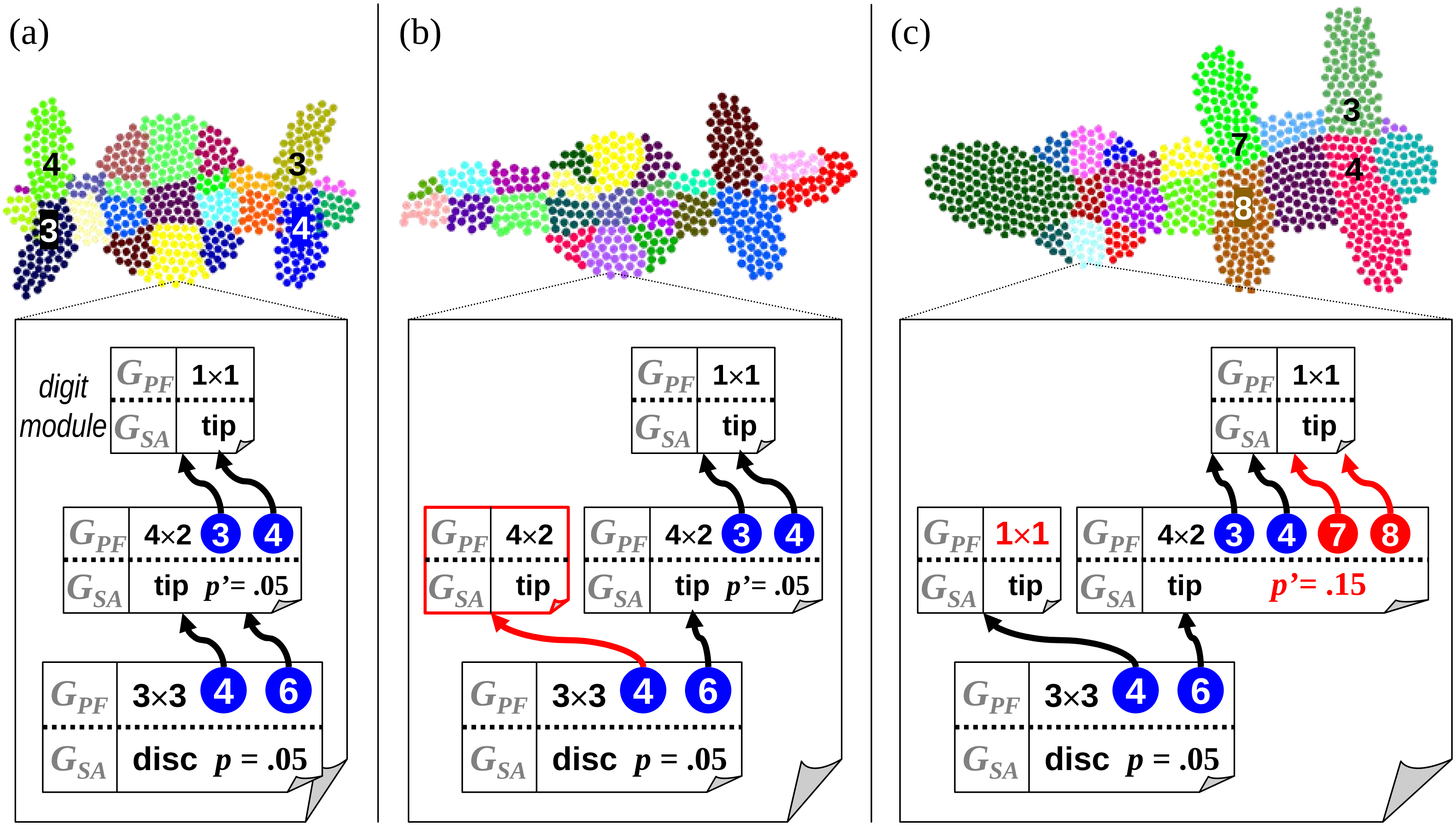
➢ Qualitative mutations: limb position and differentiation

