VUB AI-Lab / ULB IRIDIA, Winter 2012
"Current Trends in Artificial Intelligence" Course Series
Fall 2011

Complex Systems, Bio-Inspiration and Morphogenetic Engineering:

New Avenues Toward Self-Organized Architecture

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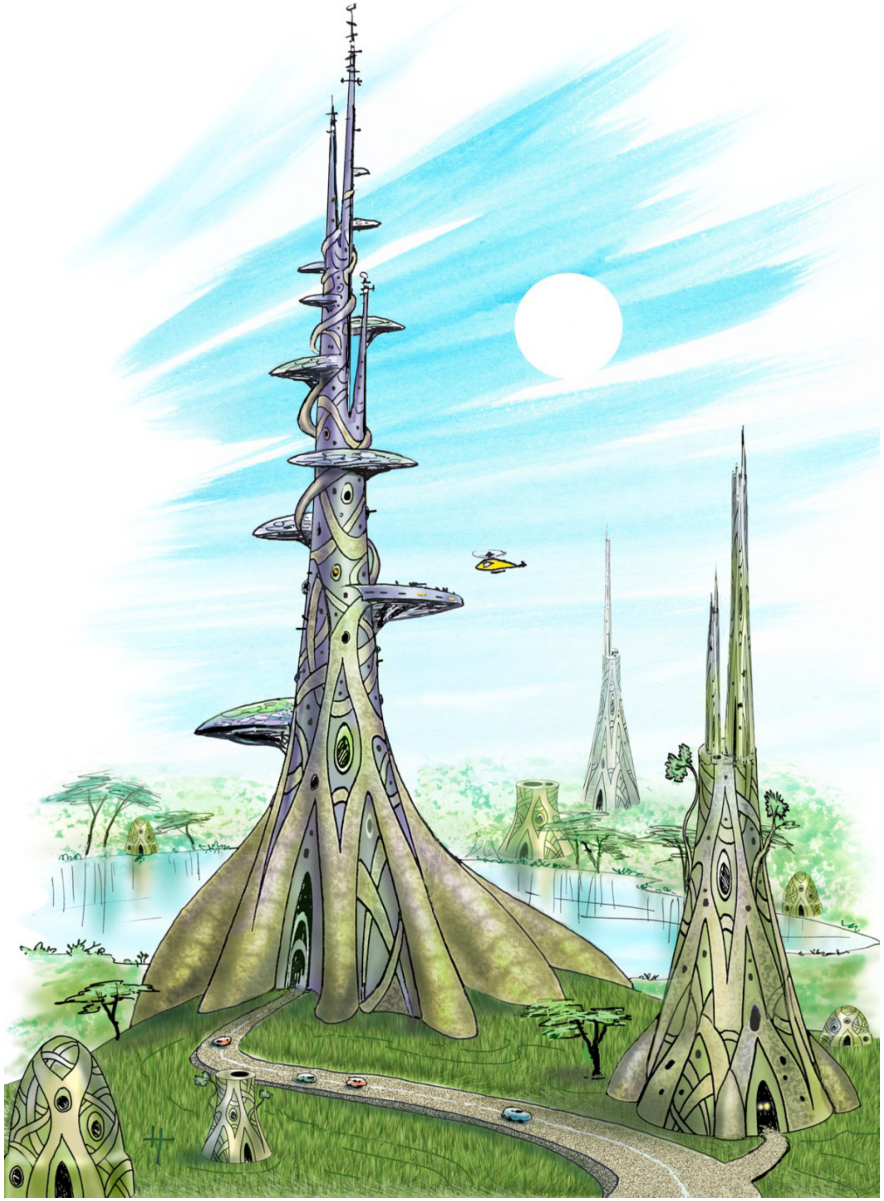
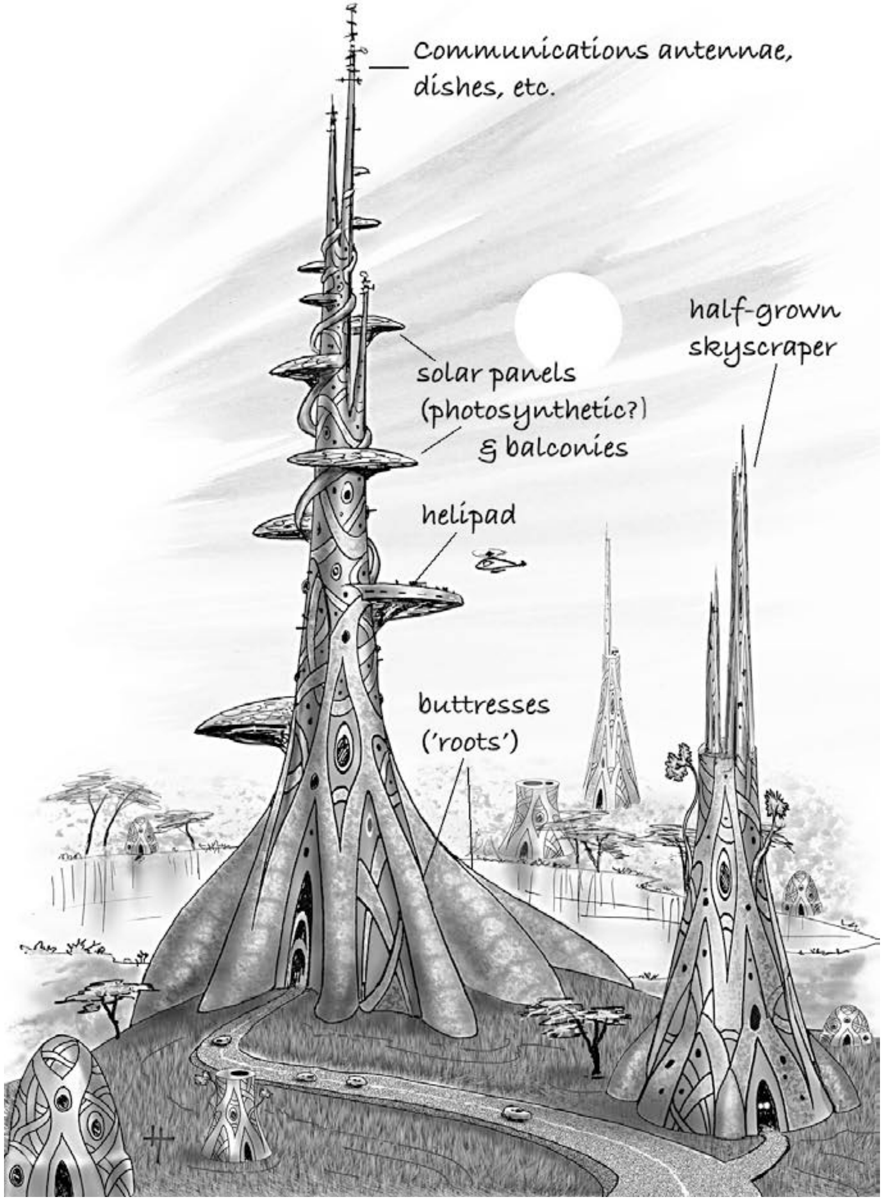
PARIS ÎLE DE FRANCE

grupo de estudios en biomimética





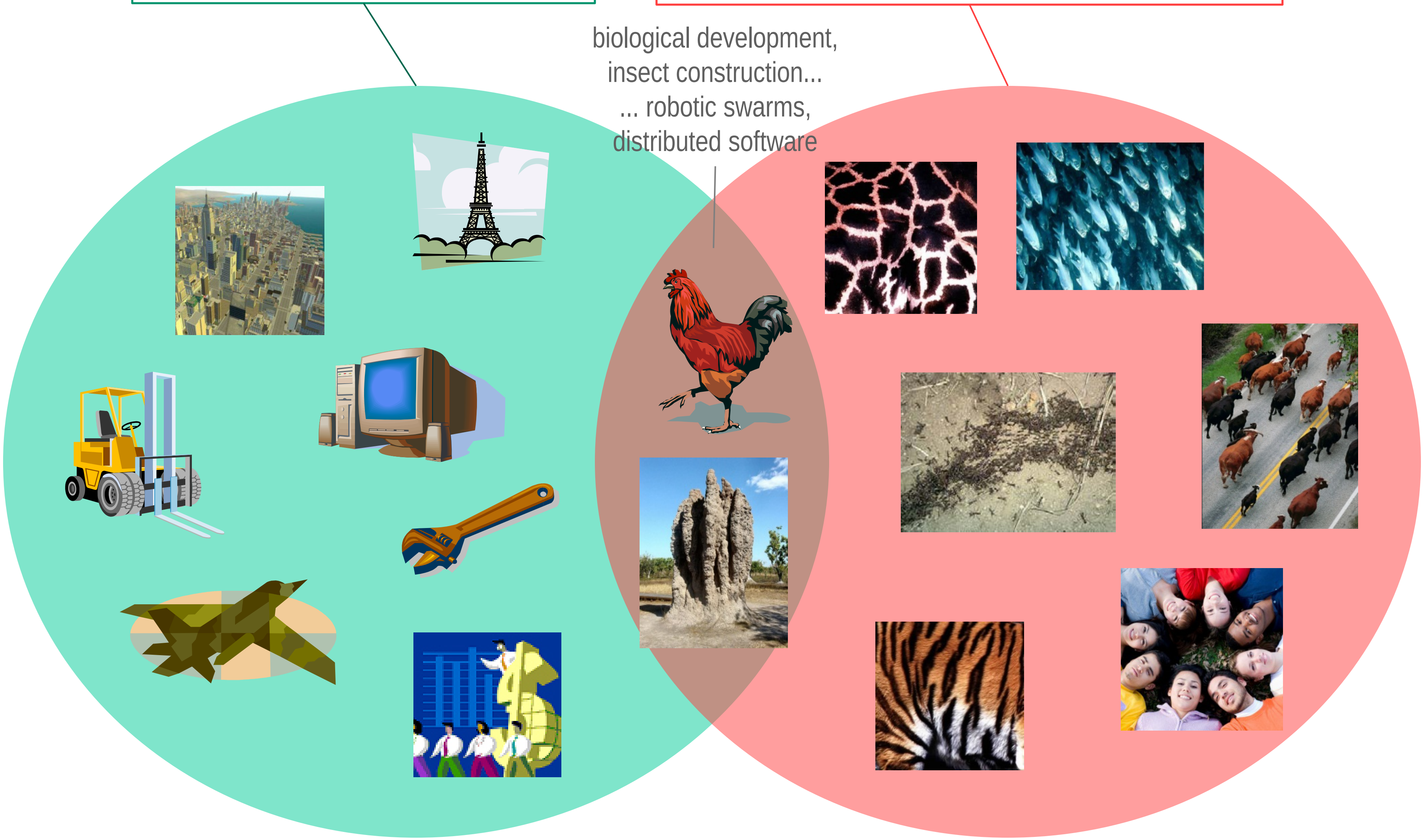
Project "GroCyPhy": Growing Cyber-Physical Systems (S. Stepney, J. Miller et al., York)

Artist's impression of a garden of fully grown, growing, and pruned skyscrapers

SYMBRION: Symbiotic Evolutionary Robot Organisms
(S. Kernbach, T. Schmickl, A. Winfield et al.)

SWARMORPH: Morphogenesis with Self-Assembling Robots
(M. Dorigo, R. O’Grady et al., IRIDIA, ULB)

ARCHITECTURE & SELF-ORGANIZATION



planned actitivities: civil engineering, mechanical engineering, electrical engineering, computer engineering, companies, (building) architecture, enterprise architecture, urbanism

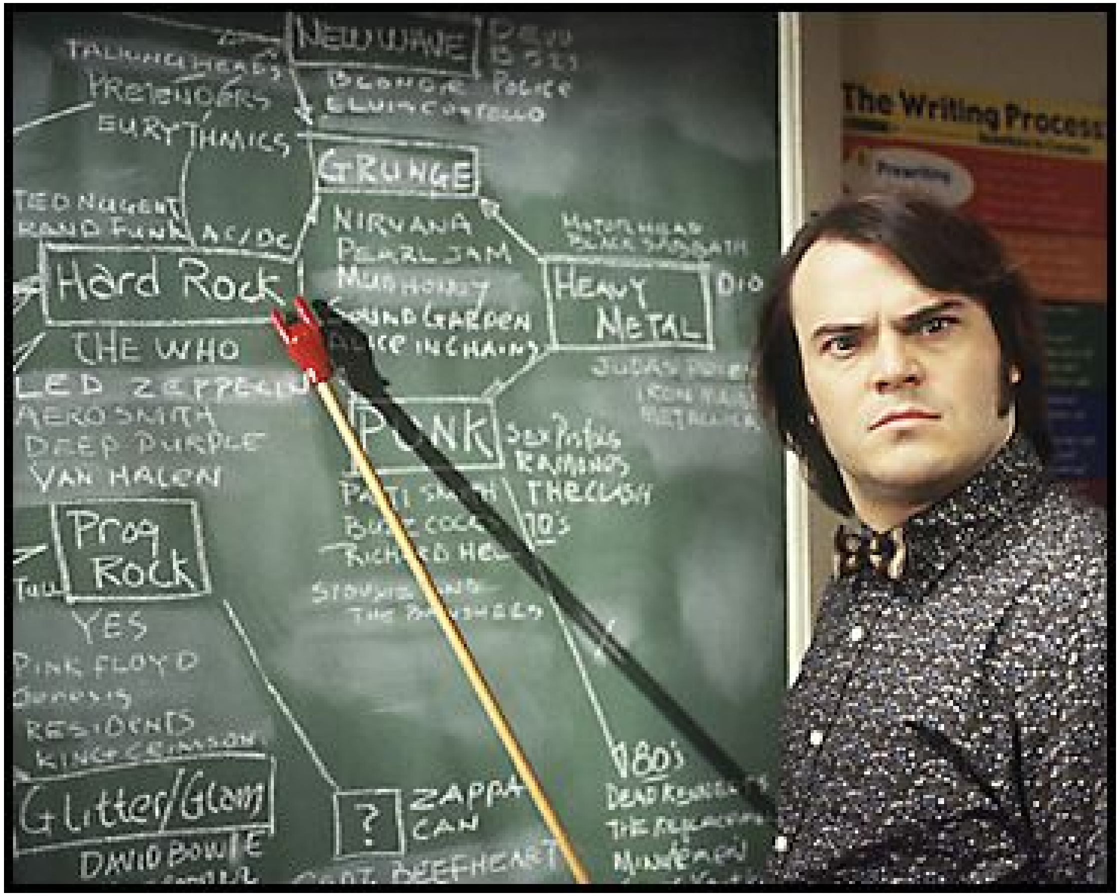
collective motion, swarm intelligence, pattern formation, complex (social) networks, spatial communities

1. What are Complex Systems?

- Decentralization
- Emergence
- Self-organization

1. What are Complex Systems?

- Any ideas?



The School of Rock (2003)
Jack Black, Paramount Pictures

1. What are Complex Systems?

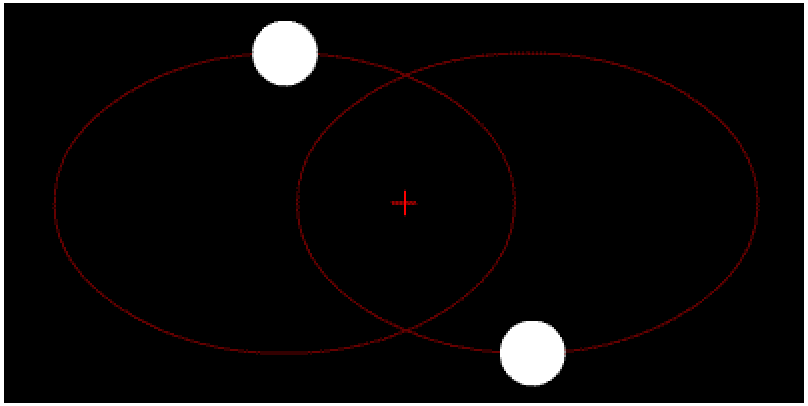
➤ A simplified classification of complex systems

Category	*Agents / Parts*	*Local Rules*	*Emergent Behavior*	*A "Complex System"?*
	few	*simple*	*“simple”*	
	few	*simple*	*complex*	
	many	*simple*	*“simple”*	
	many	*simple*	*“complex”*	
	many	*complicated*	*complex*	
	many	*complicated*	*deterministic/ centralized*	

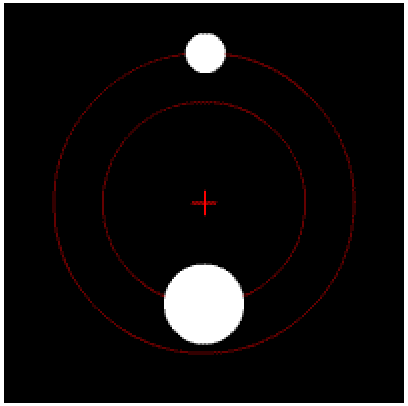
1. What are Complex Systems?

- Few agents, "simple" emergent behavior
  - → *ex: two-body problem*
  - ✓ fully solvable and ***regular*** trajectories for inverse-square force laws (e.g., gravitational or electrostatic)

$$\begin{cases} \mathbf{F}_{12}(\mathbf{x}_1, \mathbf{x}_2) = m_1 \ddot{\mathbf{x}}_1 & (Equation\ 1) \\ \mathbf{F}_{21}(\mathbf{x}_1, \mathbf{x}_2) = m_2 \ddot{\mathbf{x}}_2 & (Equation\ 2) \end{cases}$$



Two bodies with similar mass
Wikimedia Commons

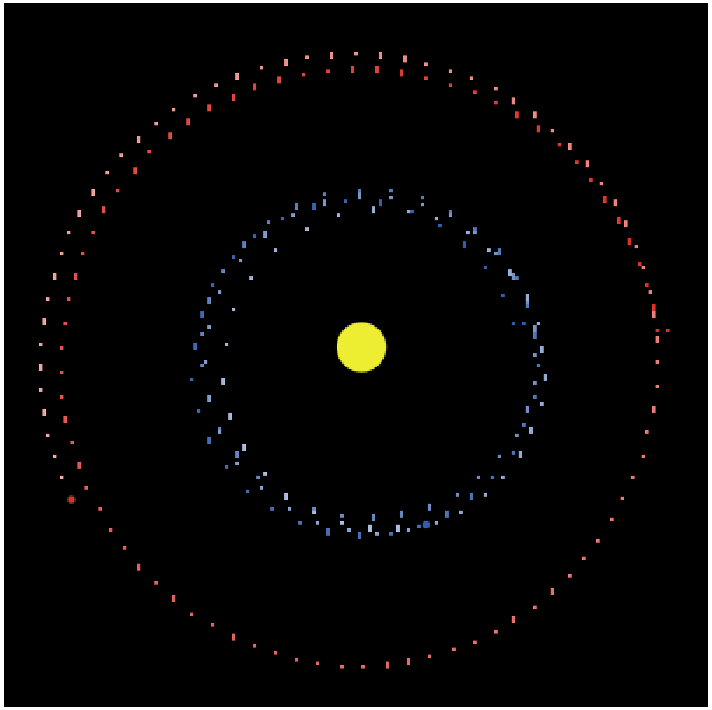


Two bodies with different mass
Wikimedia Commons

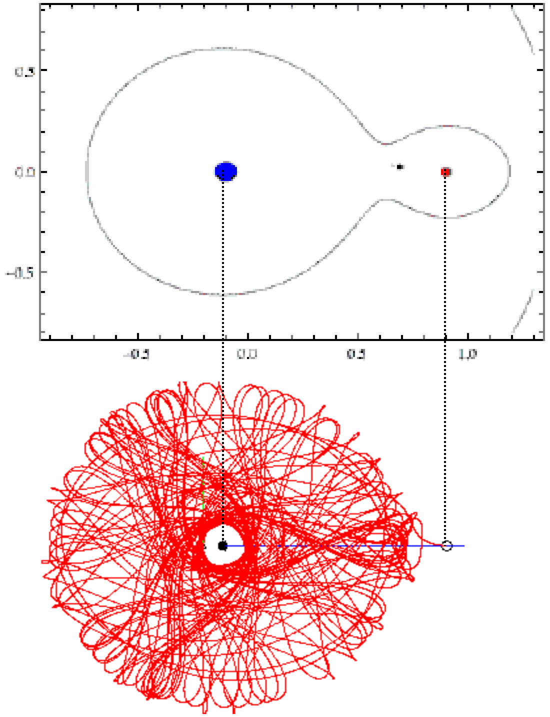
1. What are Complex Systems?

- Few agents, complex emergent behavior
  - → *ex: three-body problem*
  - ✓ generally no exact mathematical solution (even in "restricted" case $m_1 \langle\langle \; m_2 \approx m_3$): must be solved numerically → ***chaotic*** trajectories

NetLogo model: /Chemistry & Physics/Mechanics/Unverified

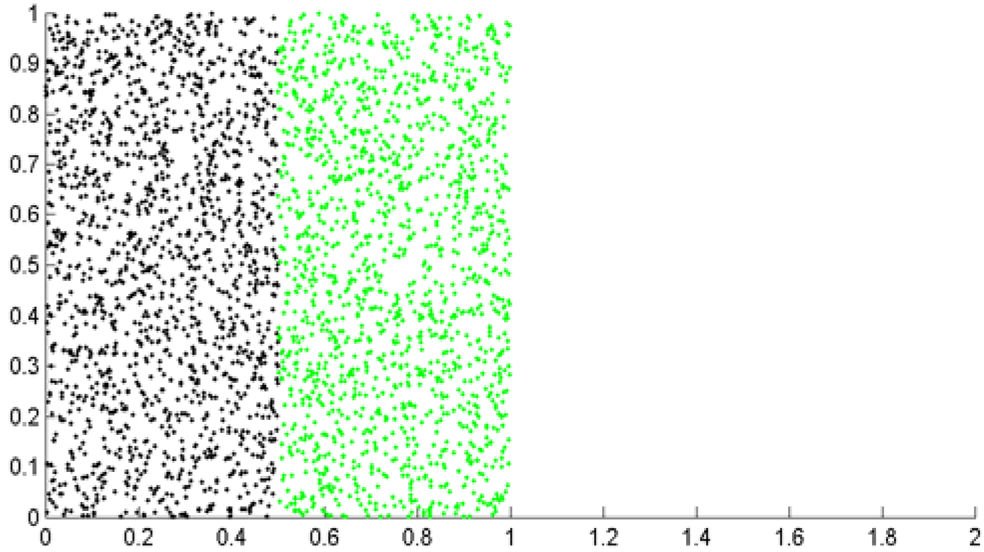


Transit orbit of the planar circular restricted problem
Scholarpedia: Three Body Problem & Joachim Köppen Kiel's applet



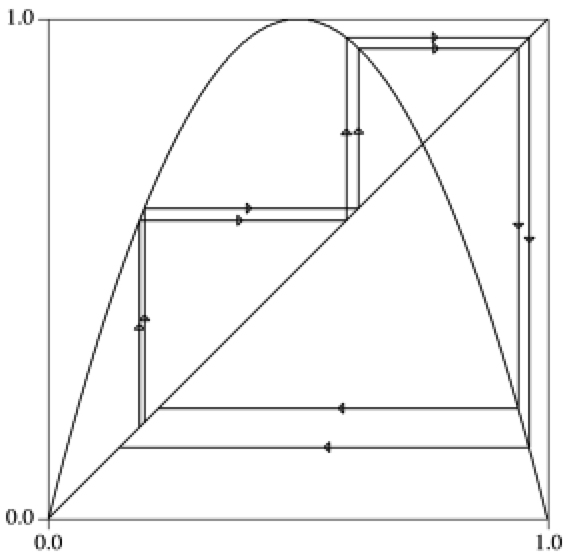
1. What are Complex Systems?

- Few agents, complex emergent behavior
  - → *ex: more chaos (baker's/horseshoe maps, logistic map, etc.)*
  - ✓ ***chaos*** generally means a ***bounded***, ***deterministic*** process that is ***aperiodic*** and ***sensitive on initial conditions*** → small fluctuations create large variations ("butterfly effect")
  - ✓ even one-variable iterative functions: $x_{n+1} = f(x_n)$ can be "complex"



Baker's transformation

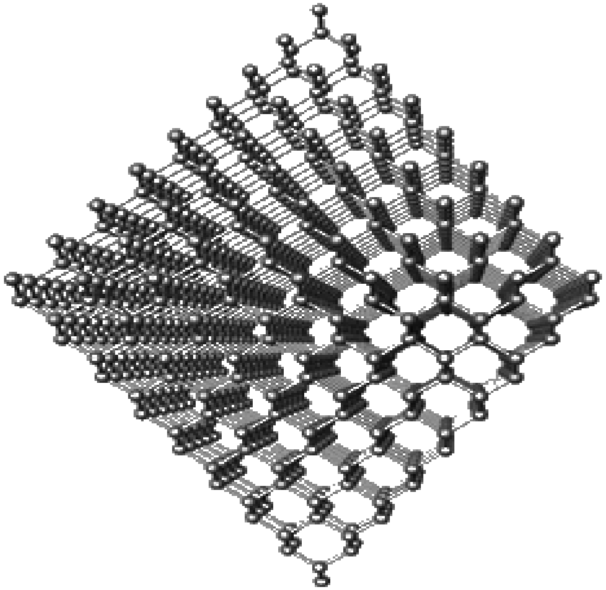
Craig L. Zirbel, Bowling Green State University, OH



Logistic map

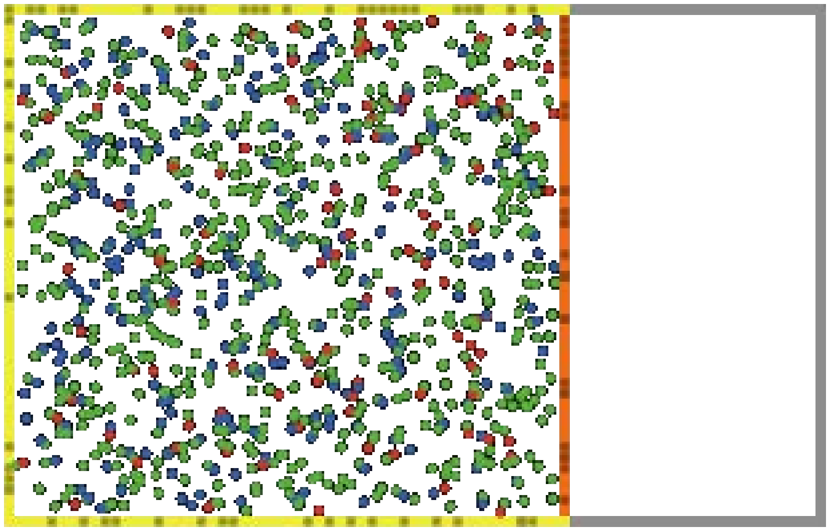
1. What are Complex Systems?