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



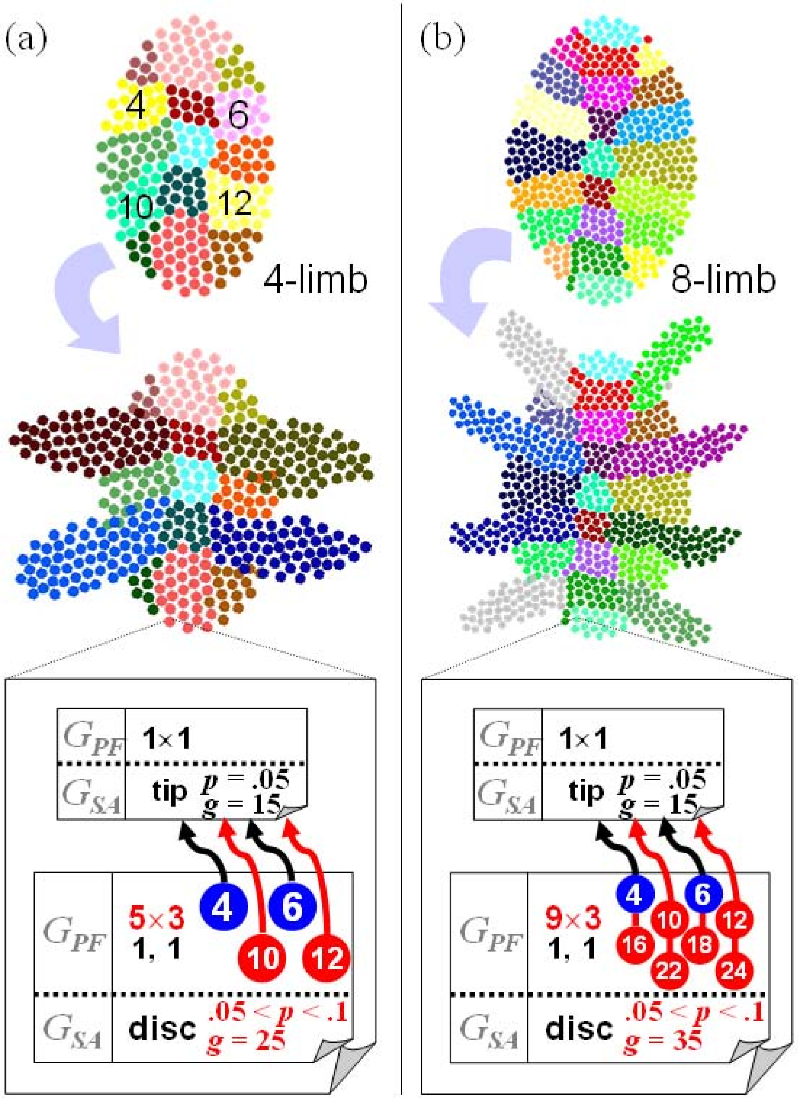
Artificial Evo-Devo

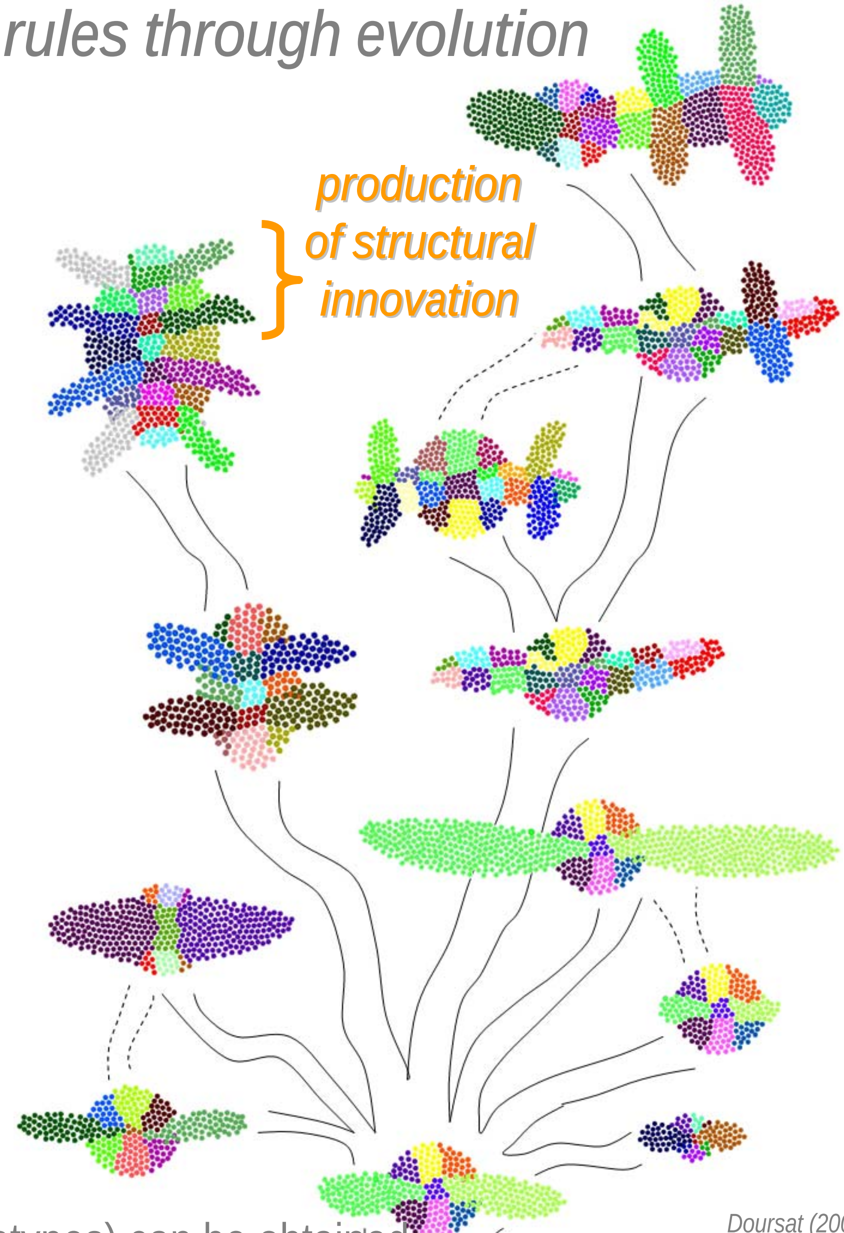
- Qualitative mutations: 3rd-level digits



Artificial Evo-Devo