- Many agents, simple rules, “simple” emergent behavior
  - → *ex: crystal and gas (covalent bonds or electrostatic forces)*
  - ✓ either highly ordered, *regular* states (crystal)
  - ✓ or disordered, random, statistically *homogeneous* states (gas): a few global variables (P, V, T) suffice to describe the system



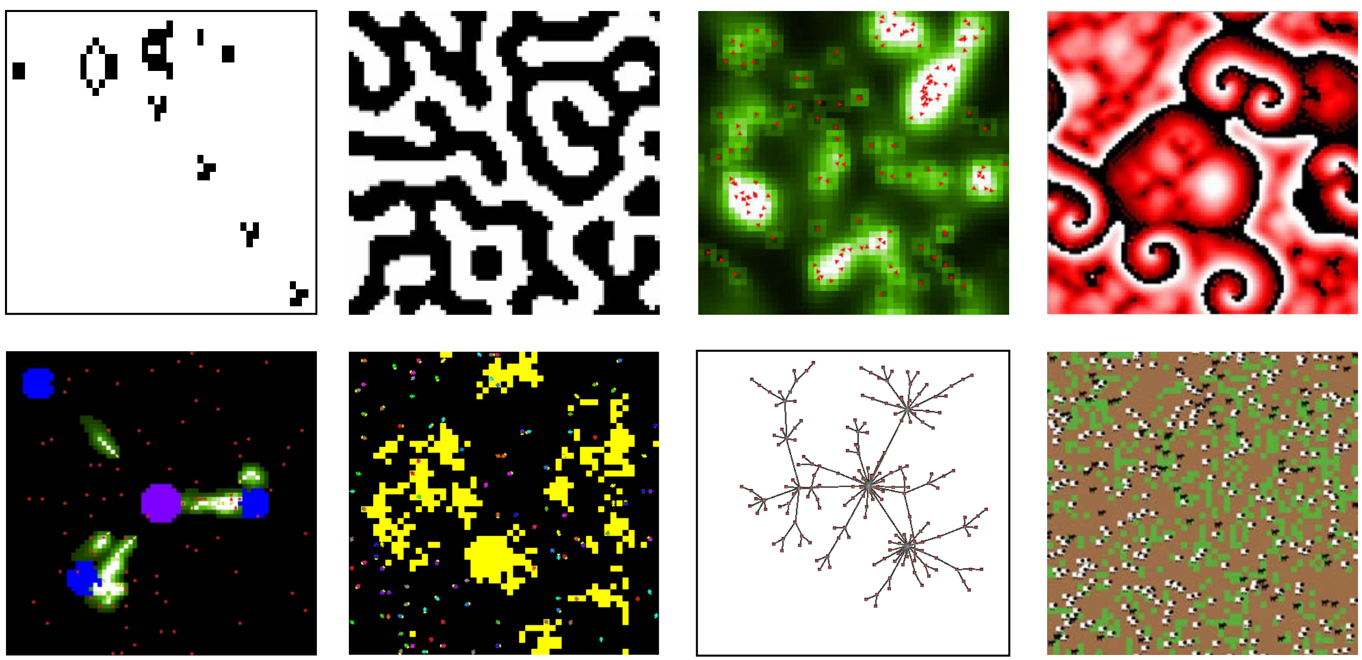
Diamond crystal structure
Tonci Balic-Zunic, University of Copenhagen

NetLogo model: /Chemistry & Physics/GasLab Isothermal Piston



1. What are Complex Systems?

- Many agents, simple rules, complex emergent behavior
  - → *ex: cellular automata, pattern formation, swarm intelligence (insect colonies, neural networks), complex networks, spatial communities*
  - ✓ the “clichés” of complex systems: a major part of this course and NetLogo models

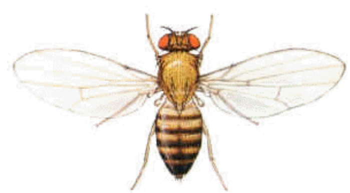
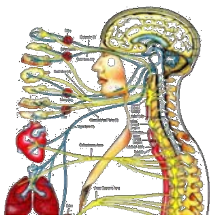


1. What are Complex Systems?

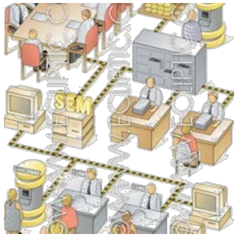
- **Many agents, complicated rules, complex emergent behavior**
  - → *natural ex: organisms (cells), societies (individuals + techniques)*
  - ✓ agent rules become more “complicated”, e.g., ***heterogeneous*** depending on the element’s *type* and/or *position* in the system
  - ✓ behavior is also complex but, paradoxically, can become more *controllable*, e.g., *reproducible* and *programmable*

biological development & evolution

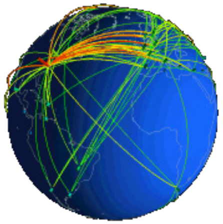


termite mounds



companies



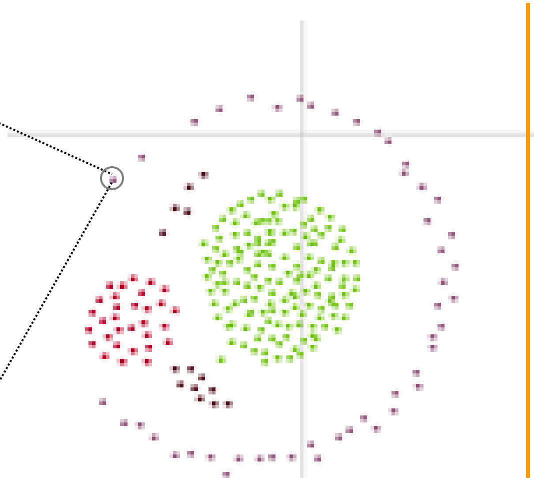
techno-networks

cities

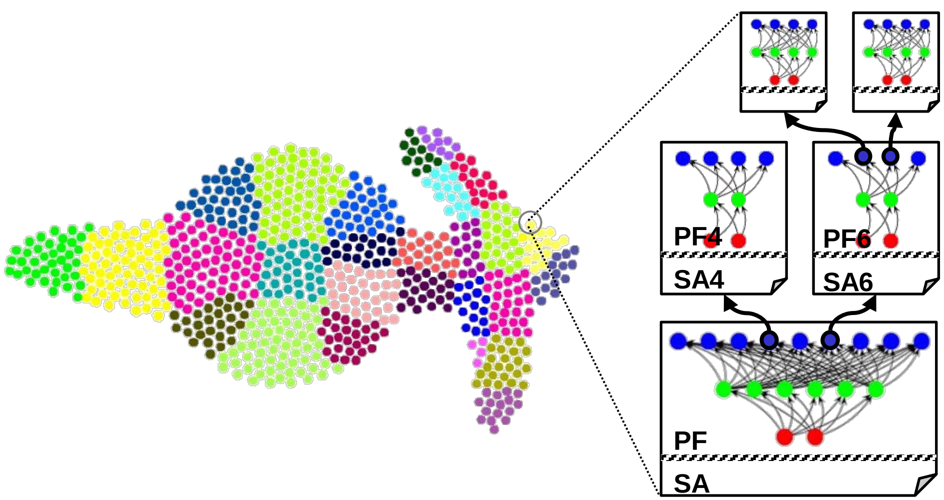
1. What are Complex Systems?

- Many agents, complicated rules, complex emergent behavior
  - → *ex: self-organized "artificial life": swarm chemistry, morphogenesis*
  - ✓ in *swarm chemistry* (Sayama 2007), mixed self-propelled particles with different flocking parameters create nontrivial formations
  - ✓ in *embryomorphic engineering* (Doursat 2006), cells contain the same genetic program, but differentiate and self-assemble into specific shapes

Name	Min	Max
R^i	0	300
V_n^i	0	20
V_m^i	0	40
c_1^i	0	1
c_2^i	0	1
c_3^i	0	100
c_4^i	0	0.5
c_5^i	0	1



Swarm chemistry
Hiroki Sayama, Binghamton University SUNY

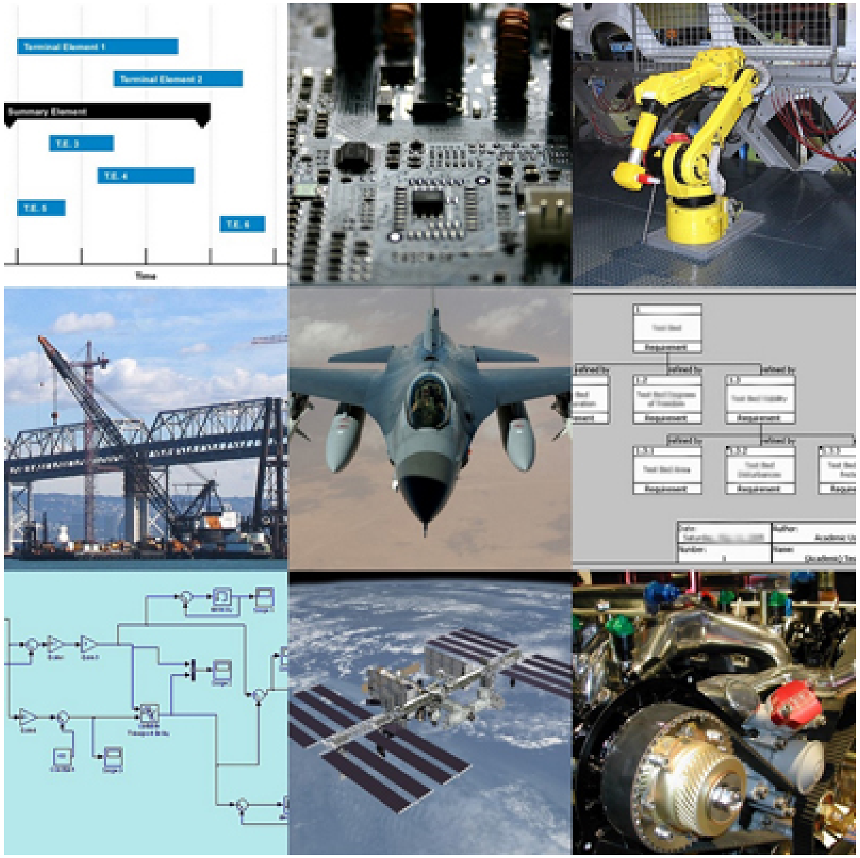


Embryomorphic engineering
René Doursat, Insitut des Systèmes Complexes, Paris

➢ Many agents, complicated rules, "deterministic" behavior

→ *classical engineering: electronics, machinery, aviation, civil construction*

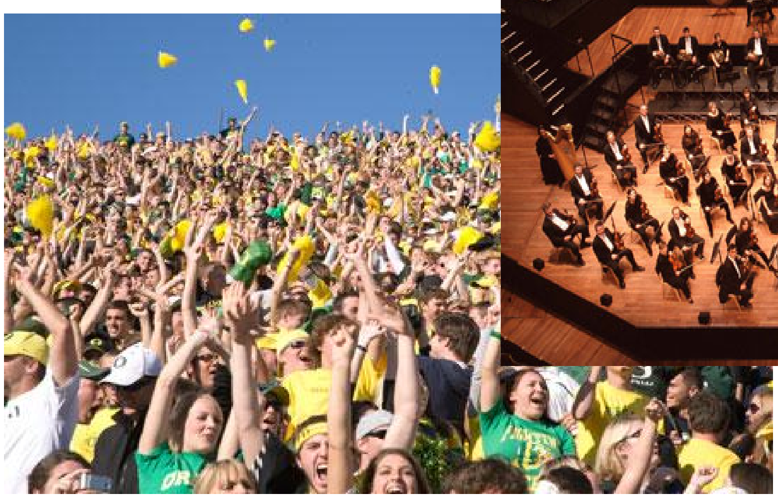
- ✓ artifacts composed of a immense number of parts
- ✓ yet still designed globally to behave in a limited and *predictable* (reliable, controllable) number of ways — "I don't want my aircraft to be creatively emergent in mid-air"
- ✓ not "complex" systems in the sense of:
  - little decentralization
  - no emergence
  - no self-organization

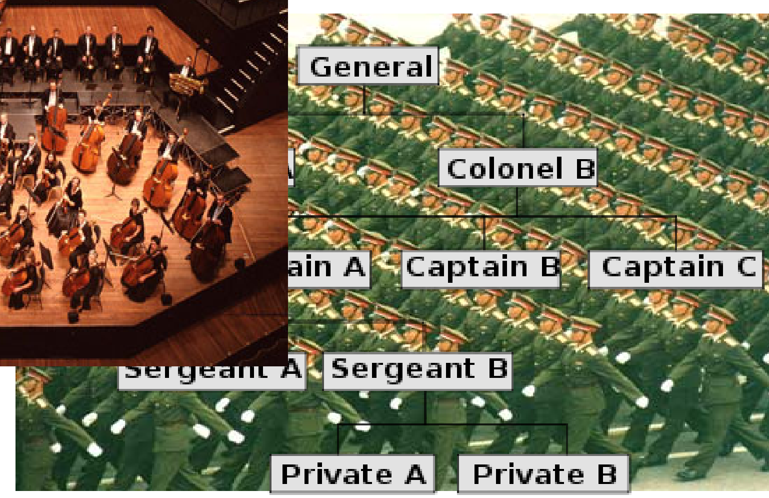


Systems engineering
Wikimedia Commons, http://en.wikipedia.org/wiki/Systems_engineering

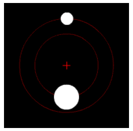
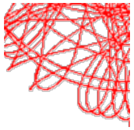
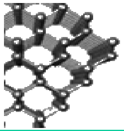
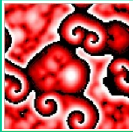
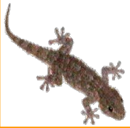
1. What are Complex Systems?

- Many agents, complicated rules, “centralized” behavior
  - → *spectators, orchestras, military, administrations*
  - ✓ people reacting similarly and/or simultaneously to cues/orders coming from a *central cause*: event, leader, plan
  - ✓ **hardly "complex" systems:** little decentralization, little emergence, little self-organization



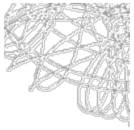
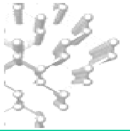
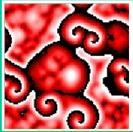
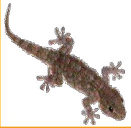


Recap: complex systems in this course

Category	*Agents / Parts*	*Local Rules*	*Emergent Behavior*	*A "Complex System"?*
 2-body problem	*few*	*simple*	*"simple"*	*NO*
 3-body problem, low-D chaos	*few*	*simple*	*complex*	*NO – too small*
 crystal, gas	*many*	*simple*	*"simple"*	*NO – few params suffice to describe it*
 patterns, swarms, complex networks	*many*	*simple*	*"complex"*	*YES – but mostly random and uniform*
 structured morphogenesis	*many*	*complicated*	*complex*	*YES – reproducible and heterogeneous*
 machines, crowds with leaders	*many*	*complicated*	*deterministic/ centralized*	*COMPLICATED – not self-organized*

1. What are Complex Systems?

➢ Recap: complex systems in this course

Category	Agents / Parts	Local Rules	Emergent Behavior	A "Complex System"?
2-body problem	*few*	*simple*	*“simple”*	*NO*
 3-body problem, low-D chaos	*few*	*simple*	*complex*	*NO – too small*
 crystal, gas	*many*	*simple*	*“simple”*	*NO – few params suffice to describe it*
 patterns, swarms, complex networks	*many*	*simple*	*“complex”*	*YES – but mostly random and uniform*
 structured morphogenesis	*many*	*complicated*	*complex*	*YES – reproducible and heterogeneous*
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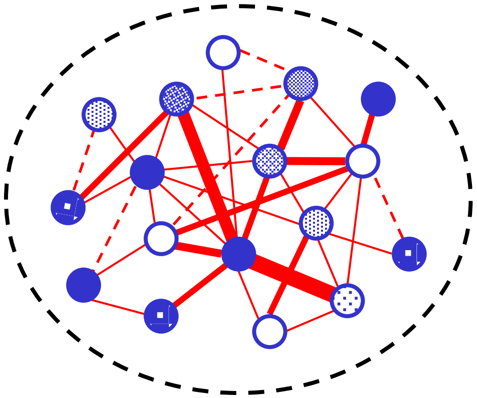
1. What are Complex Systems?

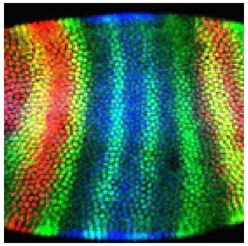
➢ Complex systems in this course



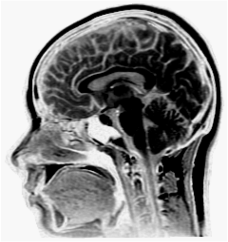
- **large** number of elementary **agents** interacting **locally**
- (more or less) simple individual agent behaviors creating a complex **emergent**, **self-organized** behavior
- *decentralized dynamics: no master blueprint or grand architect*

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

pattern
formation
○ = matter



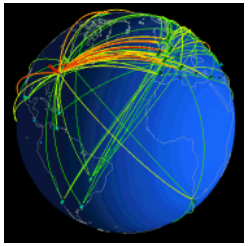
biological
development
○ = cell



the brain
& cognition
○ = neuron

insect
colonies
○ = ant

Internet
& Web
○ = host/page

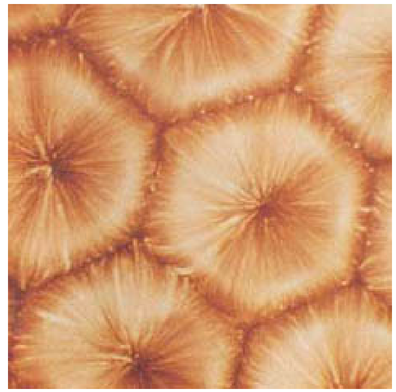


social
networks
○ = person

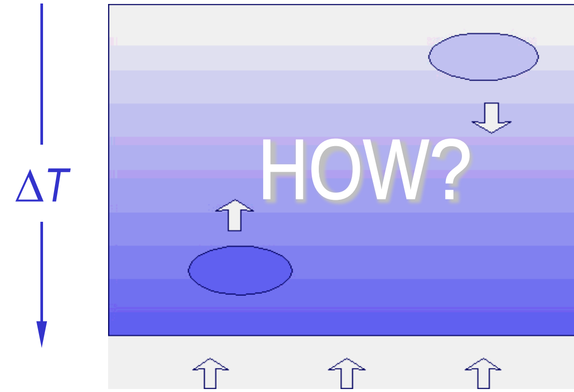
1. What are Complex Systems?

Physical pattern formation: Convection cells

Rayleigh-Bénard convection cells in liquid heated uniformly from below
(Scott Camazine, http://www.scottcamazine.com)

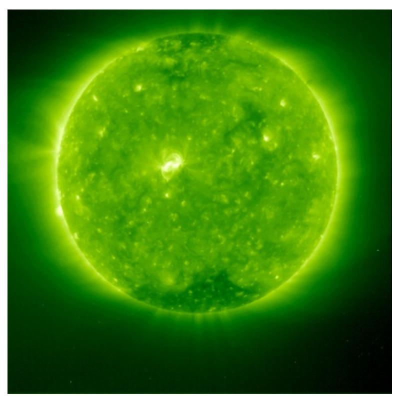


Convection cells in liquid (detail)
(Manuel Velarde, Universidad Complutense, Madrid)

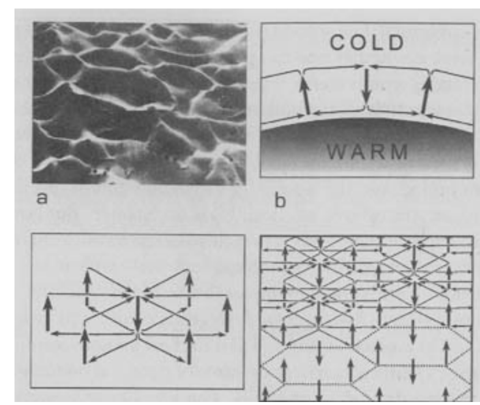


Schematic convection dynamics
(Arunn Narasimhan, Southern Methodist University, TX)

Sand dunes
(Scott Camazine, http://www.scottcamazine.com)



Solar magnetoconvection
(Steven R. Lantz, Cornell Theory Center, NY)



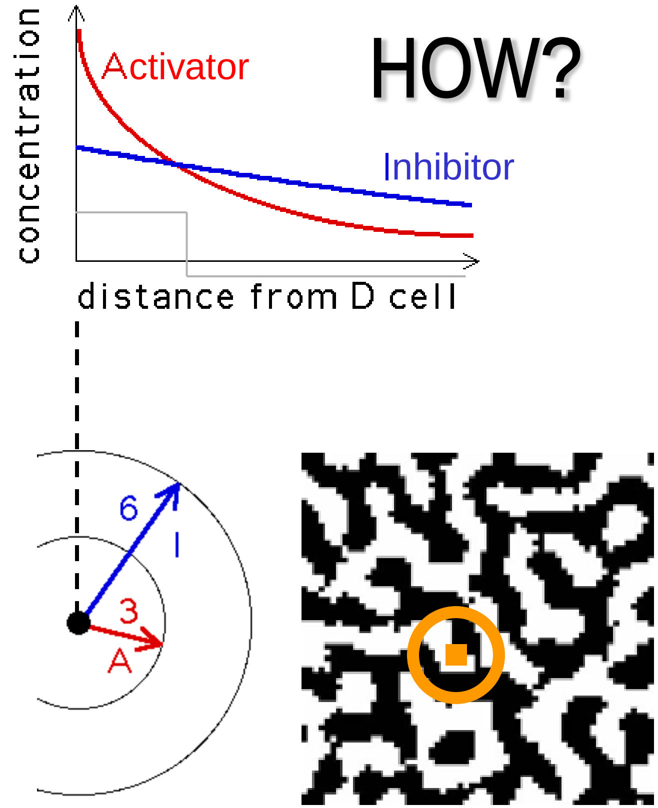
Hexagonal arrangement of sand dunes
(Solé and Goodwin, "Signs of Life", Perseus Books)

- thermal convection, due to temperature gradients, creates stripes and tilings at multiple scales, from tea cups to geo- and astrophysics

1. What are Complex Systems?

Biological pattern formation: Animal colors

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

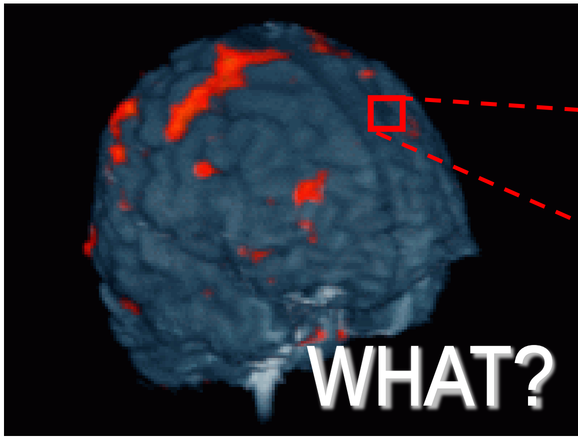


NetLogo fur coat simulation, after David Young's model of fur spots and stripes
(Michael Frame & Benoit Mandelbrot, Yale University)

- animal patterns (for warning, mimicry, attraction) can be caused by pigment cells trying to copy their nearest neighbors but differentiating from farther cells

1. What are Complex Systems?

Spatiotemporal synchronization: Neural networks

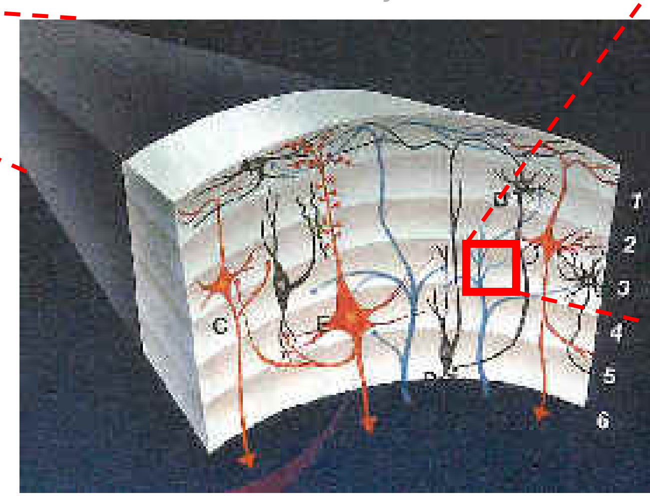


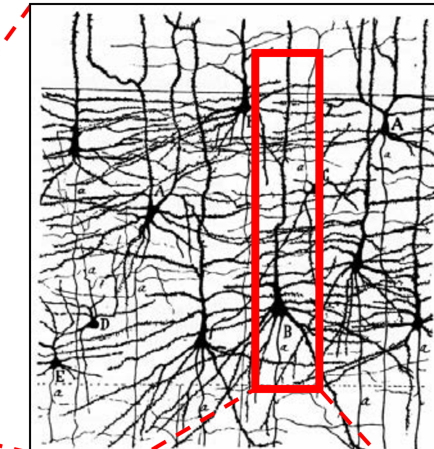
Animation of a functional MRI study
(J. Ellermann, J. Strupp, K. Ugurbil, U Minnesota)

- the brain constantly generates patterns of activity ("the mind")
- they emerge from 100 billion neurons that exchange electrical signals via a dense network of contacts

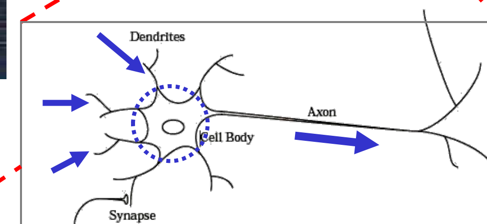
HOW?

Cortical layers

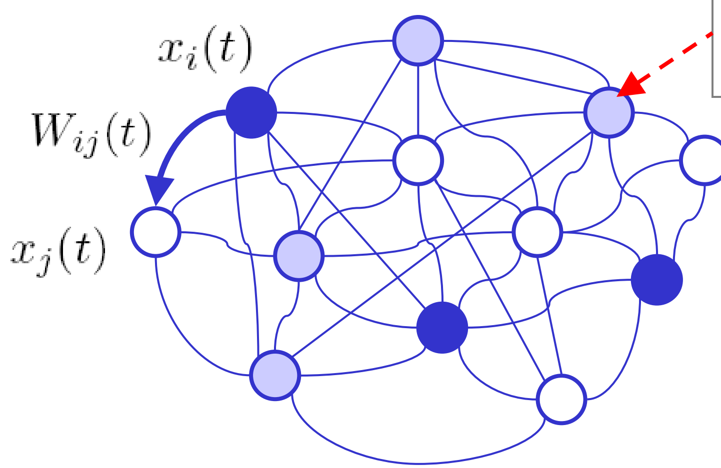


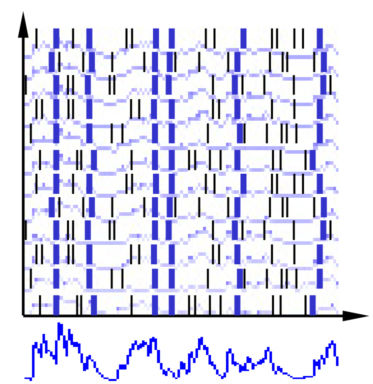


Pyramidal neurons & interneurons
(Ramón y Cajal 1900)



Schematic neural network





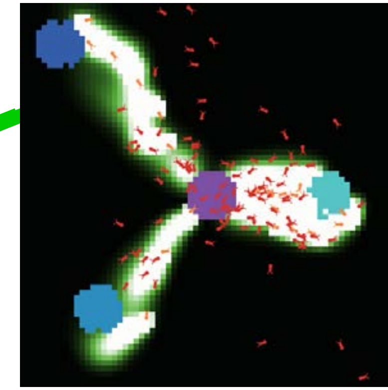
1. What are Complex Systems?

Swarm intelligence: Insect colonies (ant trails, termite mounds)

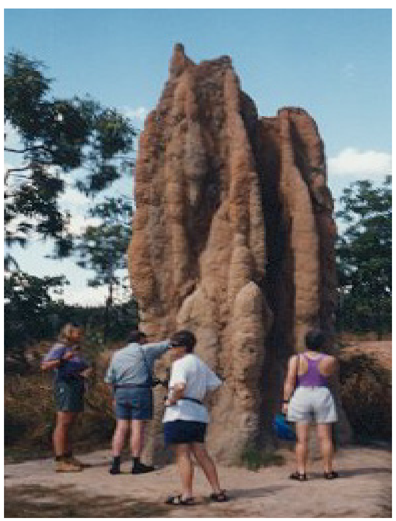
http://taos-telecommunity.org/epow/epow-archive/archive_2003/EPOW-030811_files/matabele_ants.jpg

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

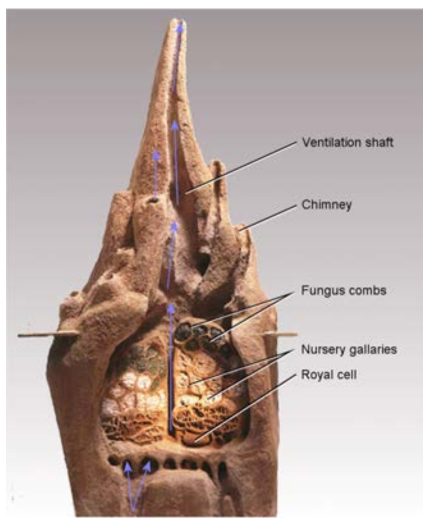
Harvester ant
(Deborah Gordon, Stanford University)



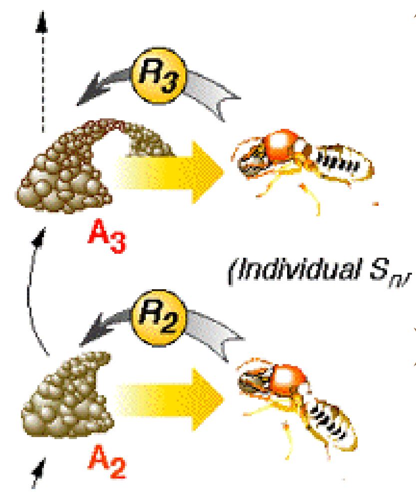
HOW?



Termite mound
(J. McLaughlin, Penn State University)



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



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

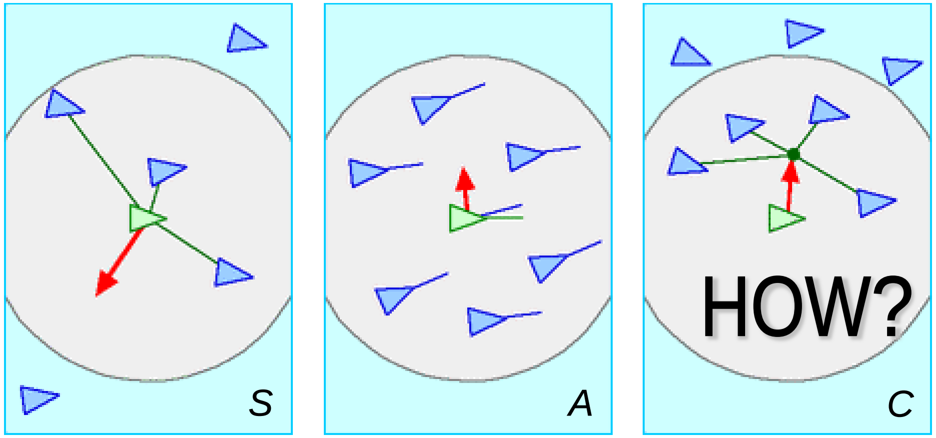
- ants form trails by following and reinforcing each other's pheromone path
- termite colonies build complex mounds by "stigmergy"

1. What are Complex Systems?

Collective motion: flocking, schooling, herding

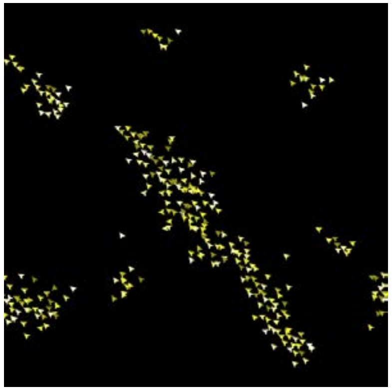
Fish school
(Eric T. Schultz, University of Connecticut)

Bison herd
(Center for Bison Studies, Montana State University, Bozeman)



Separation, alignment and cohesion
("Boids" model, Craig Reynolds, http://www.red3d.com/cwr/boids)

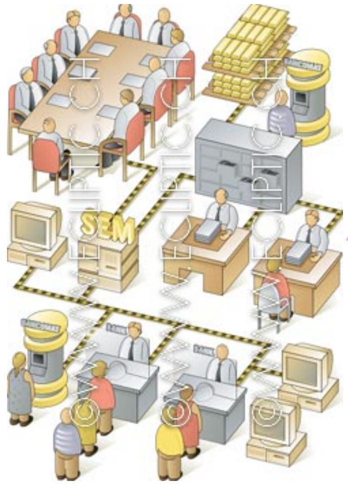
- coordinated collective movement of dozens or 1000s of individuals (confuse predators, close in on prey, improve motion efficiency, etc.)
- each individual adjusts its position, orientation and speed according to its nearest neighbors



1. What are Complex Systems?

Complex networks and morphodynamics: human organizations

organizations



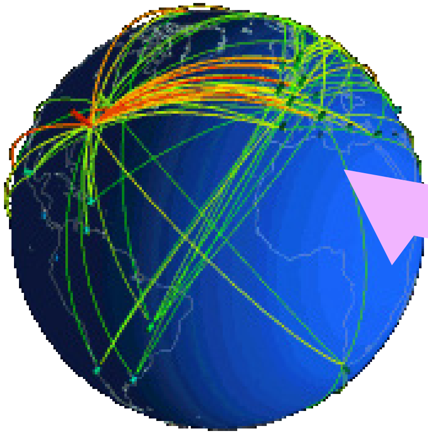
(Thomas Thü Hürlimann, http://ecliptic.ch)

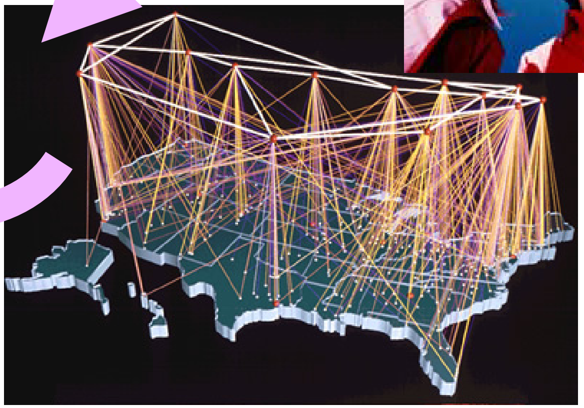
urban dynamics

SimCity (http://simcitysocieties.ea.com)

techno-social networks

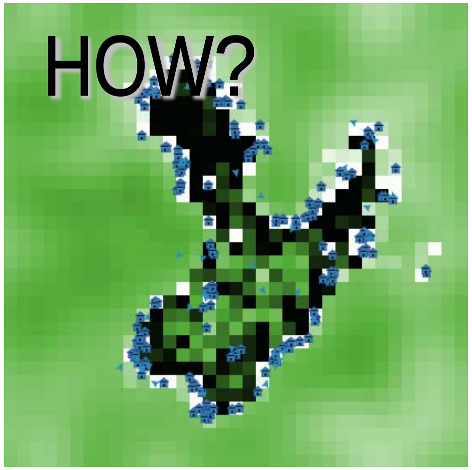
global connectivity





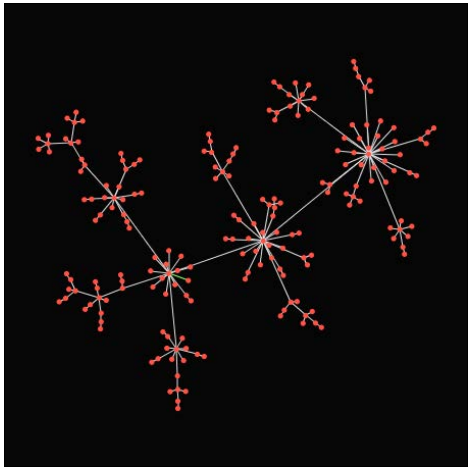
NSFNet Internet (w2.eff.org)

cellular automata model



NetLogo urban sprawl simulation

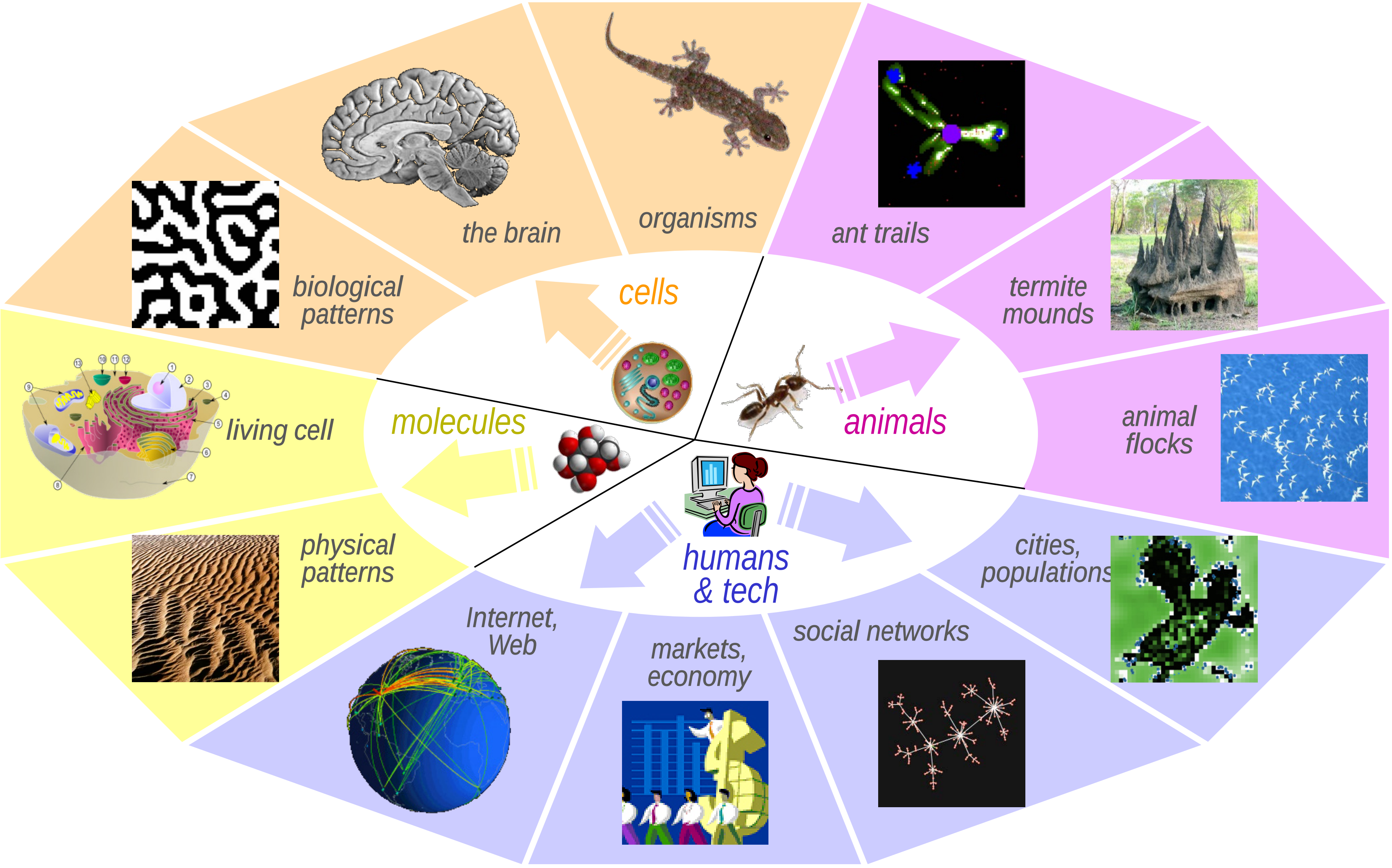
"scale-free" network model



NetLogo preferential attachment simulation

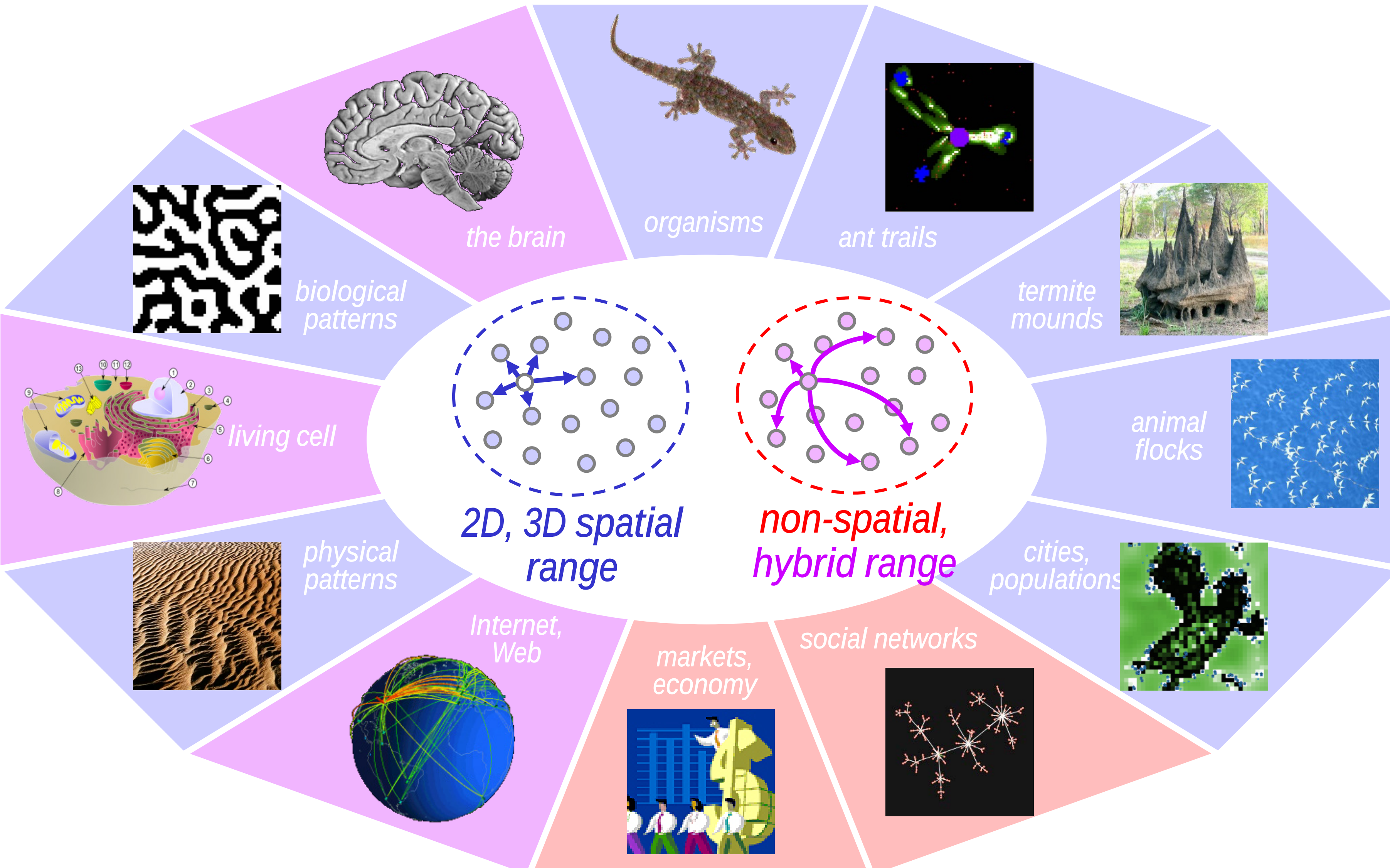
1. What Are Complex Systems?

➢ All agent types: molecules, cells, animals, humans & tech



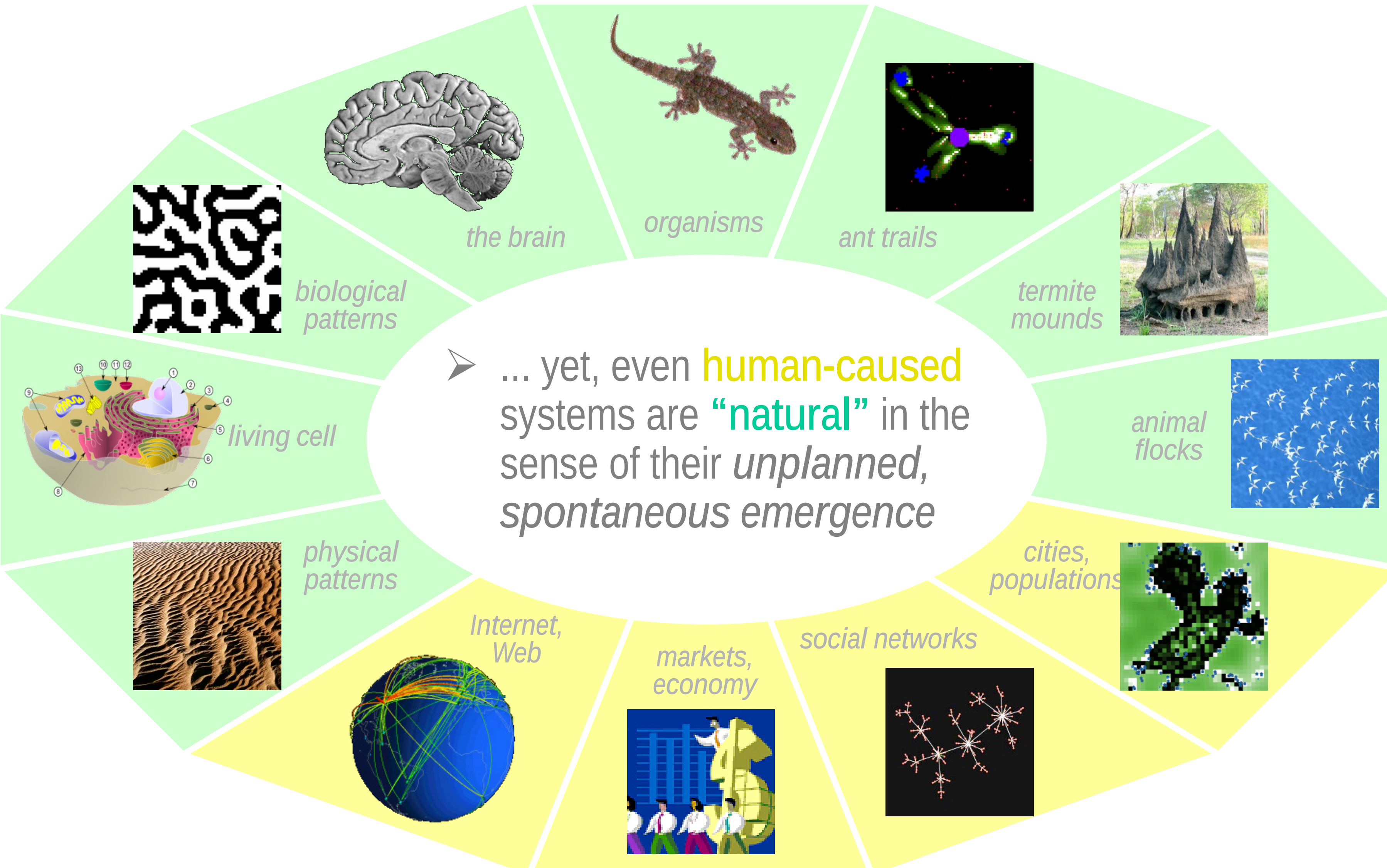
1. What Are Complex Systems?