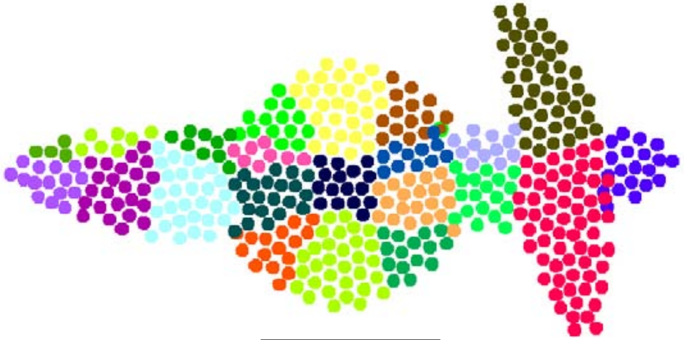
Changing the agents' self-architecting rules through evolution





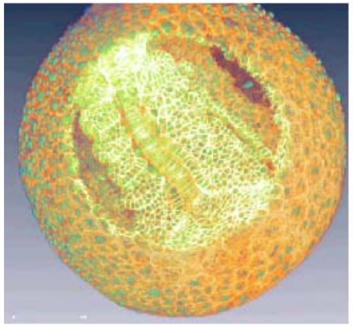
by tinkering with the genotype, new architectures (phenotypes) can be obtained