Categories of complex systems by range of interactions



1. What Are Complex Systems?

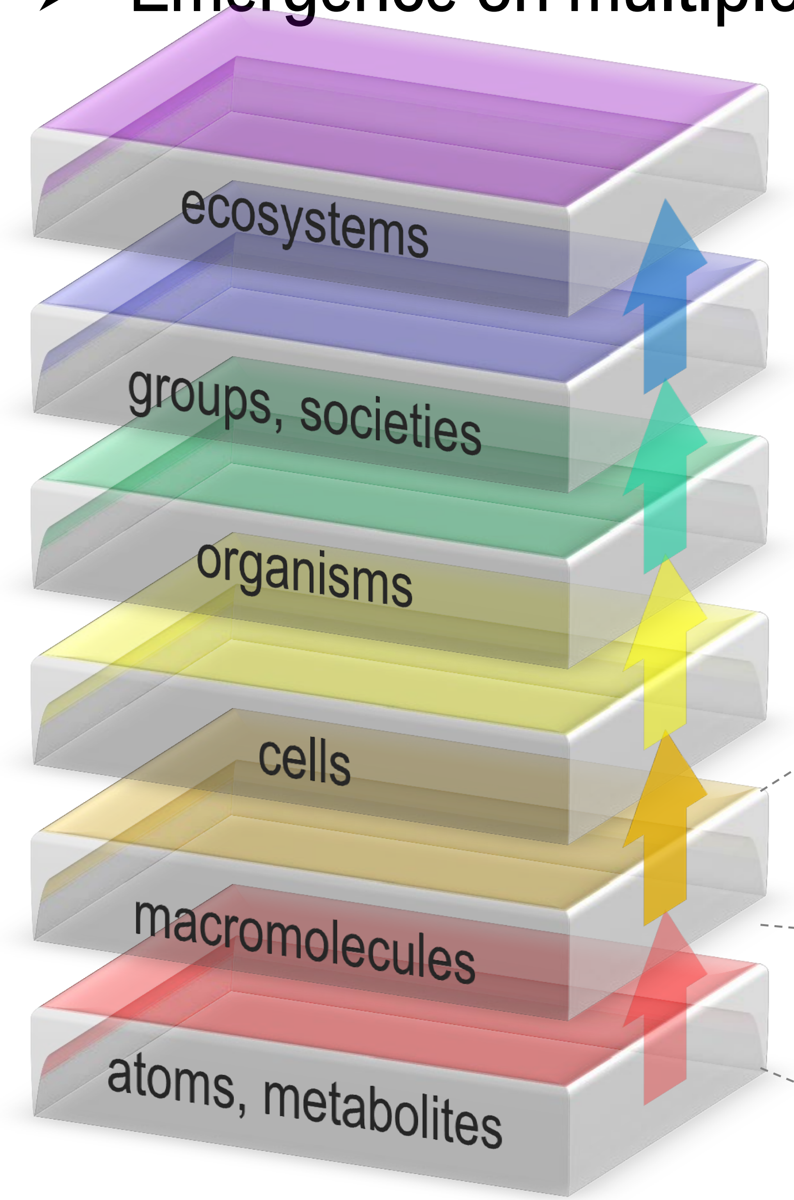
Natural and *human-caused* categories of complex systems



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

1. What Are Complex Systems?

➢ Emergence on multiple levels of self-organization

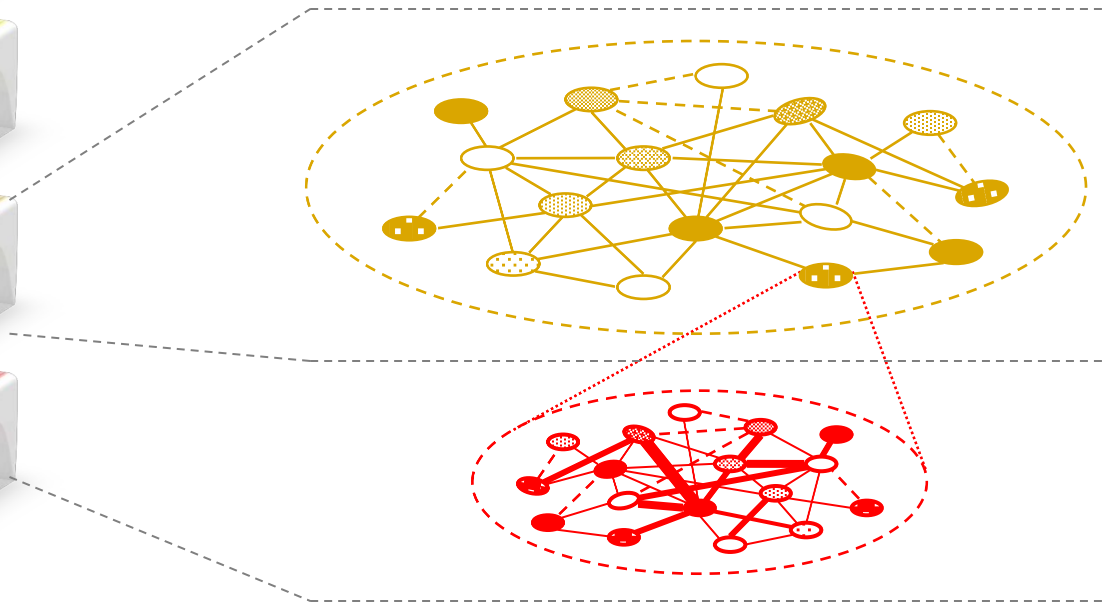


complex systems:

a) a large number of elementary agents interacting locally

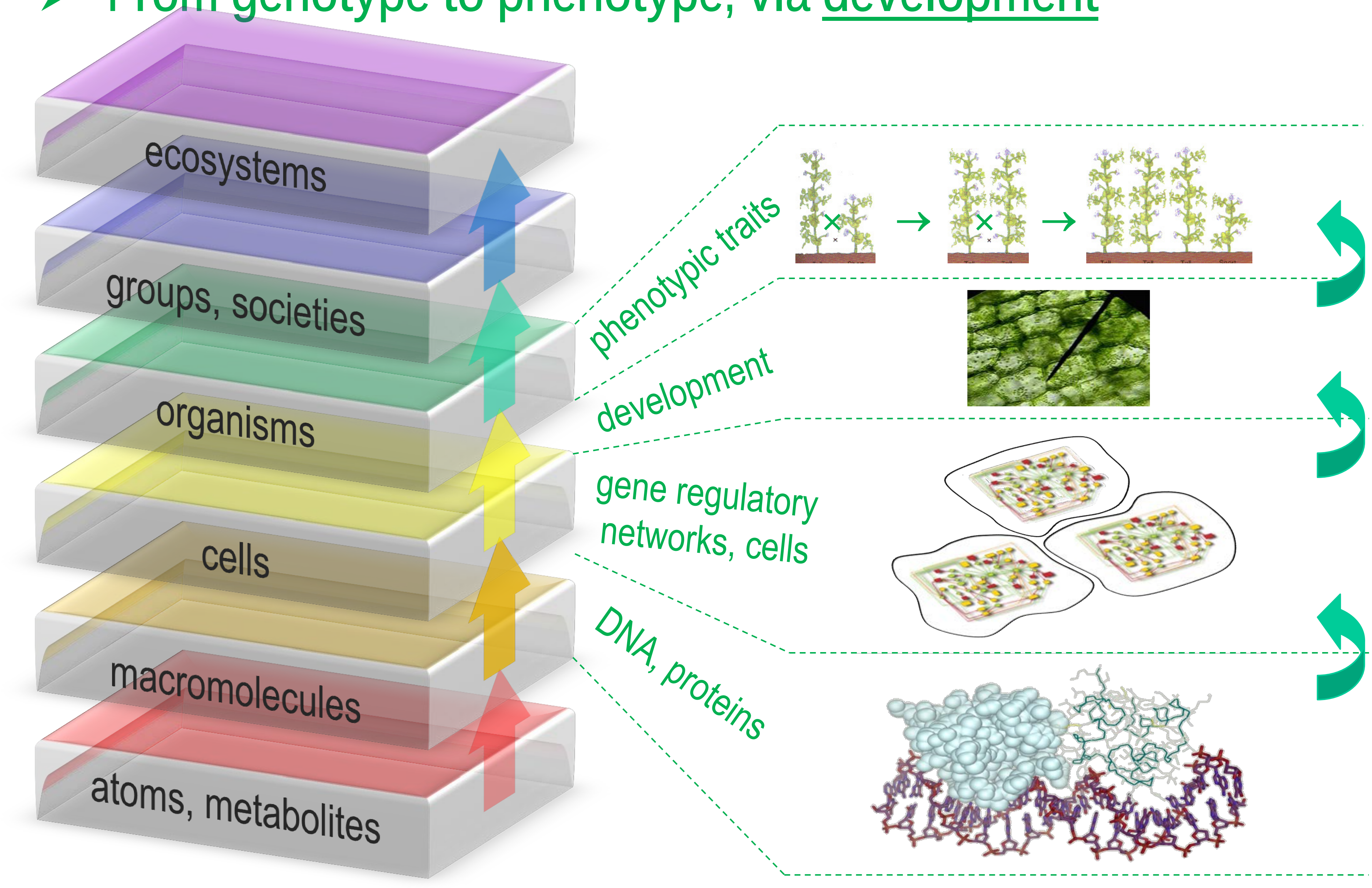
b) simple individual behaviors creating a complex emergent collective behavior

c) decentralized dynamics: no master blueprint or grand architect



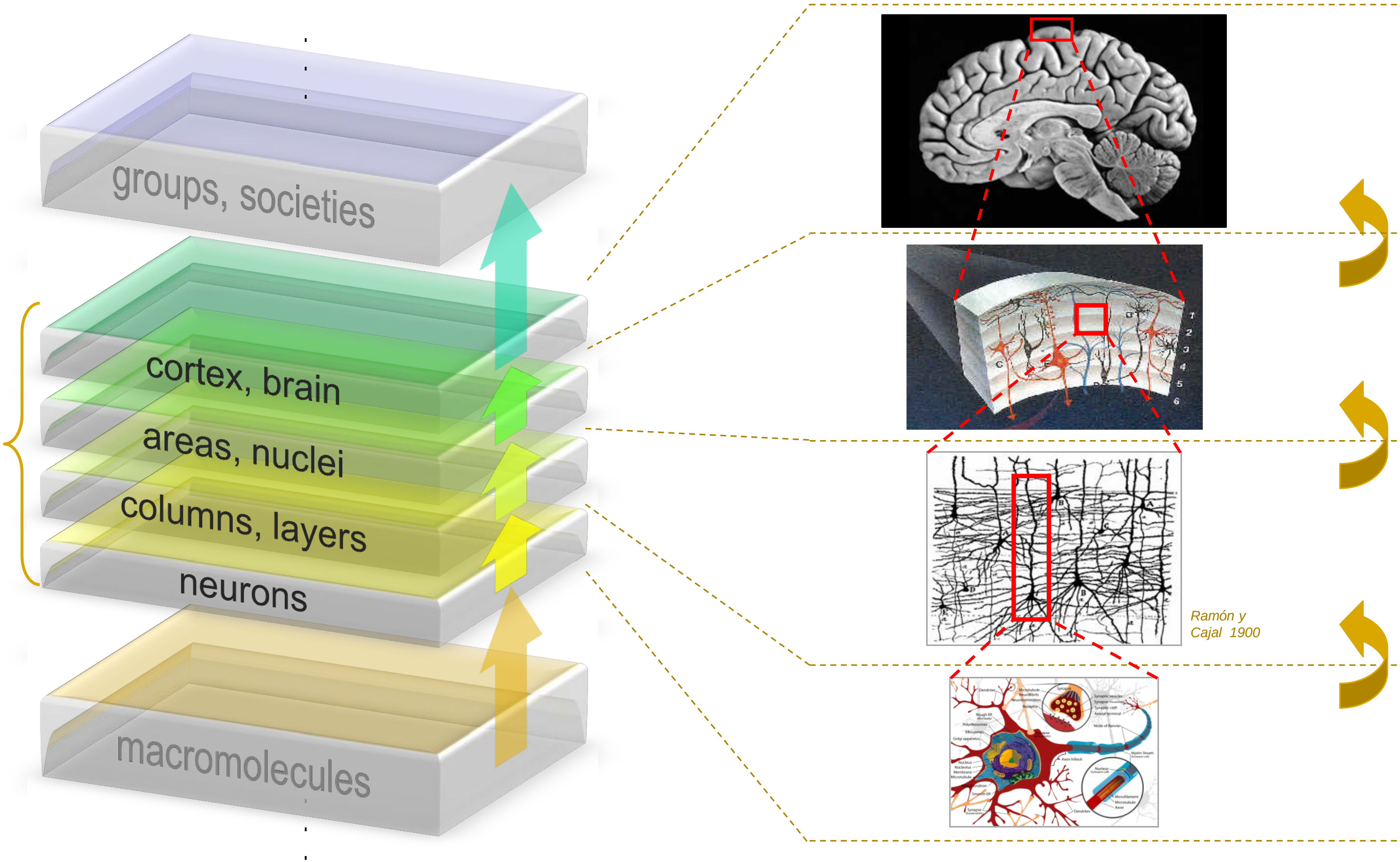
1. What Are Complex Systems?

- From genotype to phenotype, via development



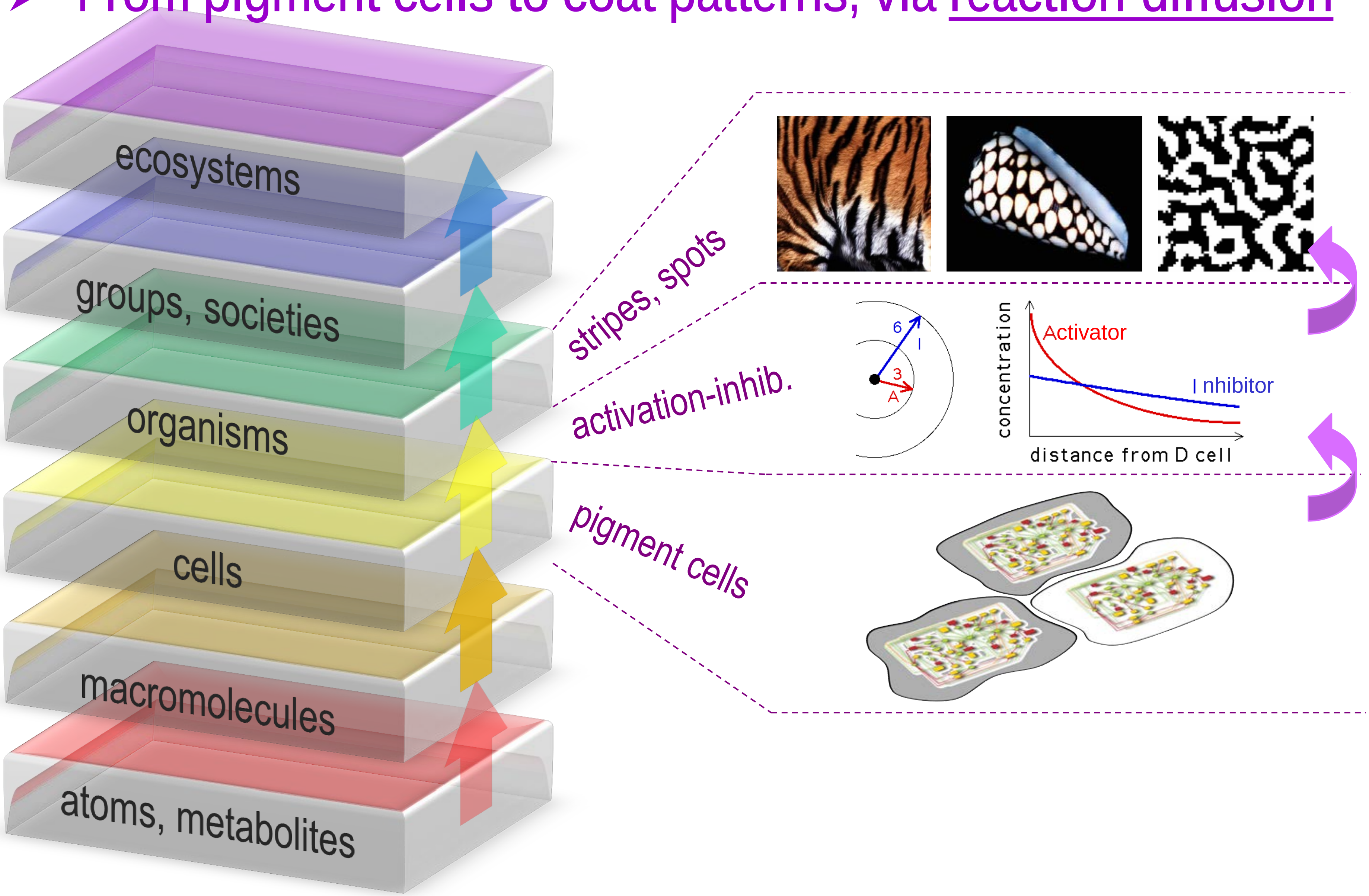
1. What Are Complex Systems?

➢ From neurons to brain, via neural development (anatomy)



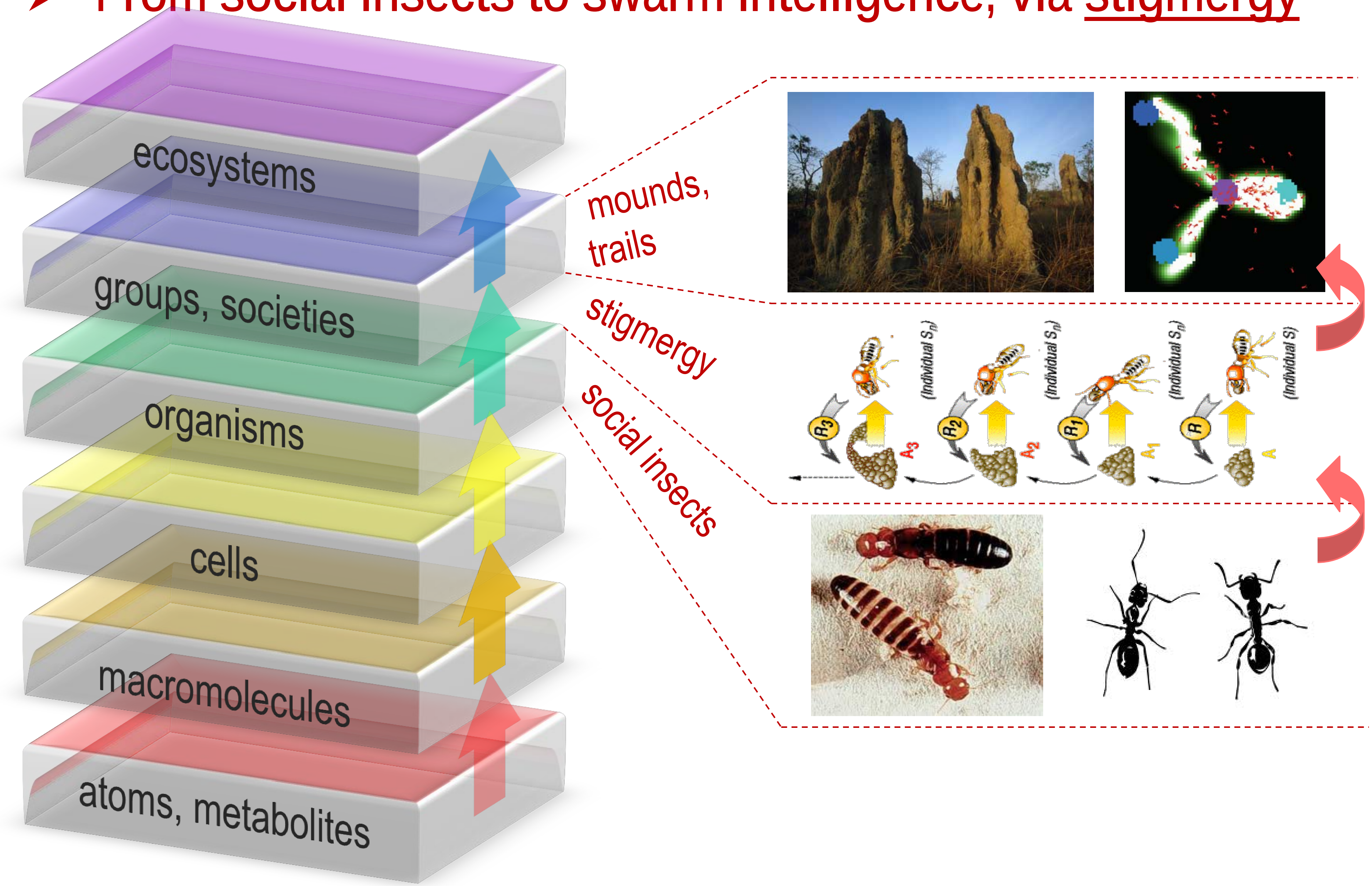
1. What Are Complex Systems?

➢ From pigment cells to coat patterns, via reaction-diffusion



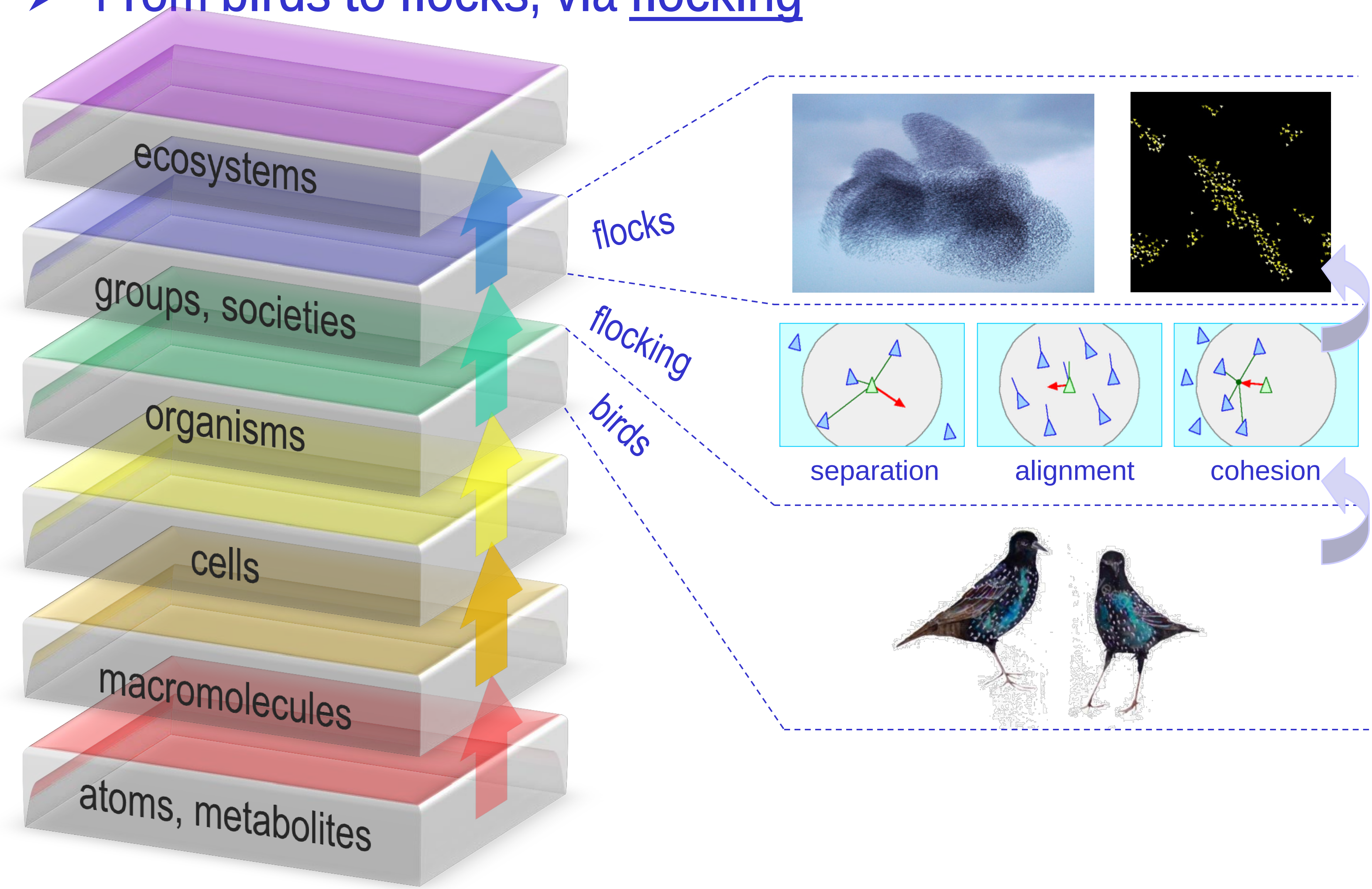
1. What Are Complex Systems?

➢ From social insects to swarm intelligence, via stigmergy



1. What Are Complex Systems?

- From birds to flocks, via flocking



1. What Are Complex Systems?

- So, there is no general “complex systems science” or “complexity theory”...
  - there are a lot of theories and results in related disciplines (“systems theory”, “computational complexity”, etc.), yet
    - such generic names often come from one researcher with one particular view
    - there is no unified viewpoint on *complex systems, especially autonomous*
    - in fact, there is not even any agreement on their *definition*
  - we are currently dealing with an intuitive set of criteria, more or less shared by researchers, but still hard to formalize and quantify:
    - complexity
    - emergence
    - self-organization
    - multitude / decentralization
    - adaptation, etc.

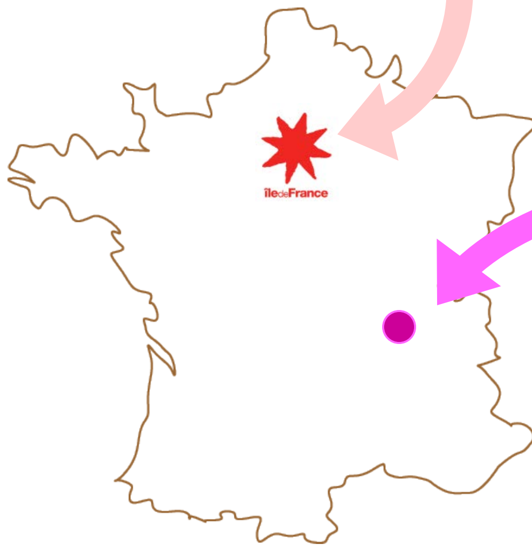
INSTITUT DES SYSTEMES COMPLEXES

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

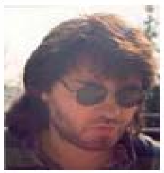
Artificial development (self-assembly, pattern formation, spatial computing, evolutionary computation) - Mesoscopic neurodynamics (segmentation, schematization, categorization, perception, cognitive linguistics).

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

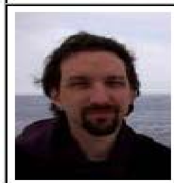
Nonequilibrium statistical mechanics (Active matter, collective motion, flocking, nonequilibrium wetting, directed percolation, long range interactions) - Dynamical system theory (Lyapunov exponents, Lyapunov vectors, synchronization, stable chaos, spatiotemporal chaos, structural stability, hyperbolicity).

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 syste
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

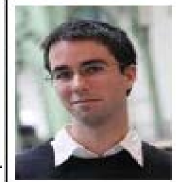
Peer-to-Peer networks, Blog networks, Complex networks, Statistical mechanics, Networks modeling, Optical networks, Wireless Internet.

peer-to-peer networks

Romain Reuillon

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

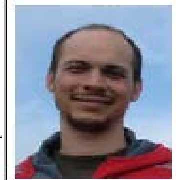
high performance computing



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

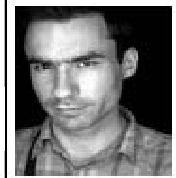
Grid Computing,Bioemergences Platform (workflow), Mophodynamics reconstruction, Images processing algorithms.

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

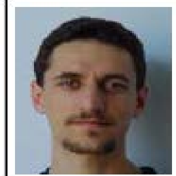
Neuroscience théoriques - Spiking Neurons - Dynamiques Stochastic-ques.

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

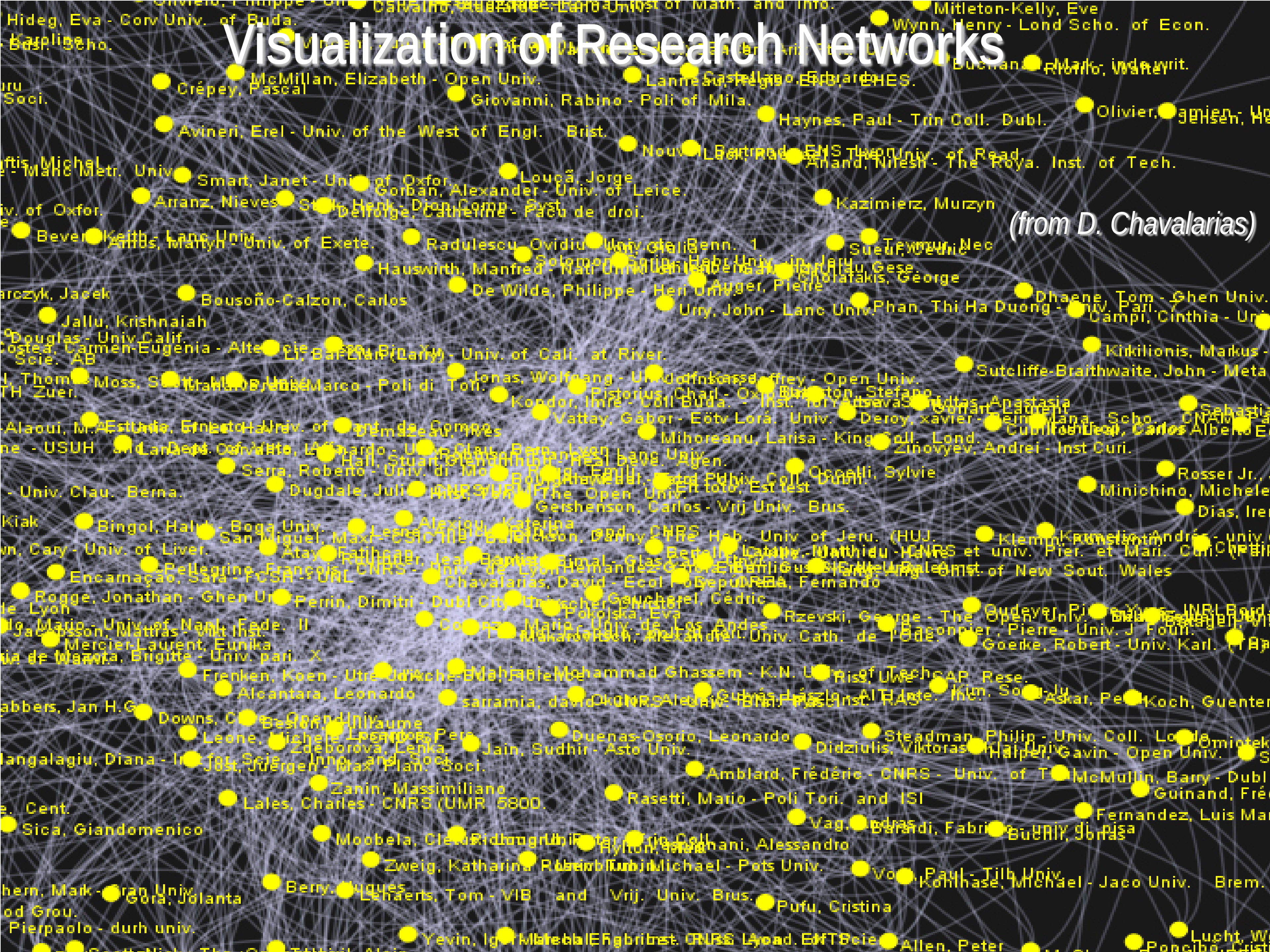
Francesco d'Ovidio

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

nonlinear dynamics / oceanography

ISC PARIS ÎLE-DE-FRANCE

Visualization of Research Networks



(from D. Chavalarias)

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

adaptation: change in typical functional regime of a system

systems sciences: holistic (non-reductionist) view on interacting parts

dynamics: behavior and activity of a system over time

multitude, statistics: large-scale properties of systems

- ✓ different families of disciplines *focus* on different aspects
- ✓ (naturally, they intersect a lot: don't take this taxonomy too seriously)

1. What are Complex Systems?

A vast archipelago of precursor and neighboring disciplines

complexity: measuring the length to describe, time to build, or resources to run, a system
- information theory (Shannon; entropy)
- computational complexity (P, NP)
- Turing machines & cellular automata

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

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

systems sciences: holistic (non-reductionist) view on interacting parts
- systems theory (von Bertalanffy)
- systems engineering (design)
- cybernetics (Wiener; goals & feedback)
- control theory (negative feedback)

dynamics: behavior and activity of a system over time
- nonlinear dynamics & chaos
- stochastic processes
- systems dynamics (macro variables)

multitude, statistics: large-scale properties of systems
- graph theory & networks
- statistical physics
- agent-based modeling
- distributed AI systems

COMPLEX SYSTEMS

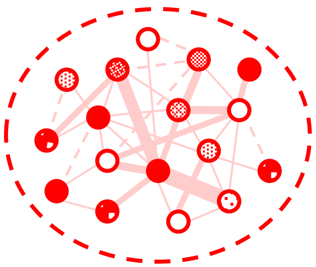
1. What are Complex Systems?
- Decentralization
- Emergence
- Self-organization

5. Bio-Inspiration and Artificial Evo-Devo

Or how to control spontaneity

5. Bio-Inspiration and Artificial Evo-Devo

➢ Between natural and engineered emergence



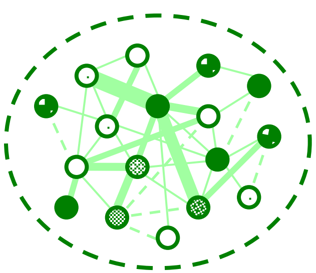
CS science: observing and understanding "natural", spontaneous emergence (including human-caused)

→ *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 <u>and</u> guiding complex systems at the level of their elements*



CS engineering: creating and programming a new "artificial" emergence

→ *Multi-Agent Systems (MAS)*

5. Bio-Inspiration and Artificial Evo-Devo

- Exporting models of natural complex systems to ICT
  - ✓ already a tradition, but 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. Bio-Inspiration and Artificial Evo-Devo

- 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

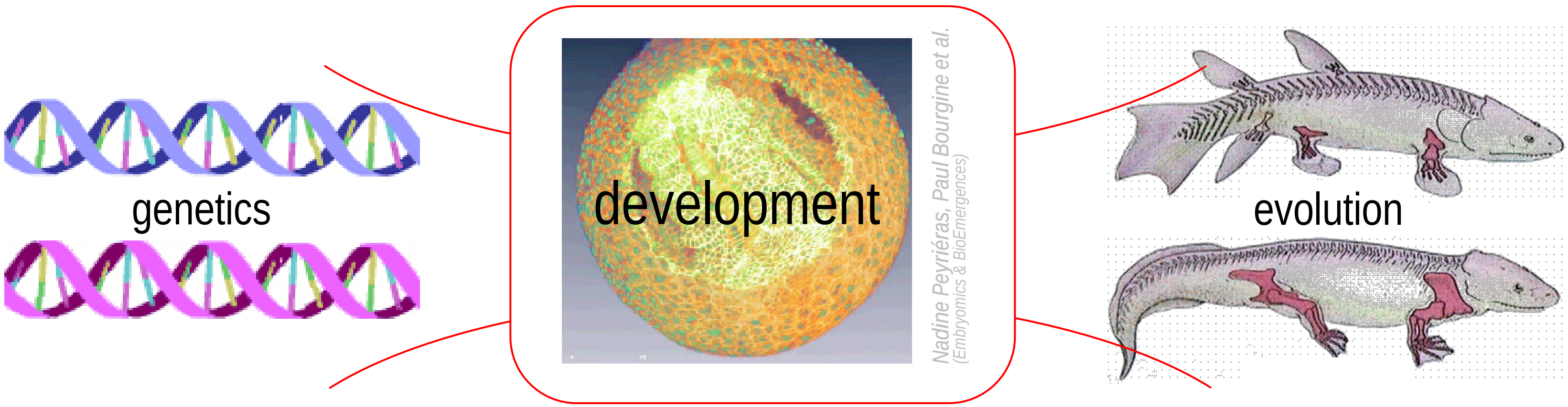
ant colony optimization (ACO) applied to graph theoretic & networking problems

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

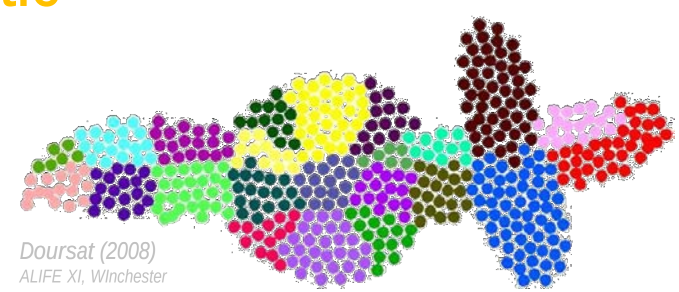
TOMORROW: implemented in bioware, nanoware, etc.

5. Bio-Inspiration and Artificial Evo-Devo

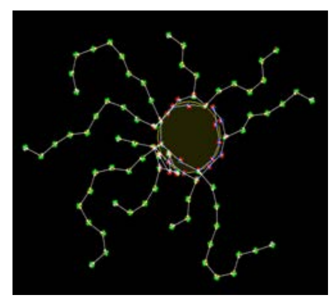
- A new line of bio-inspiration: biological morphogenesis
  - ✓ designing multi-agent models for decentralized systems engineering



Morphogenetic Engineering



Doursat (2008)
ALIFE XI, Winchester



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

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

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

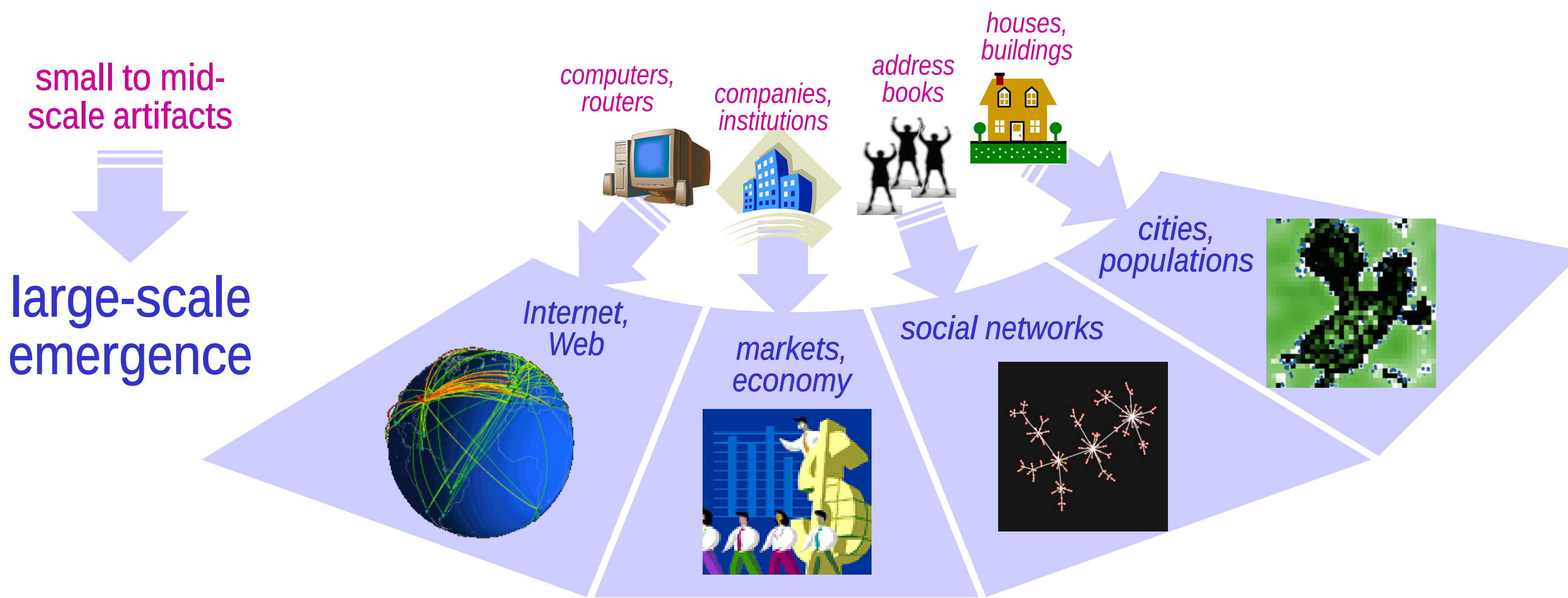
5. Bio-Inspiration and Artificial Evo-Devo

Or how to control spontaneity

2. Architects Overtaken by their Architecture

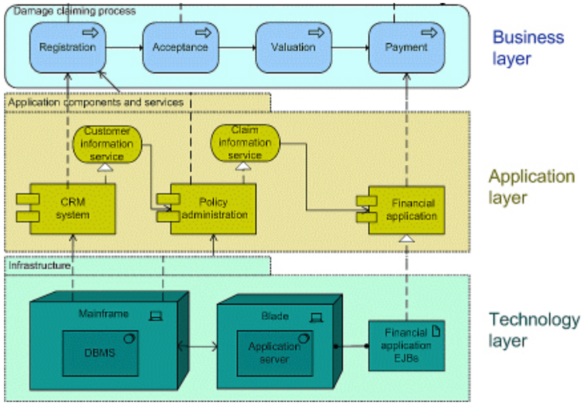
➢ At large scales, human superstructures are "natural" CS

by their unplanned, spontaneous emergence and adaptivity...		... arising from a multitude of traditionally designed artifacts
geography: cities, populations	⇐	houses, buildings
people: social networks	⇐	address books
wealth: markets, economy	⇐	companies, institutions
technology: Internet, Web	⇐	computers, routers



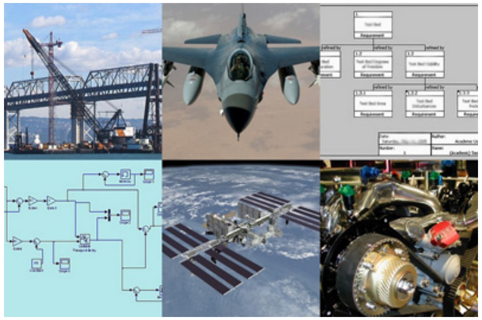
2. Architects Overtaken by their Architecture

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

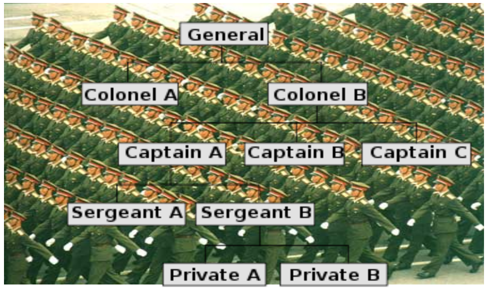


ArchiMate EA example

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

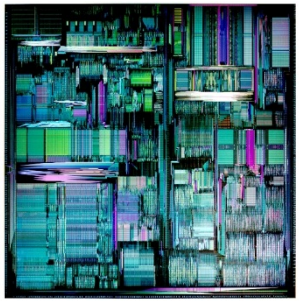


Systems engineering
Wikimedia Commons

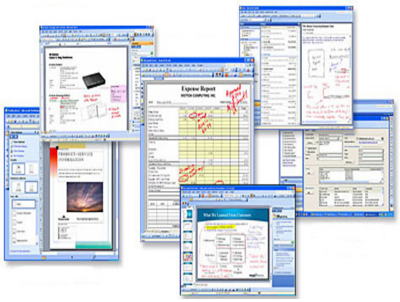


2. Architects Overtaken by their Architecture

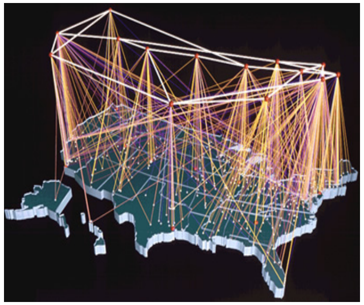
- **Burst to large scale: *de facto* complexification of ICT systems**
  - ✓ ineluctable breakup into, and *proliferation* of, modules/components



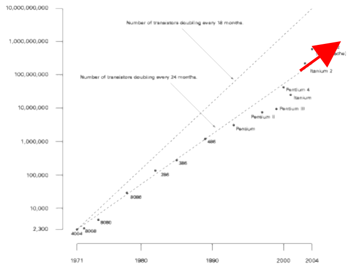
in hardware,



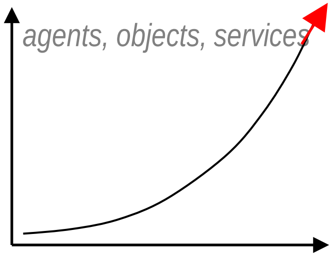
software,



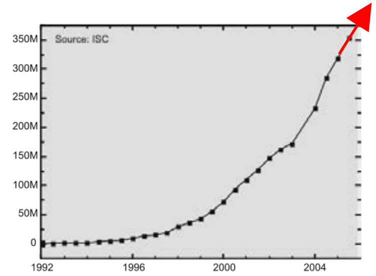
networks...



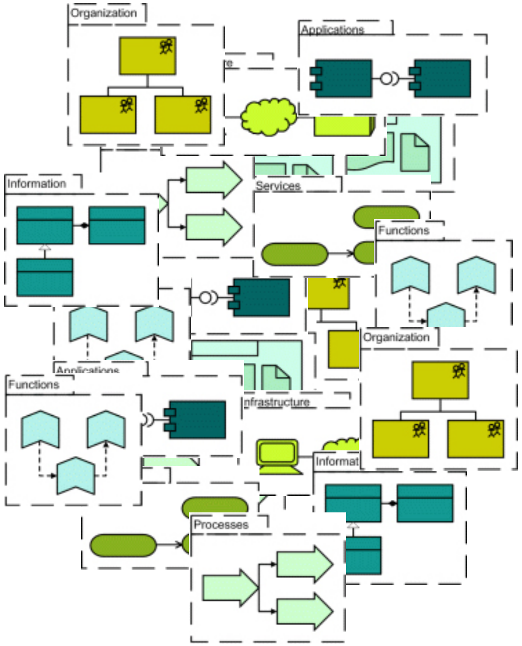
number of transistors/year



number of O/S lines of code/year



number of network hosts/year



... and enterprise architecture?

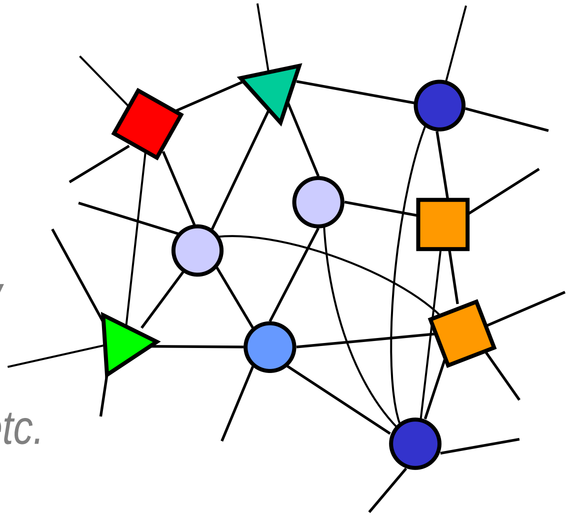
→ *trying to keep the lid on complexity won't work in these systems:*

- 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*

ARCHITECTURE & SELF-ORGANIZATION

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but were not

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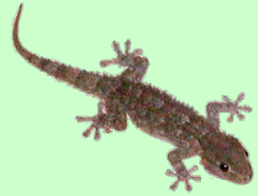
Or how to control spontaneity

3. Architecture Without Architects

➢ "Simple"/random vs. architectured complex systems

biological patterns

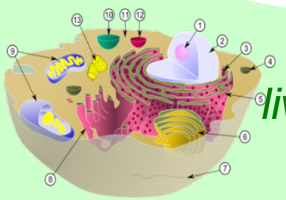
the brain



organisms

ant trails

termite mounds



living cell

animal flocks

physical patterns

➢ biology strikingly demonstrates the possibility of combining pure self-organization and elaborate architecture, i.e.:

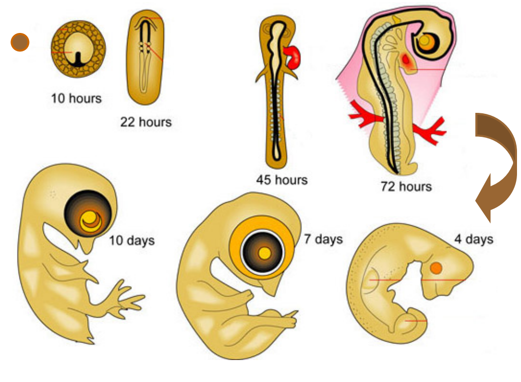
✓ a non-trivial, sophisticated morphology

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

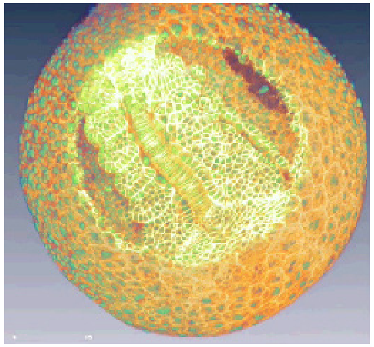
✓ *random* at agent level, *reproducible* at system level

3. Architecture Without Architects

➢ Ex: Morphogenesis – Biological development



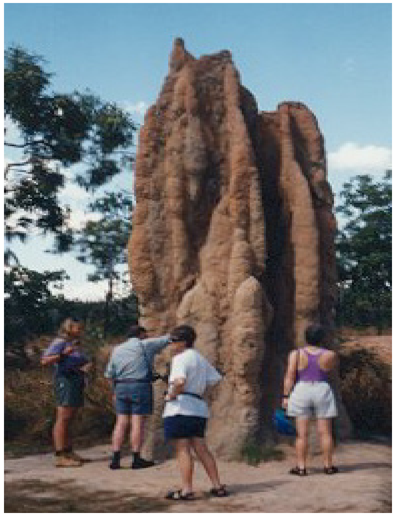
www.infovisual.info



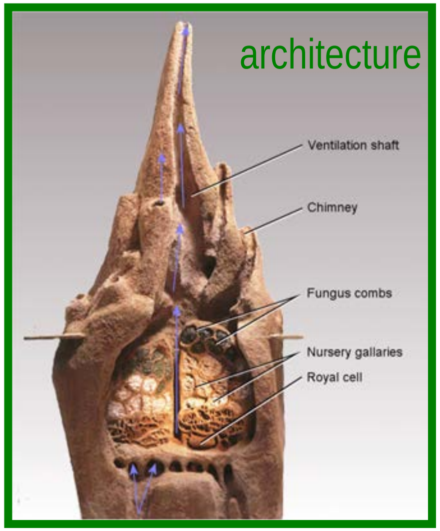
Nadine Peyriéras, Paul Bourgine et al.
(Embryomics & BioEmergences)

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

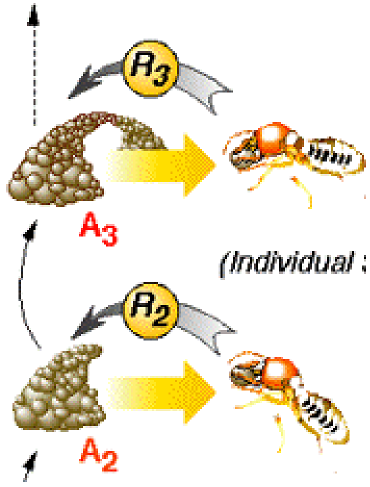
➢ Ex: Swarm intelligence – Termite mounds



Termite mound
(J. McLaughlin, Penn State University)



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

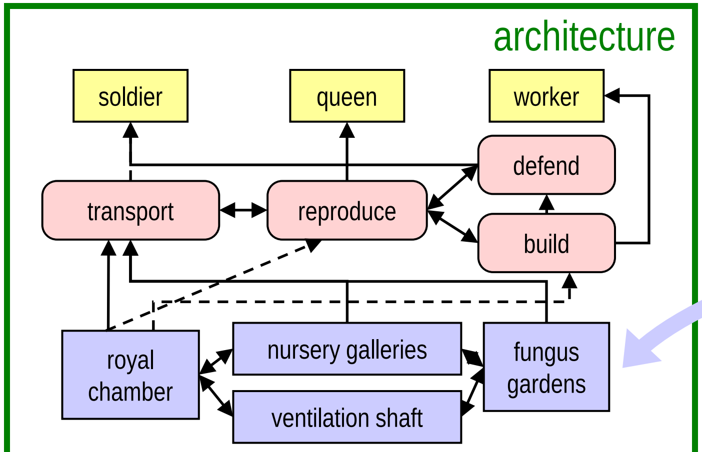


Termite stigmergy
(after Paul Grassé; from Solé and Goodwin, "Signs of Life", Perseus Books)