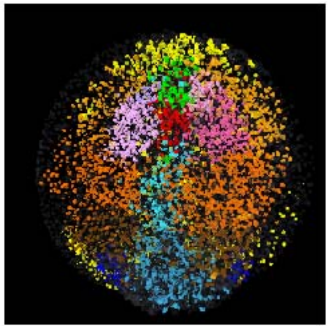
Toward More Realistic Biomodeling



top-down, abstract,
heuristic approach

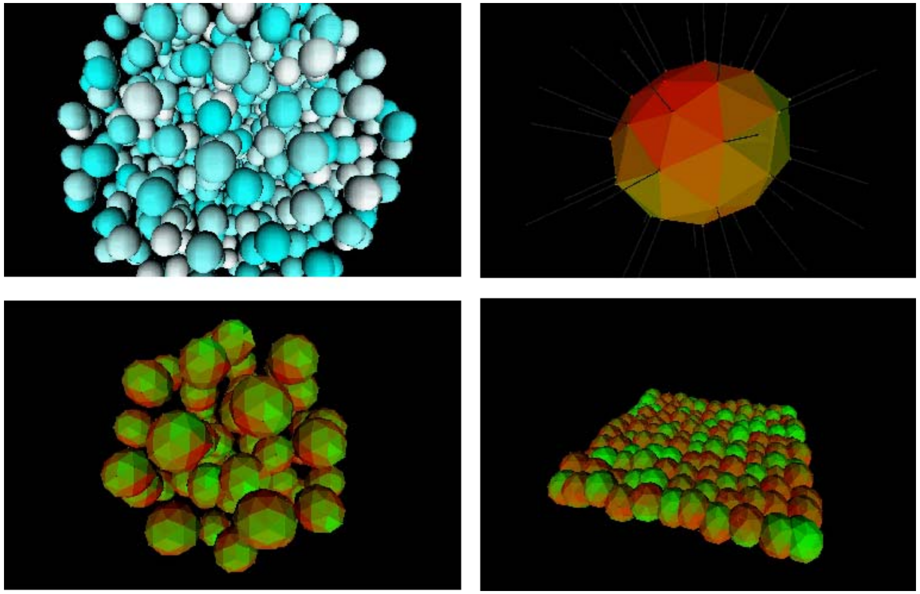
bottom-up, data-driven,
induction approach





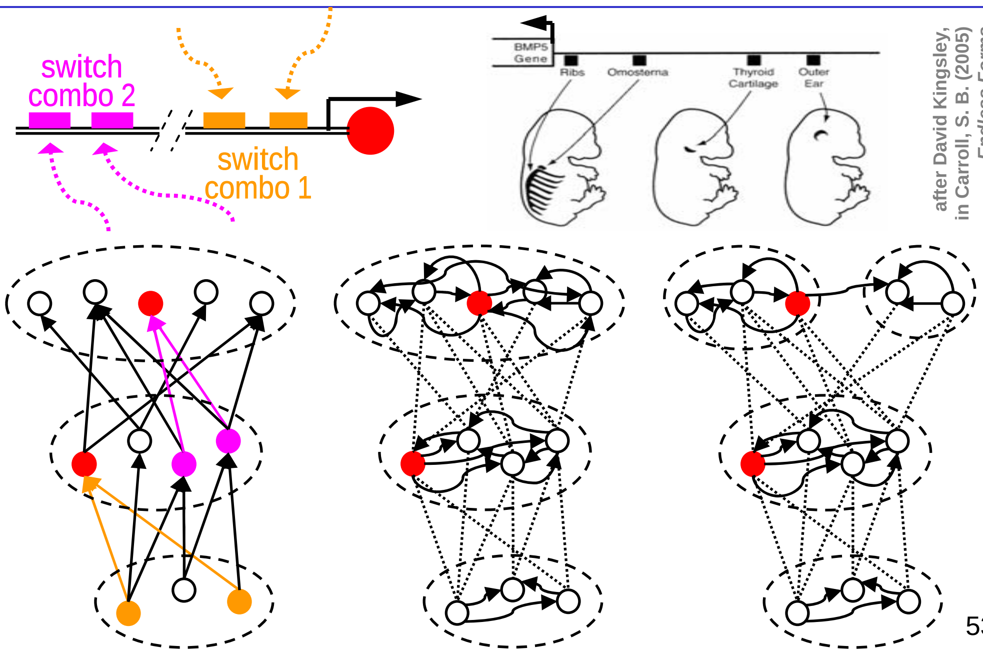
Toward More Realistic Biomodeling

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



(Delile, Doursat, Peyrieras)

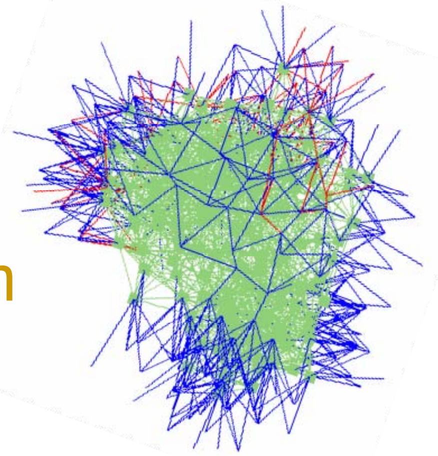
- **Better gene regulation**
  - ✓ recurrent links
  - ✓ gene reuse
  - ✓ kinetic reaction ODEs
  - ✓ attractor dynamics

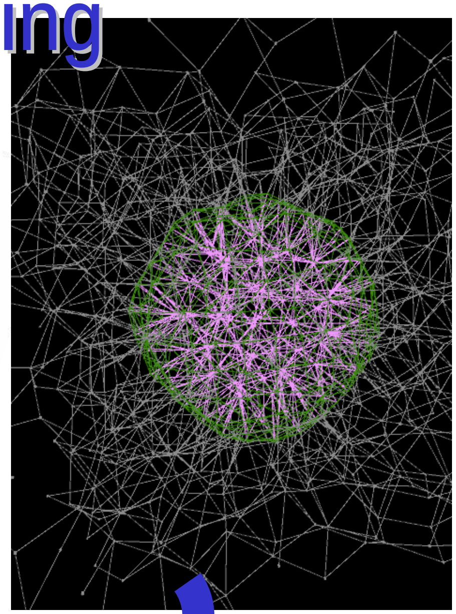


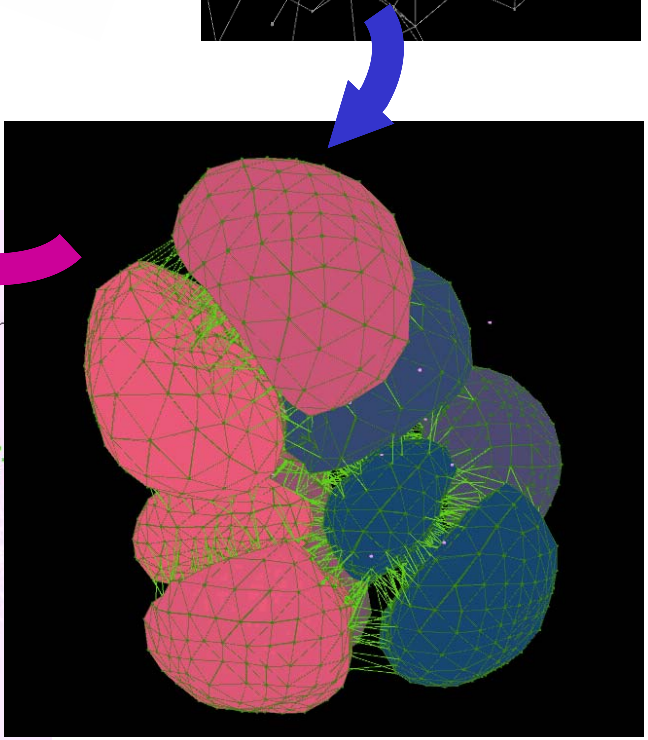
after David Kingsley, in Carroll, S. B. (2005) *Endless Forms Most Beautiful*, p125