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

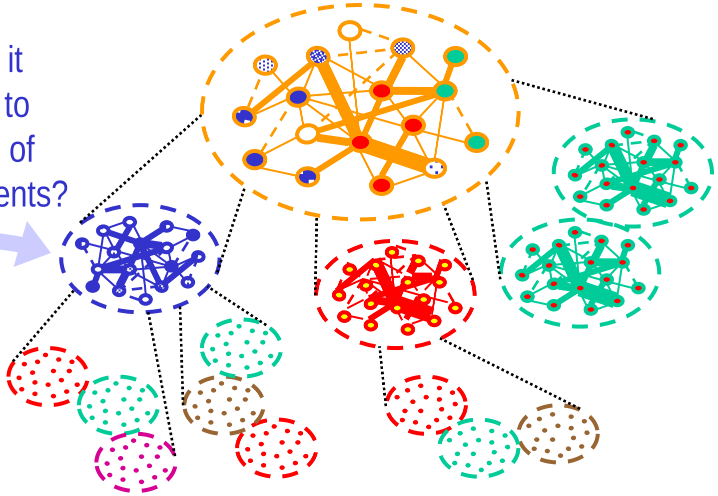
3. Architecture Without Architects

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



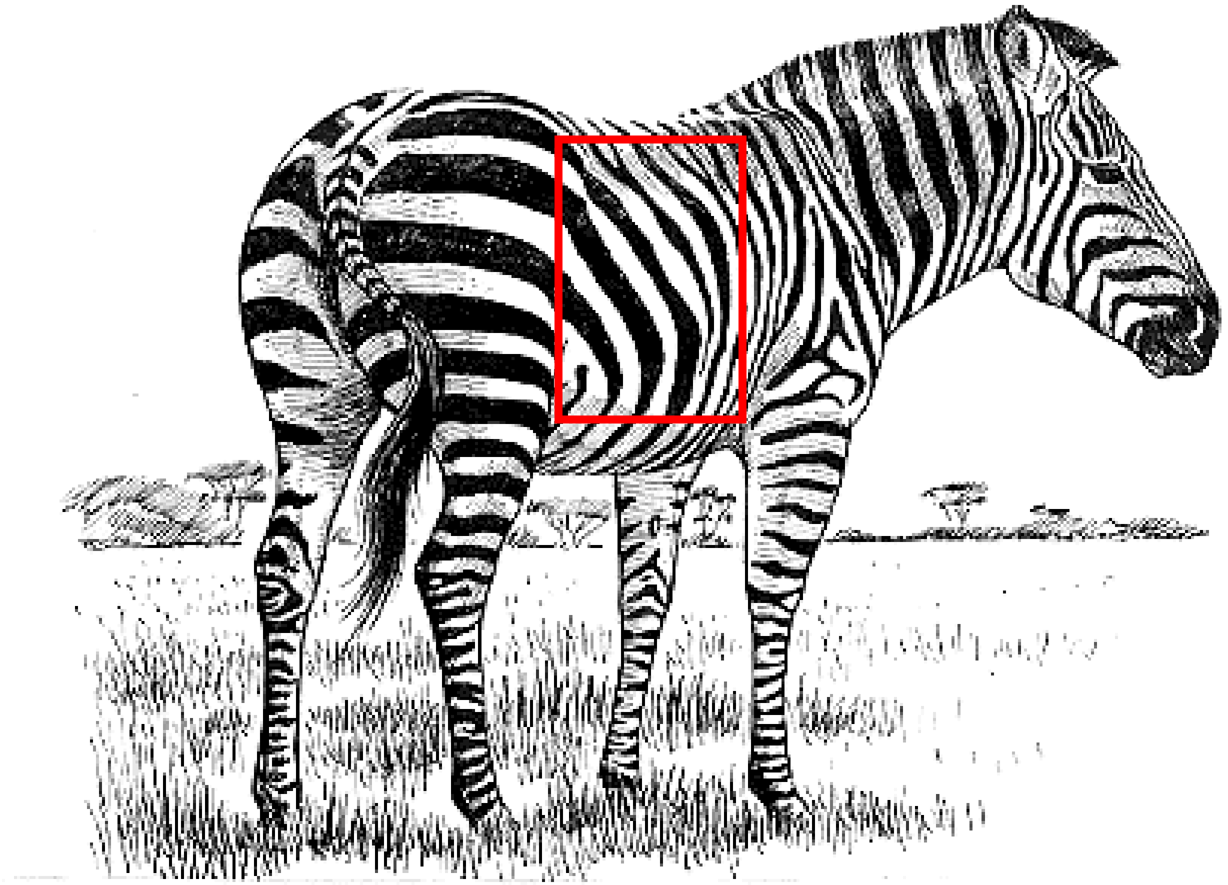
(mockup) EA-style diagram of a termite mound

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



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

Pattern Formation → Morphogenesis



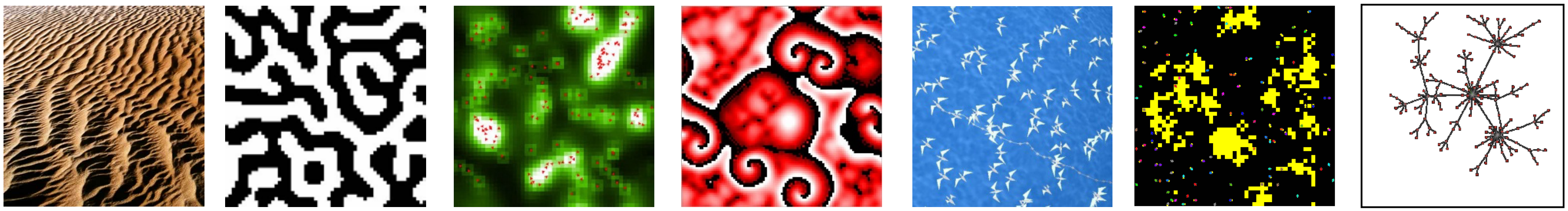
"I have the stripes, but where is the zebra?" OR
"The stripes are easy, it's the horse part that troubles me"
—attributed to A. Turing, after his 1952 paper on morphogenesis

3. Architecture Without Architects

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

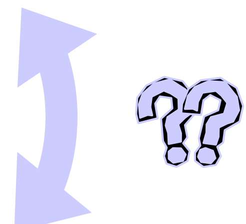
(a) "simple"/random self-organization

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



more architecture

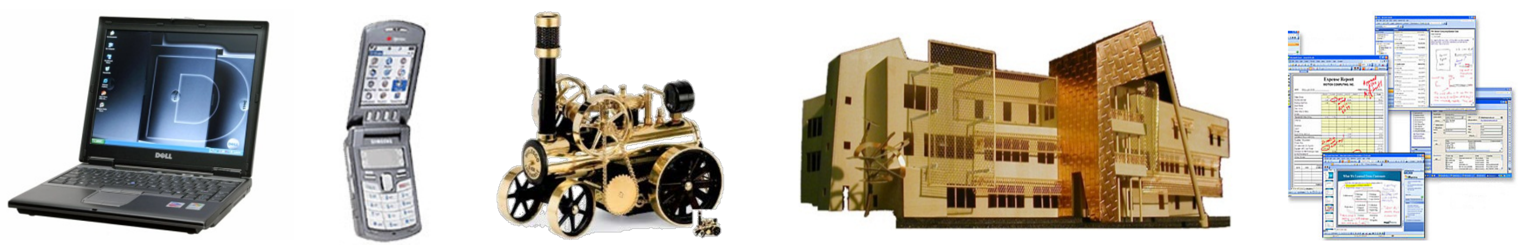
gap to fill



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

more self-organization

(d) direct design (top-down)

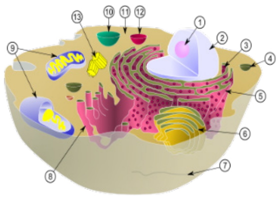


3. Architecture Without Architects

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

more architecture

(b) natural self-organized architecture

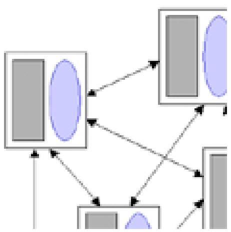


natural

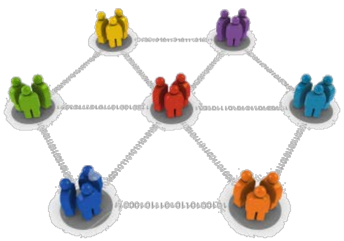
artificial

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

. . . .



SYMBRION Project



. . . .

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

Architecture & Self-Organization

1. What are Complex Systems?
- Decentralization
- Emergence
- Self-organization

2. Architects Overtaken by their Architecture

Designed systems that became suddenly complex

3. Architecture Without Architects

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

but were not

4. Morphogenetic Engineering

From cells and insects to robots and networks

5. Bio-Inspiration and Artificial Evo-Devo

Or how to control spontaneity

4. Morphogenetic Engineering

A closer look at morphogenesis: it couples assembly and patterning

➢ Sculpture → forms

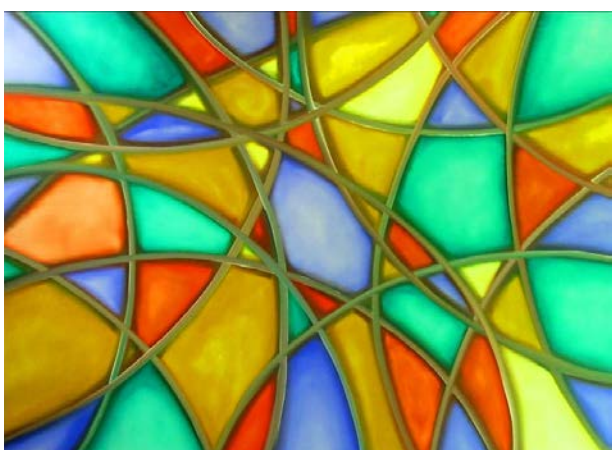
Ádám Szabó, *The chicken or the egg* (2005)
http://www.szaboadam.hu

“shape from patterning”

✓ the forms are “sculpted” by the self-assembly of the elements, whose behavior is triggered by the colors

Niki de Saint Phalle

➢ Painting → colors



“patterns from shaping”

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

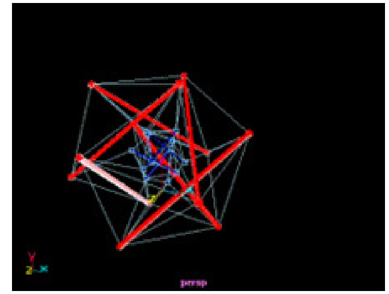
4. Morphogenetic Engineering

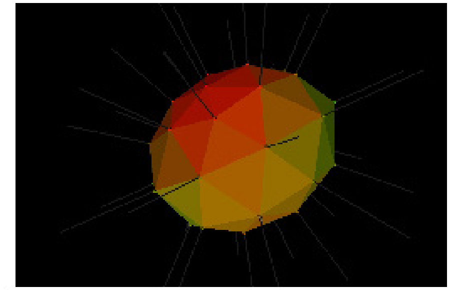
A closer look at morphogenesis: ⇔ it couples mechanics and genetics

➢ Cellular mechanics

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

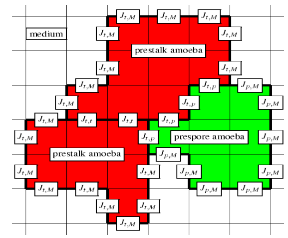
Tensional integrity
Donald Ingber, Harvard

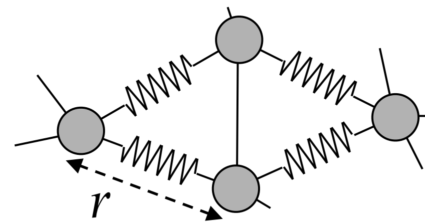




Deformable volume
Doursat, simul. by Delile

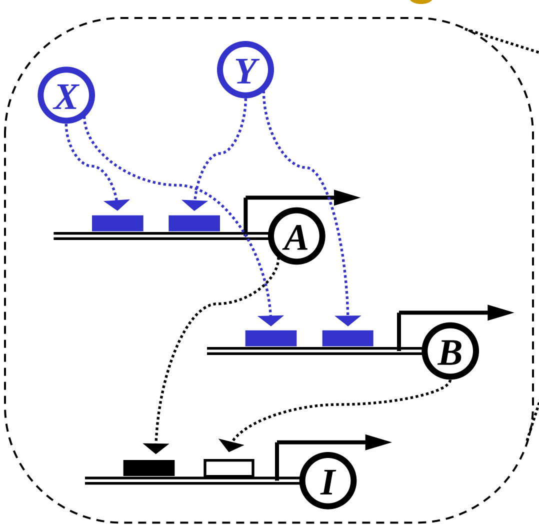
Cellular Potts model
Graner, Glazier, Hogeweg
http://www.compucell3d.org

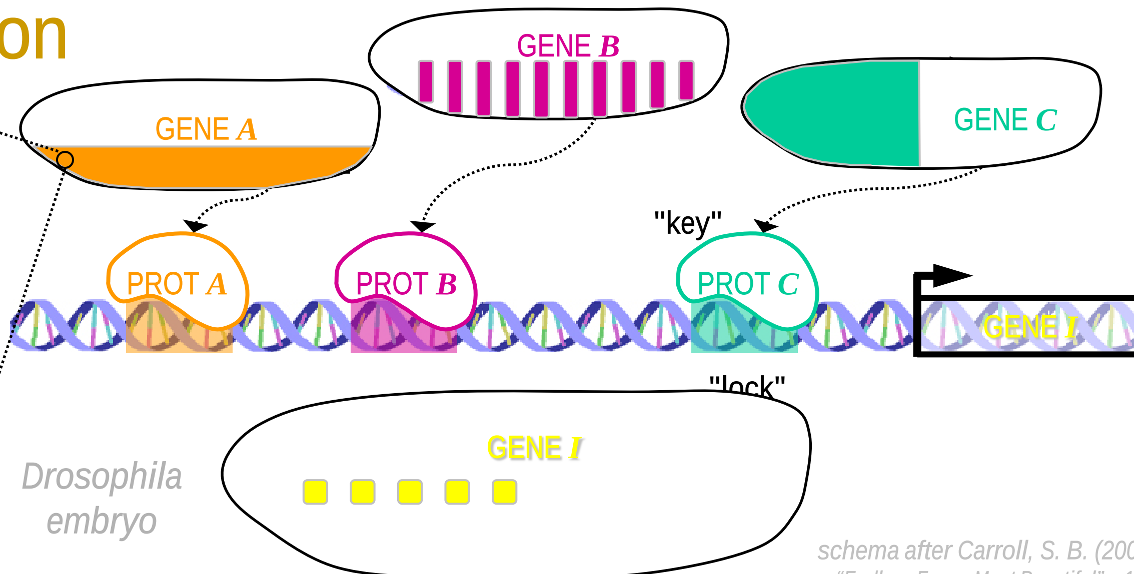




Spring-mass model
Doursat (2009) ALIFE XI

➢ Genetic regulation



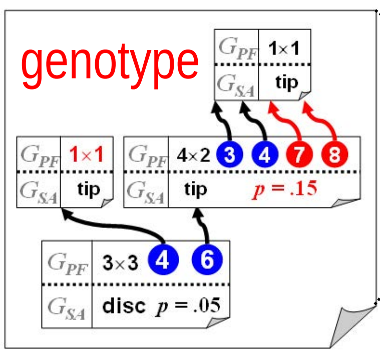


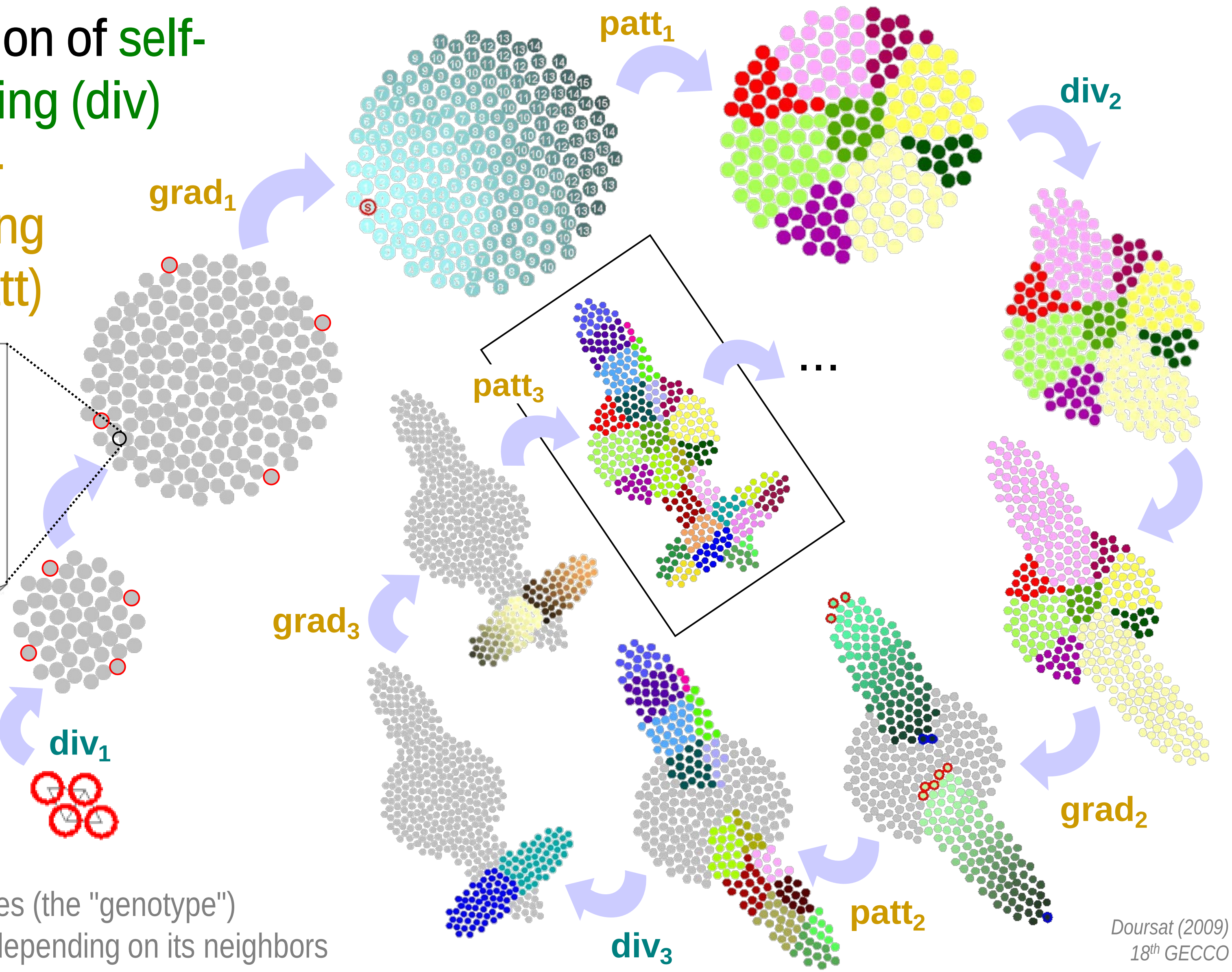
schema after Carroll, S. B. (2005)
"Endless Forms Most Beautiful", p117

4. Morphogenetic Engineering

Capturing the essence of morphogenesis in an Artificial Life agent model

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

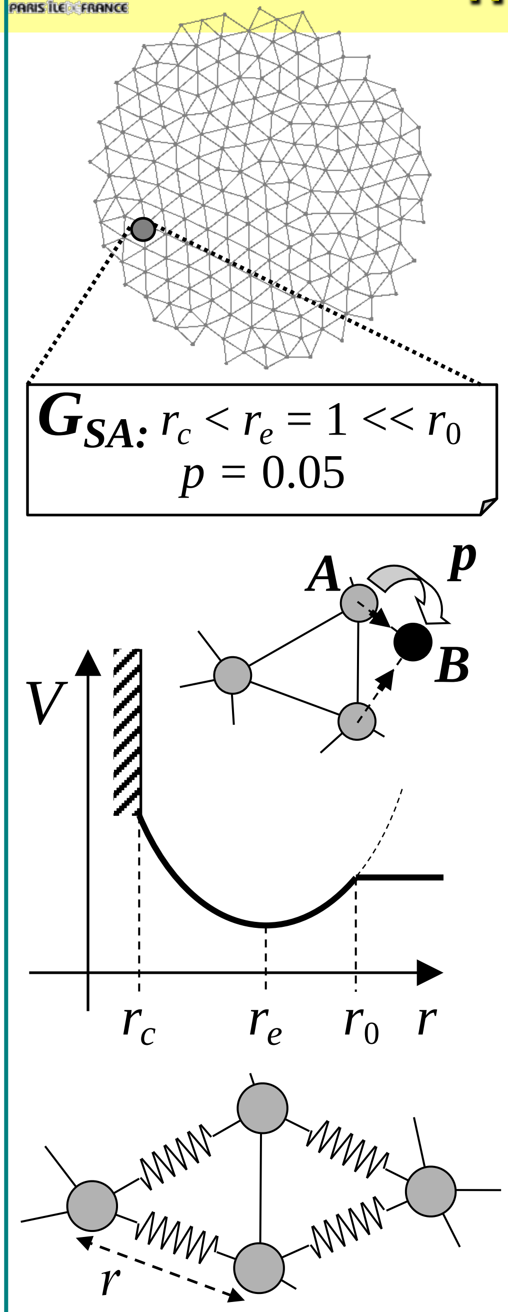


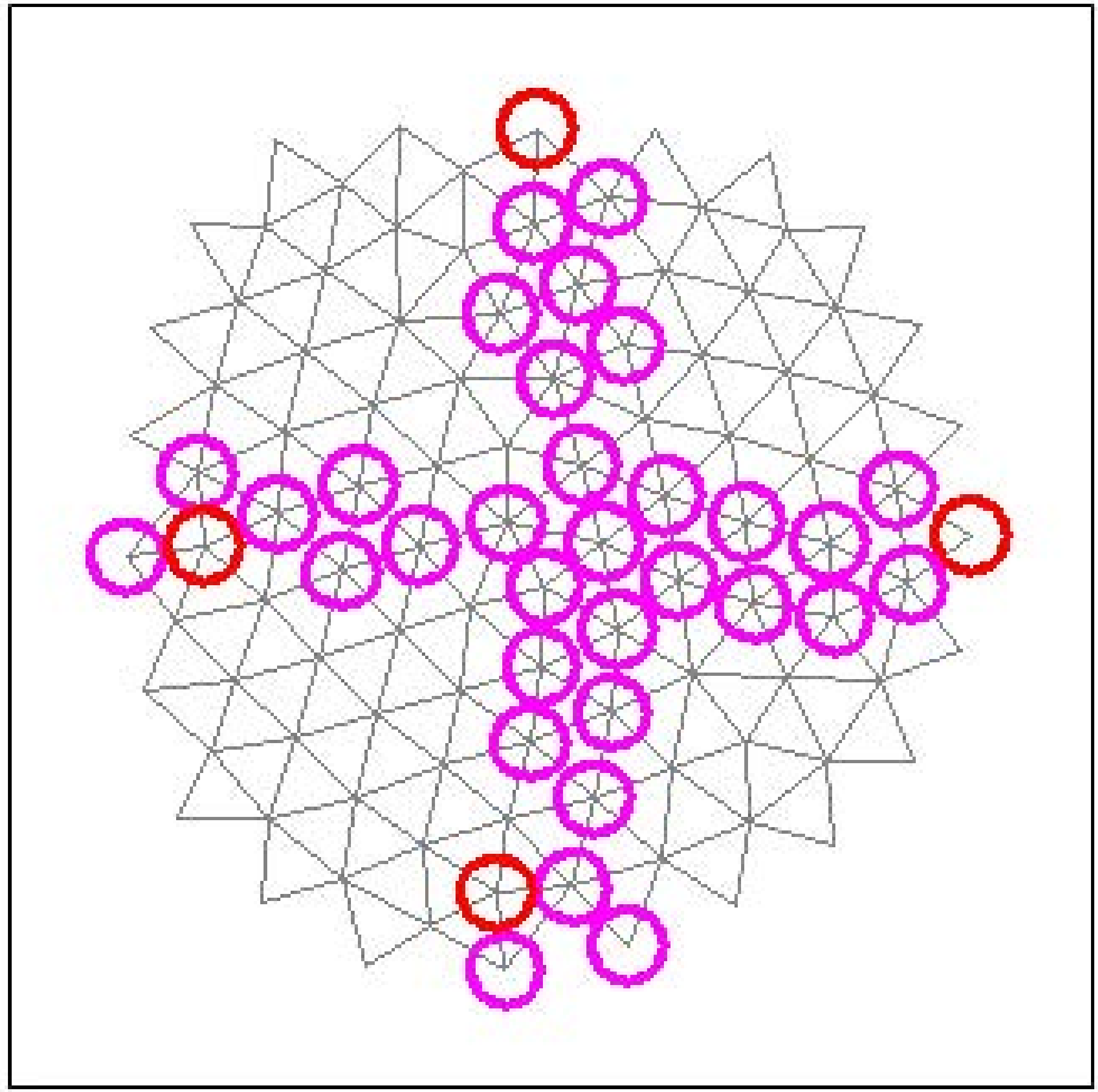


each agent
follows the same set
of self-architecting rules (the "genotype")
but reacts differently depending on its neighbors