Toward More Realistic Biomodeling

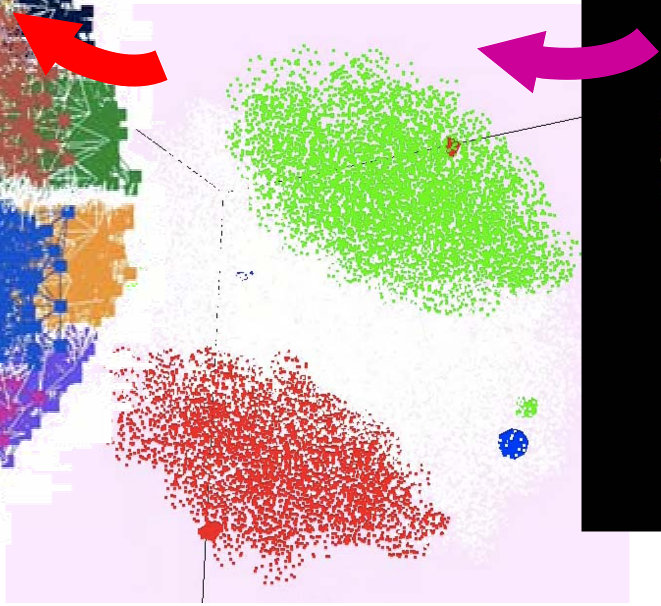
- Latest progress
  - ✓ 3D particle-based mechanics
  - ✓ kinetic-based gene regulation

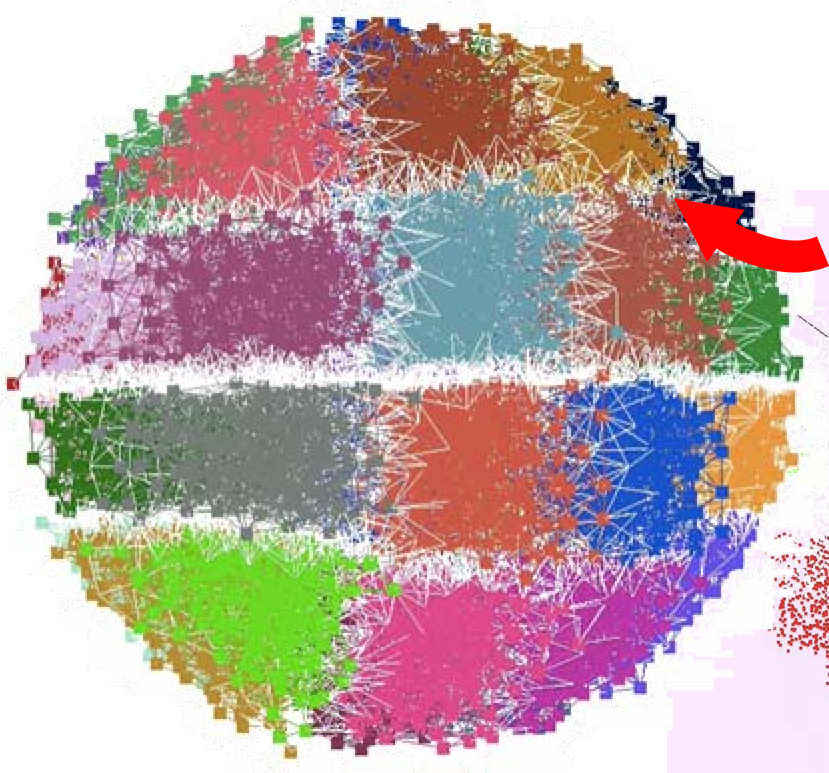






simulations by
Julien Delile





The self-made puzzle of embryogenesis

1. Self-organized and structured systems

2. A two-side challenge: heterogeneous motion / moving patterns

3. Artificial Multi-Agent Embryogenesis

4. Artificial Evo-Devo & Future Work