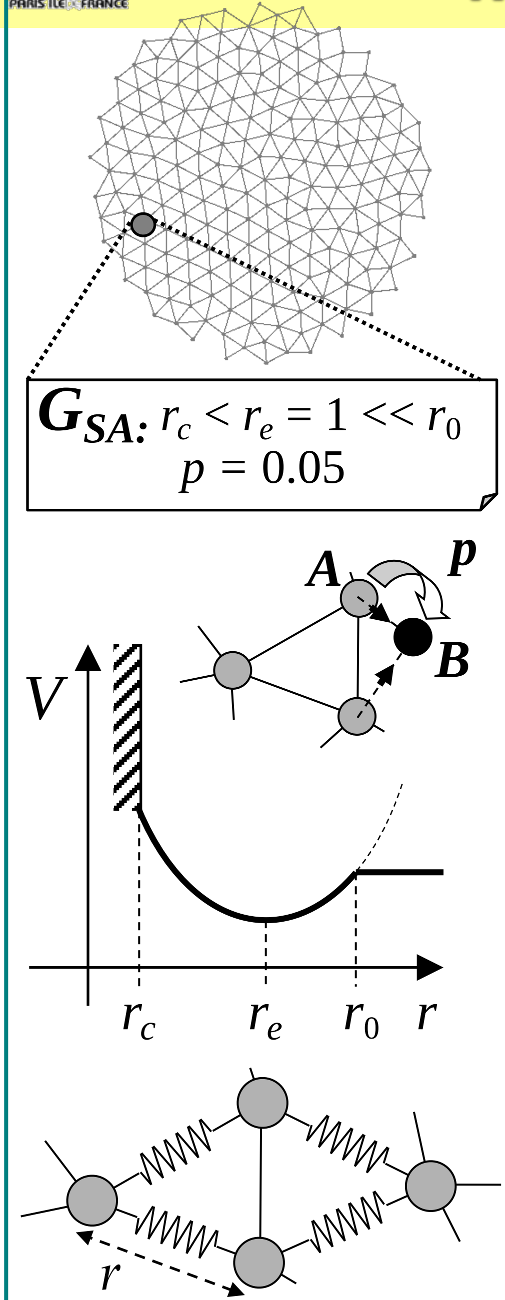
Doursat (2009)
18th GECCO

4. Morphogenetic Engineering





4. Morphogenetic Engineering

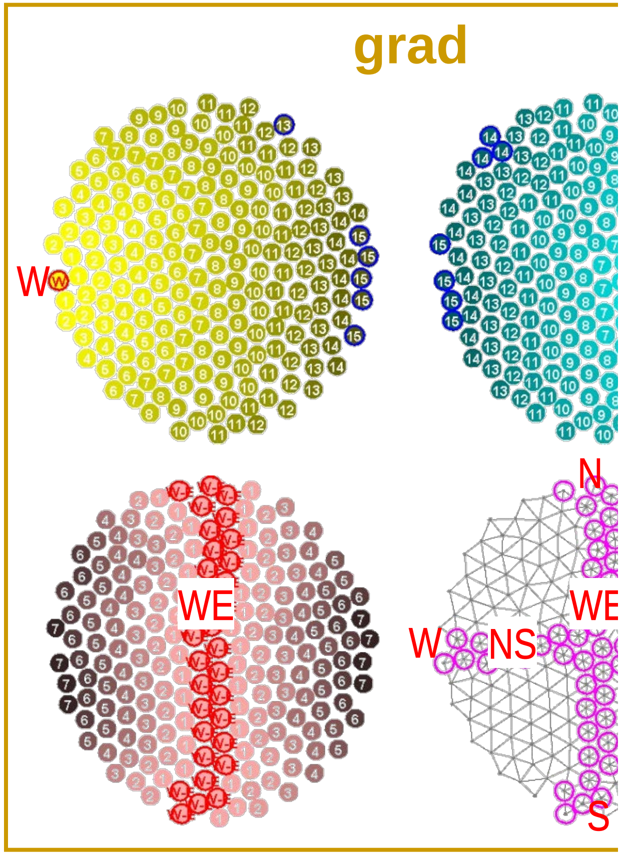


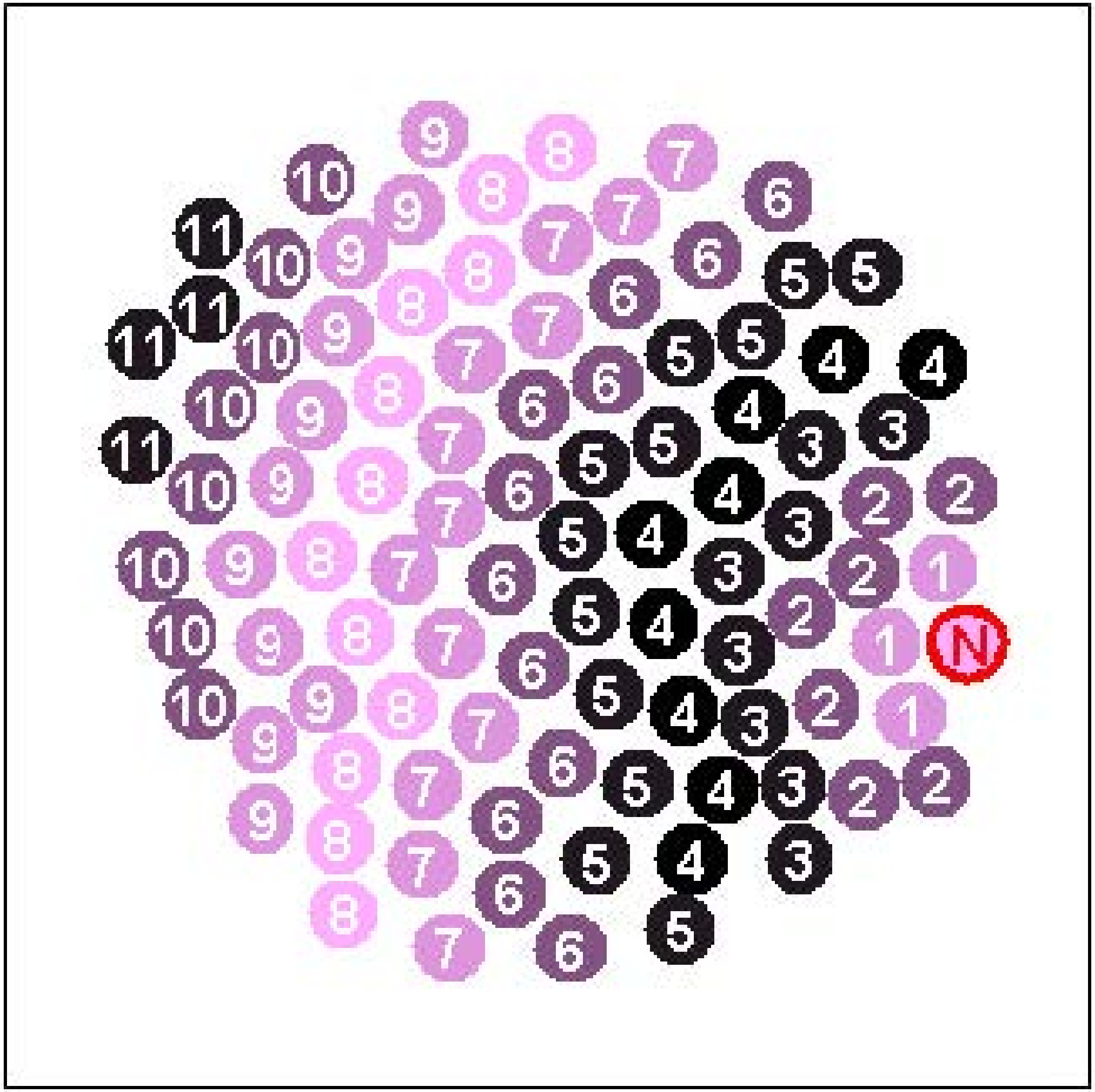
$$m\ddot{\mathbf{r}}^{cd} = -k\left(1-\frac{r_0}{\left\|\mathbf{r}^{cd}\right\|}\right)\mathbf{r}^{cd} - \eta\dot{\mathbf{r}}^{cd}.$$

$$\Downarrow$$

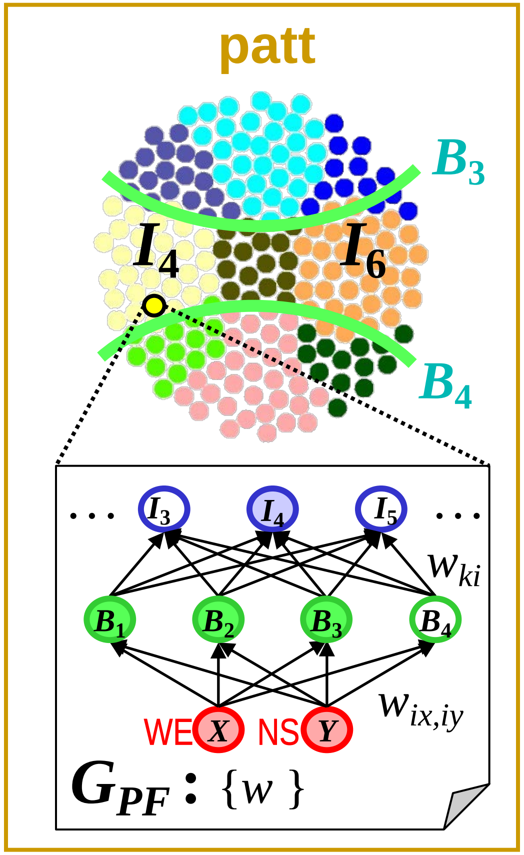
$$\Delta\mathbf{r}^{c} = -\Delta\mathbf{r}^{d} = \frac{\Delta\mathbf{r}^{cd}}{2} = -\frac{k}{2\eta}\left(1-\frac{r_0}{\left\|\mathbf{r}^{cd}\right\|}\right)\mathbf{r}^{cd}.$$

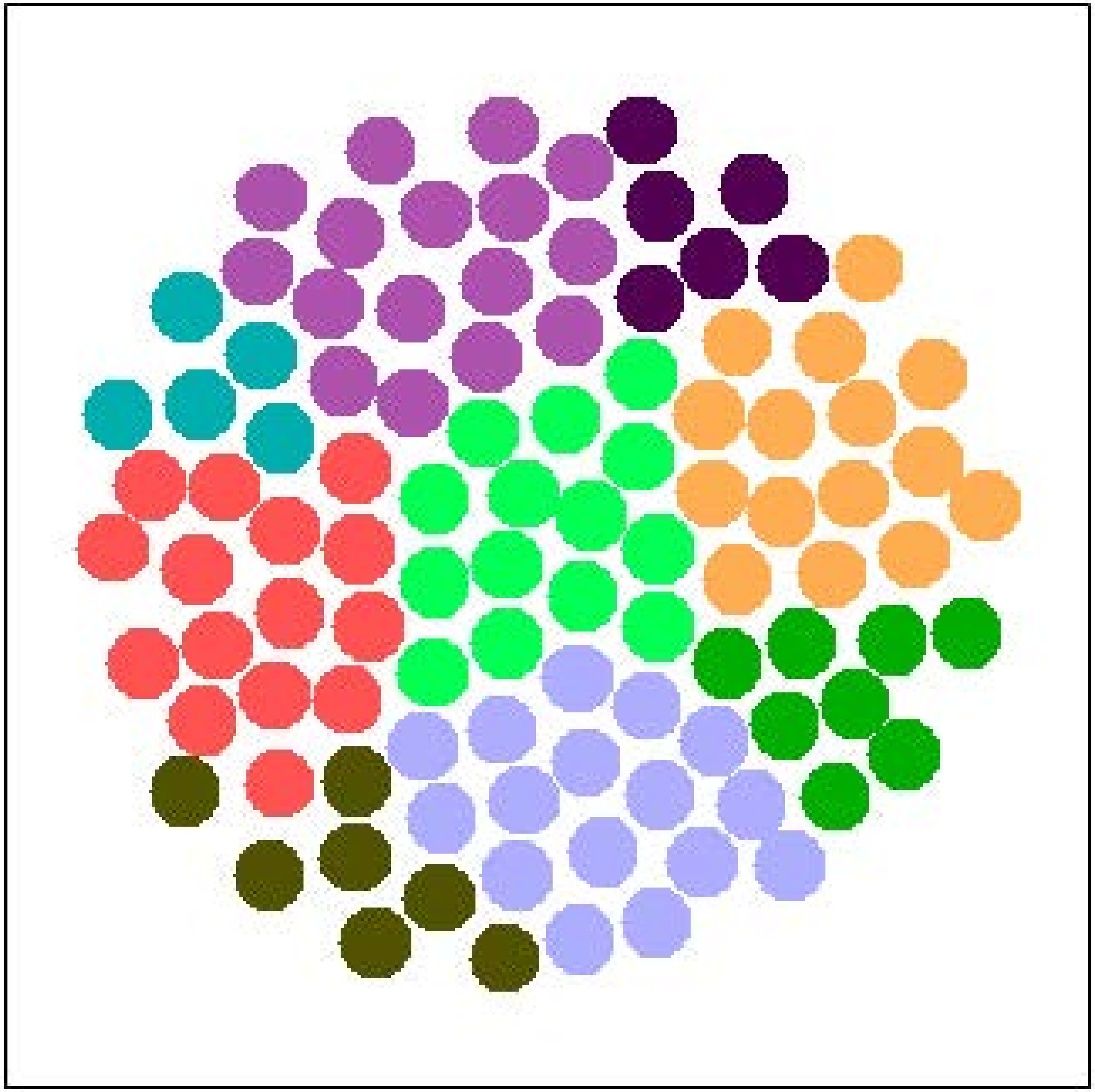
4. Morphogenetic Engineering





4. Morphogenetic Engineering



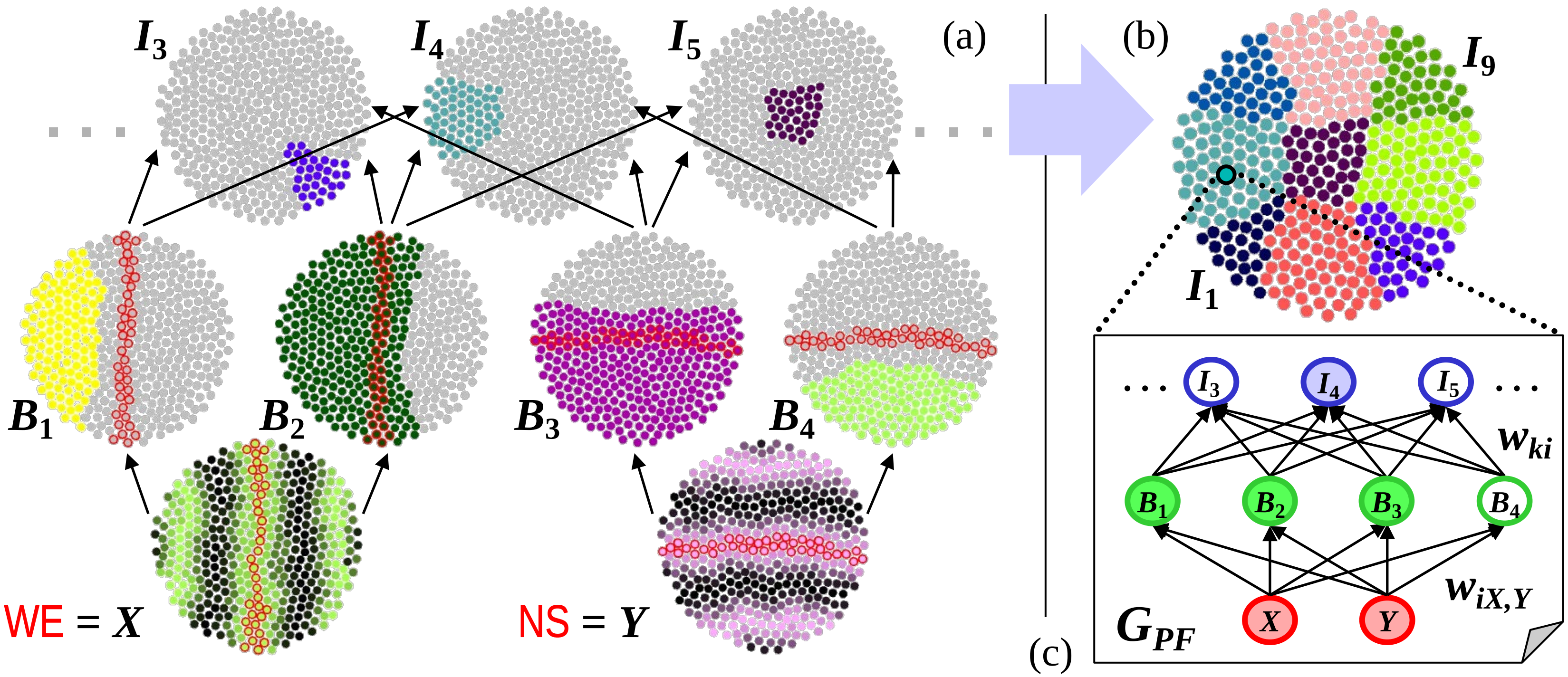


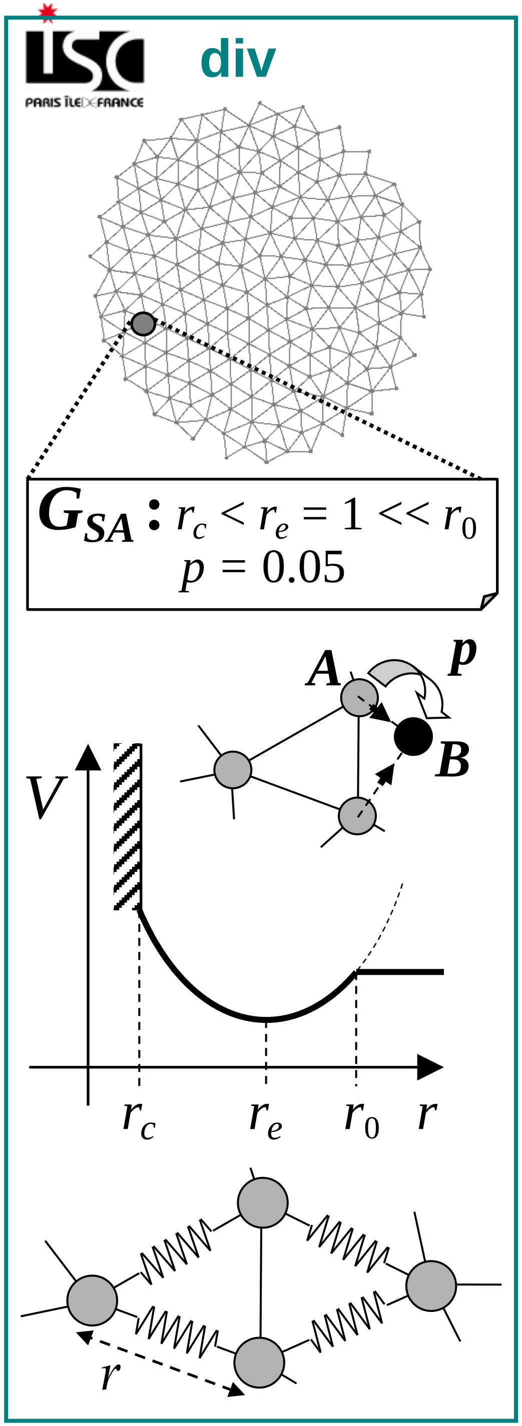
➢ Programmed patterning (patt): the hidden embryo atlas

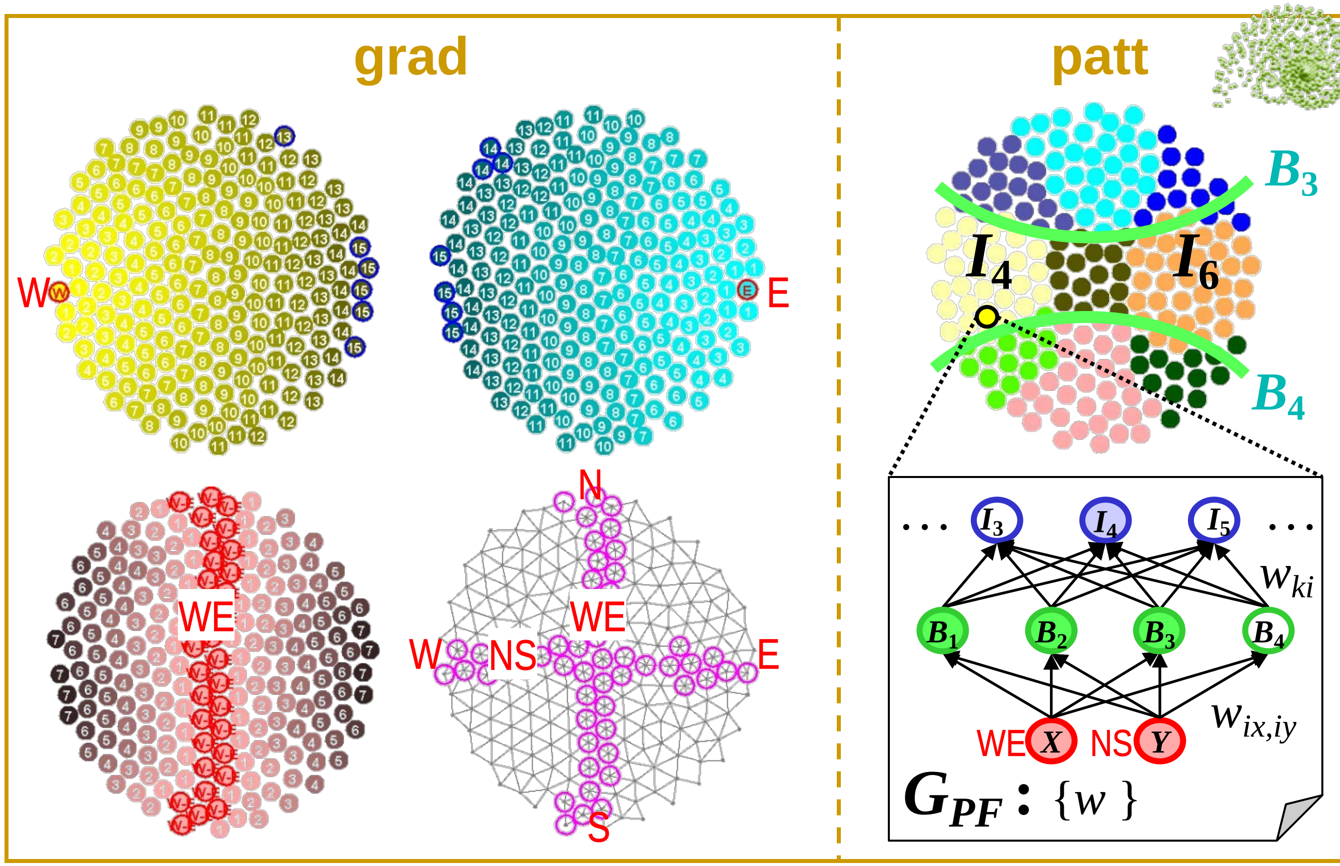
a) same swarm in different colormaps to visualize the agents' internal patterning variables X, Y, B_i and I_k (virtual *in situ hybridization*)

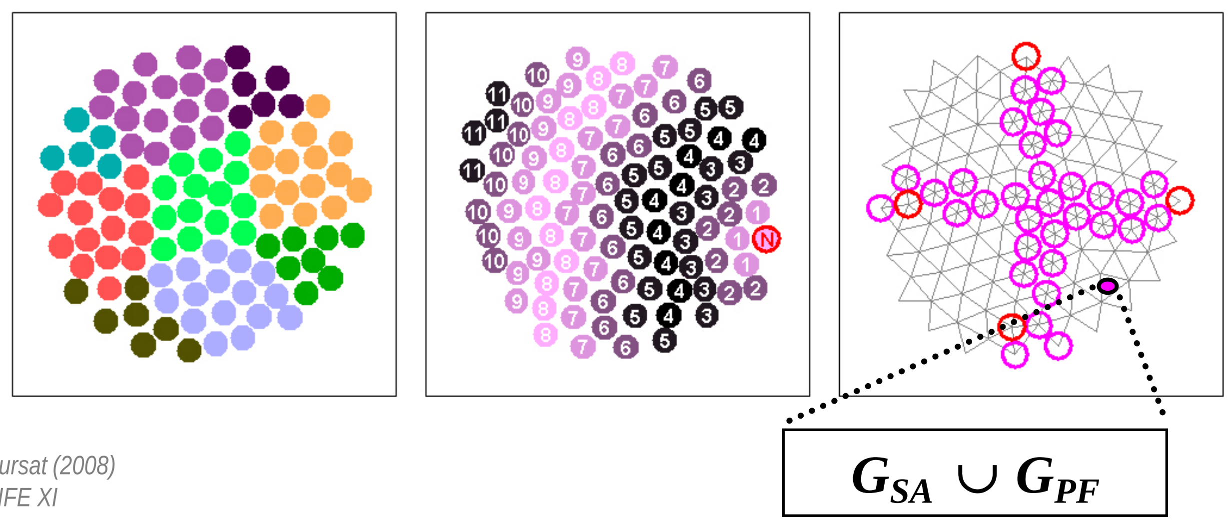
b) consolidated view of all identity regions I_k for $k = 1...9$

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.









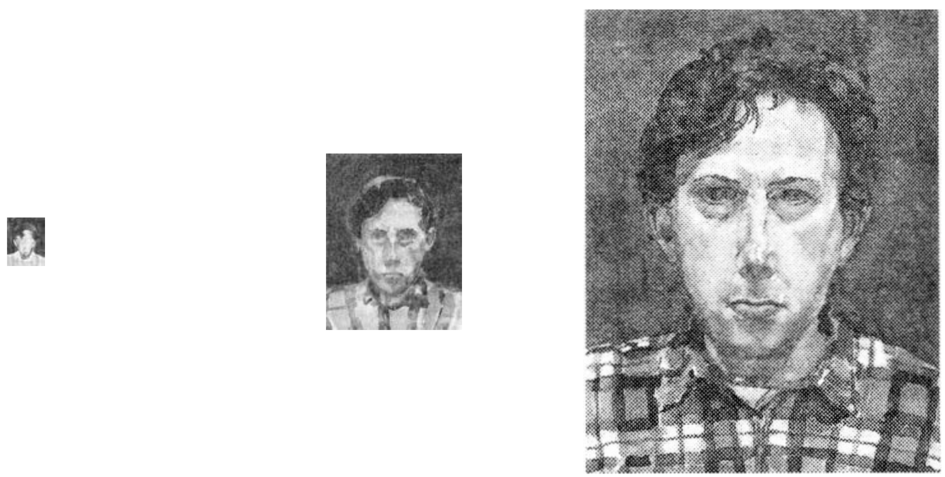
Doursat (2008)
ALIFE XI

4. Morphogenetic Engineering

➢ Morphological refinement by iterative growth

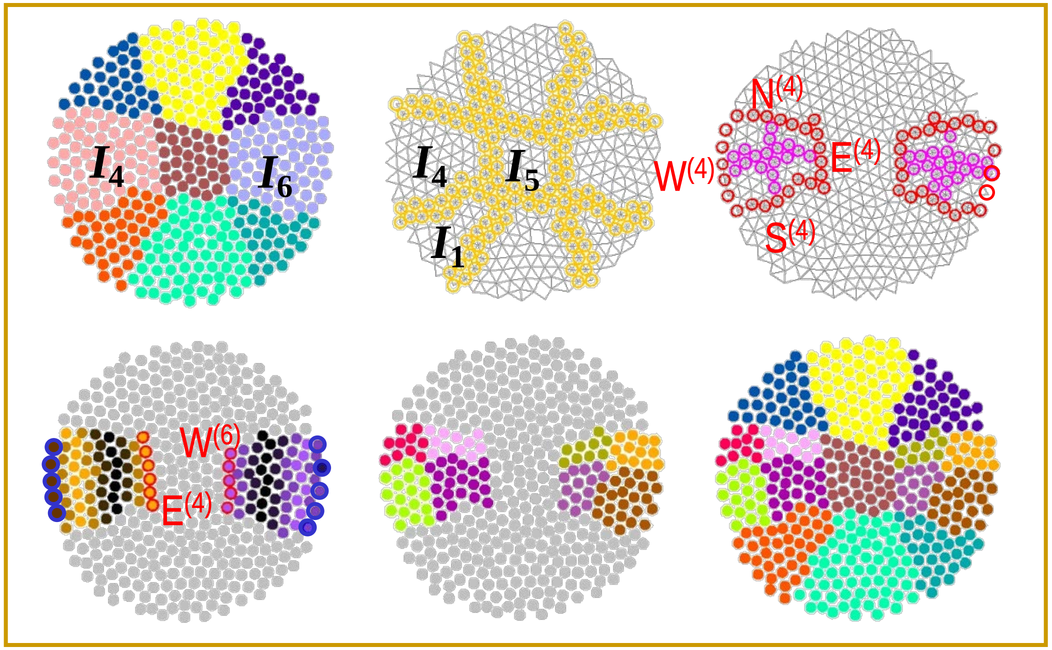
- ✓ details are not created in one shot, but gradually added. . .

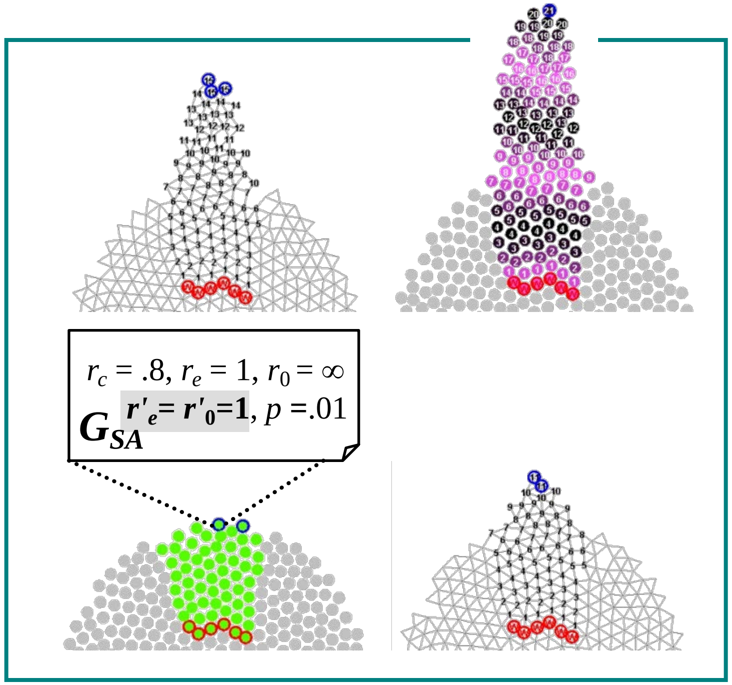
- ✓ . . . while, at the same time, the canvas grows

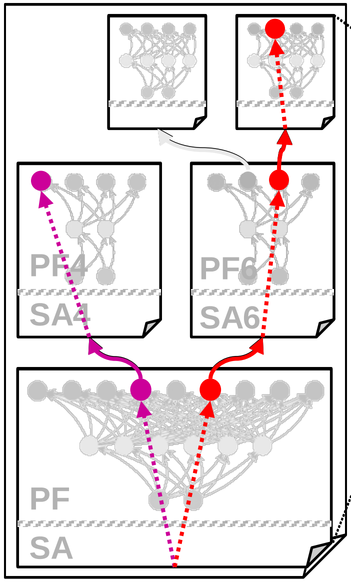


from Coen, E. (2000)
The Art of Genes, pp131-135

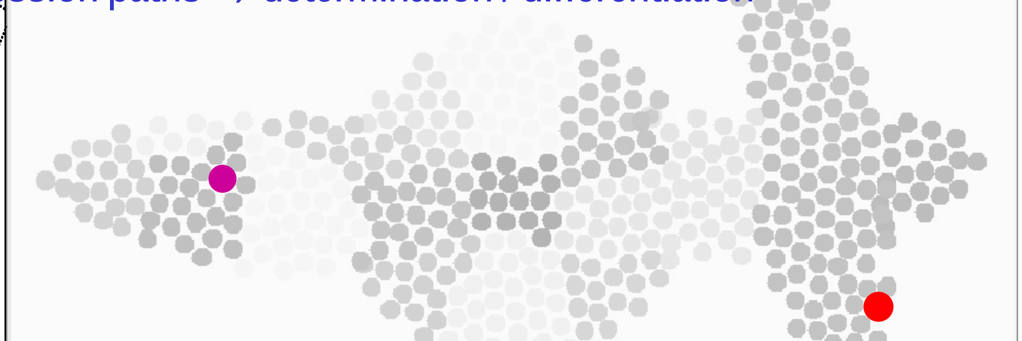
4. Morphogenetic Engineering: Devo







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



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

Doursat (2008)
ALIFE XI, Winchester

- Derivative projects

ME: Devo-Evo

ME: Devo-MecaGen

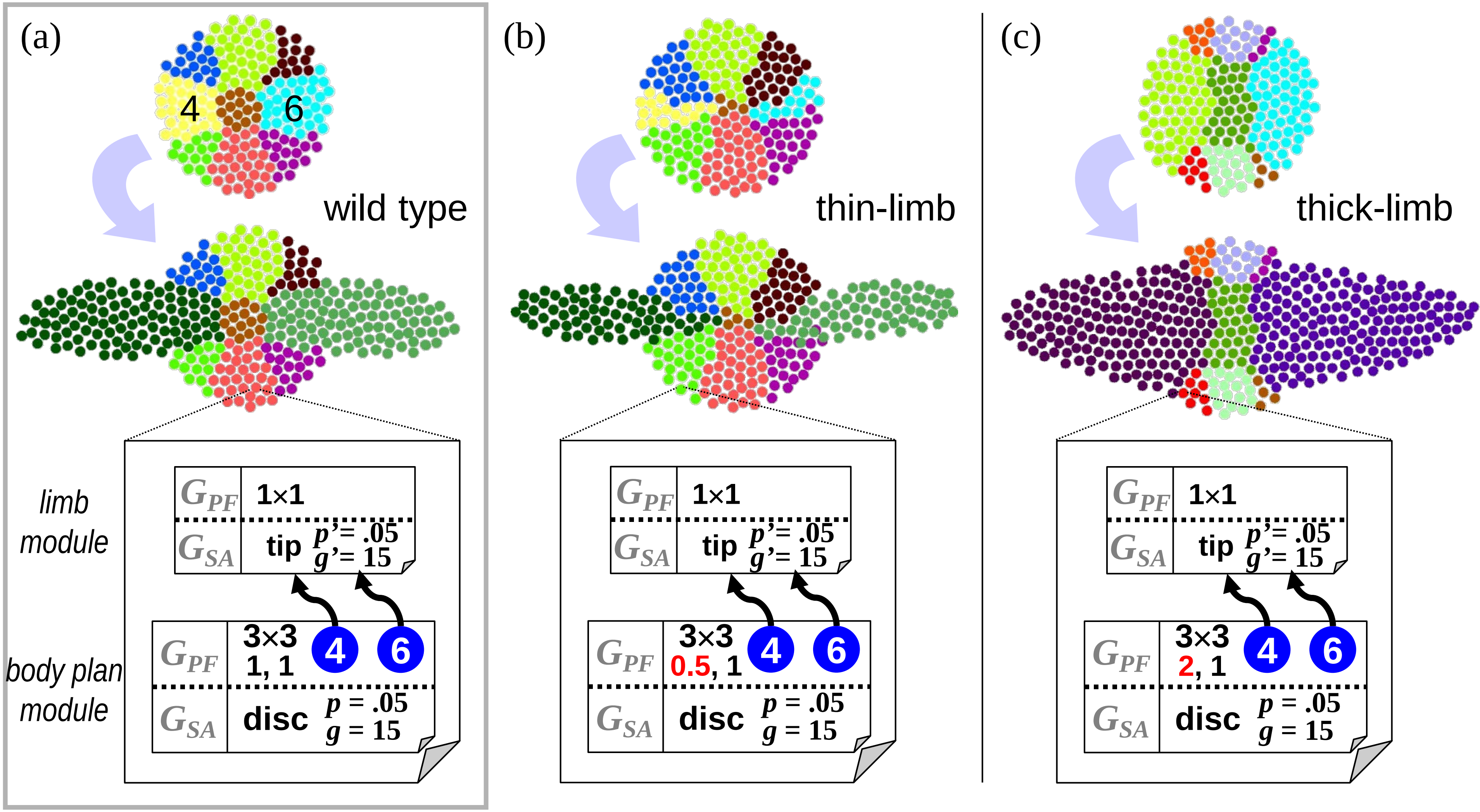
ME: Devo-Bots

ME: Devo-SynBioTIC

ME: ProgNet

ME: ProgNet-Ecstasy

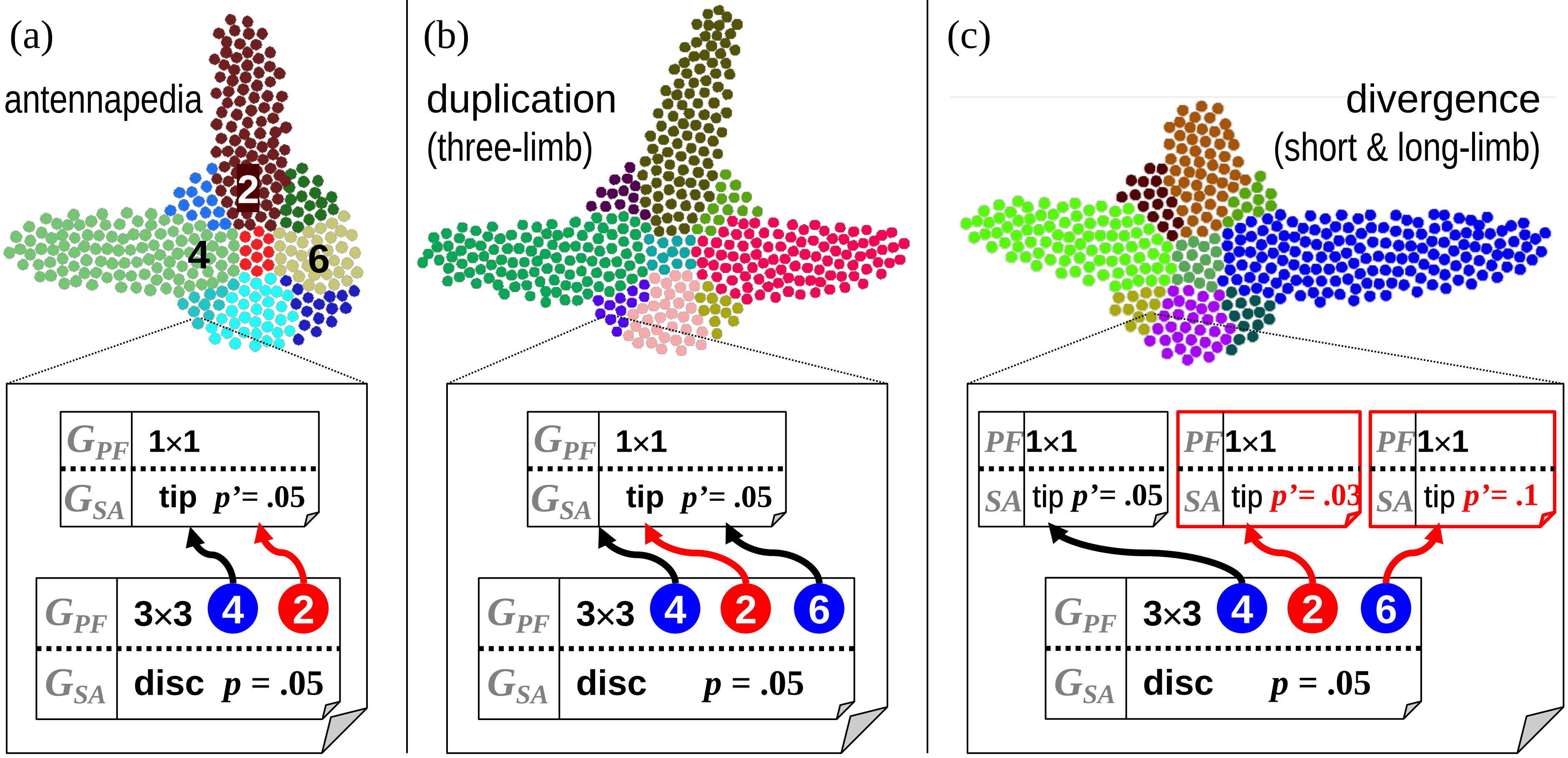
- Quantitative mutations: limb thickness



4. Morphogenetic Engineering: Devo-Evo

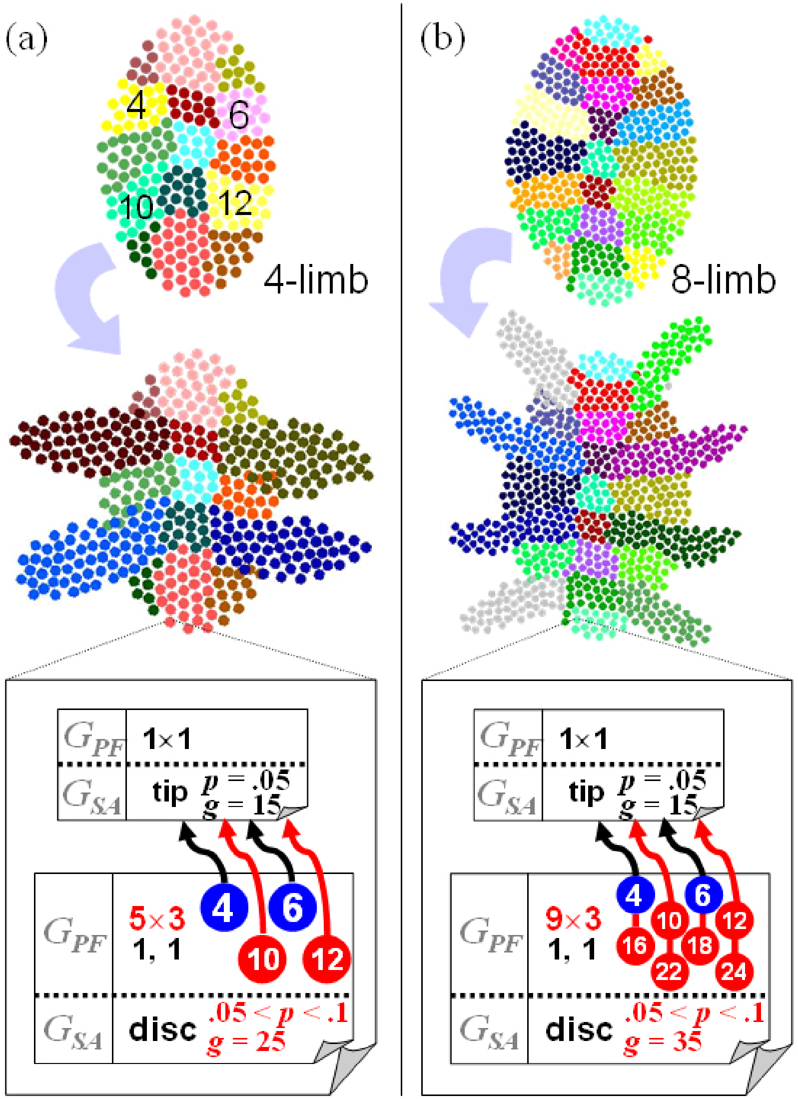
➢ Qualitative mutations: limb position and differentiation

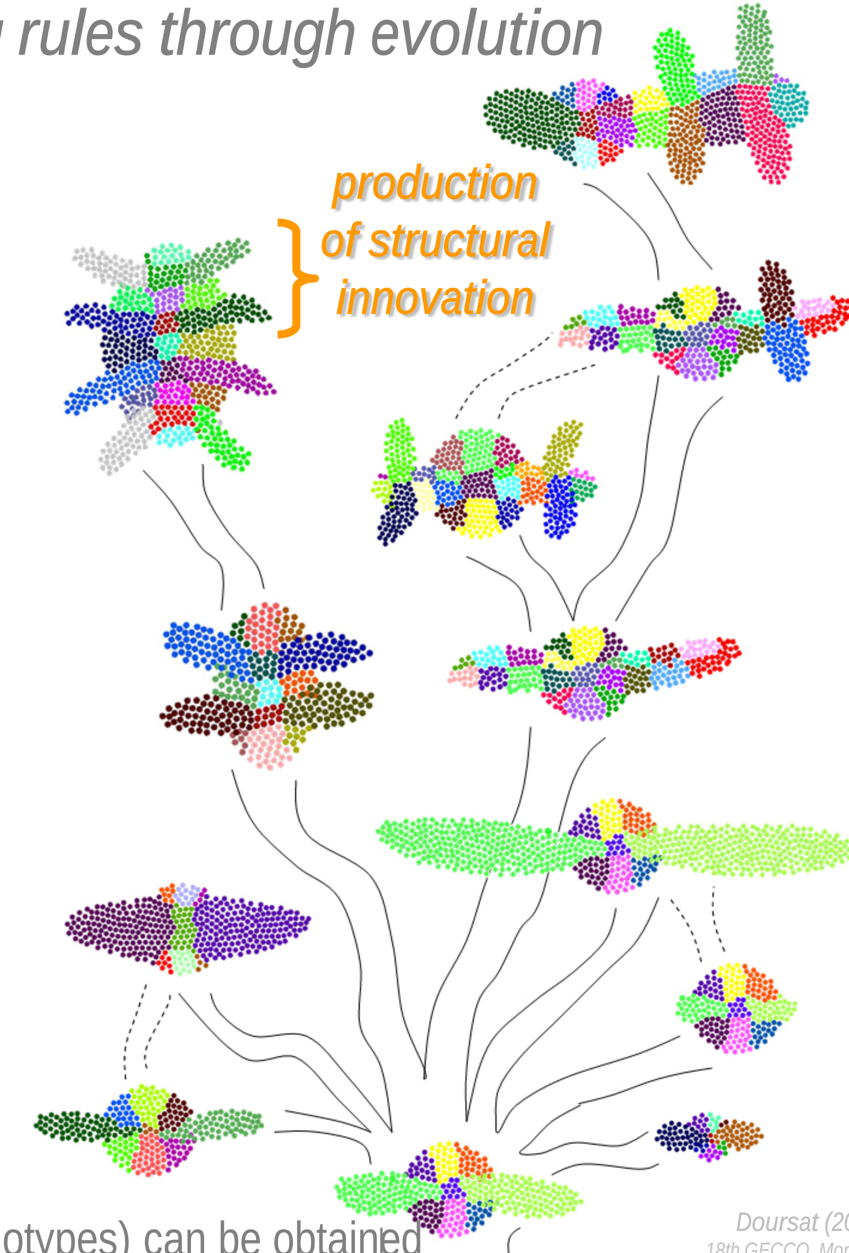
antennapedia | *homology* by *duplication* | *divergence* of the homology



4. Morphogenetic Engineering: Devo-Evo

Changing the agents' self-architecting rules through evolution





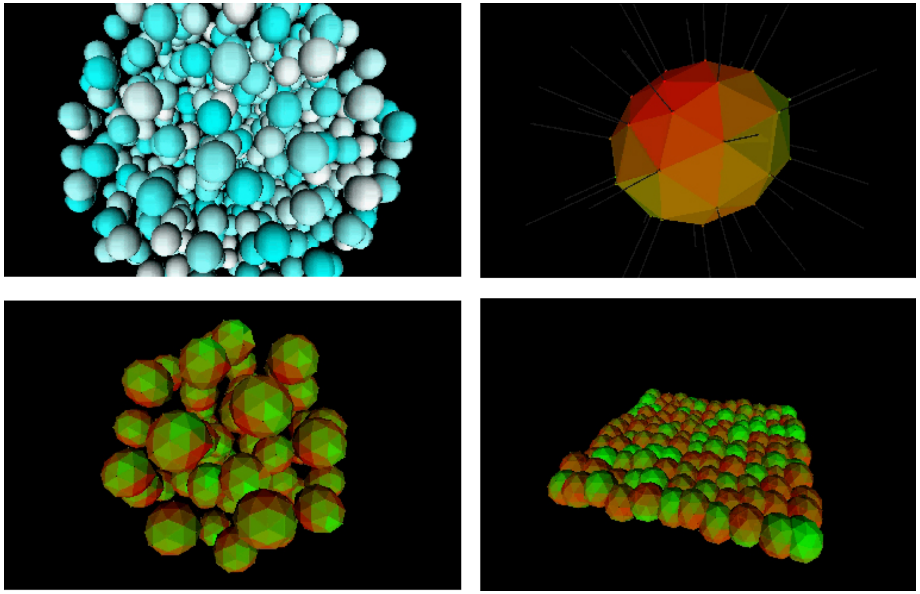
by tinkering with the genotype, new architectures (phenotypes) can be obtained

Doursat (2009)
18th GECCO, Montreal

4. Morphogenetic Engineering: Devo-MecaGen

➢ More accurate mechanics

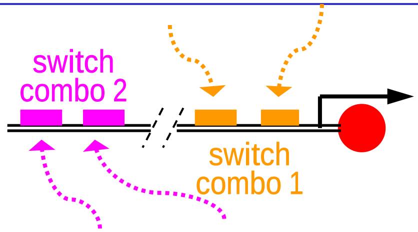
- ✓ 3-D
- ✓ individual cell shapes
- ✓ collective motion, migration
- ✓ adhesion

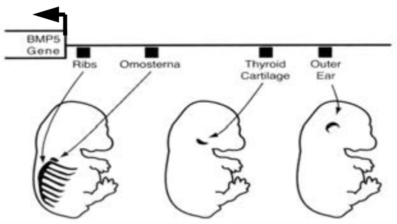


(Delile, Doursat, Peyrieras)

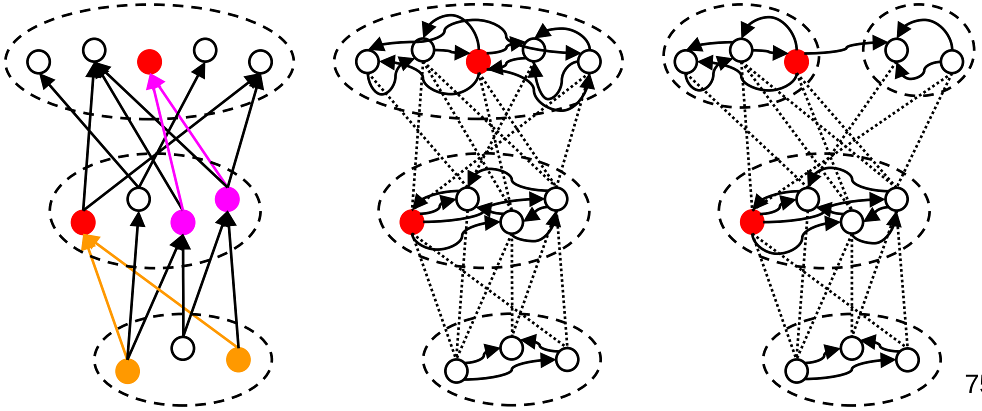
➢ Better gene regulation

- ✓ recurrent links
- ✓ gene reuse
- ✓ kinetic reaction ODEs
- ✓ attractor dynamics



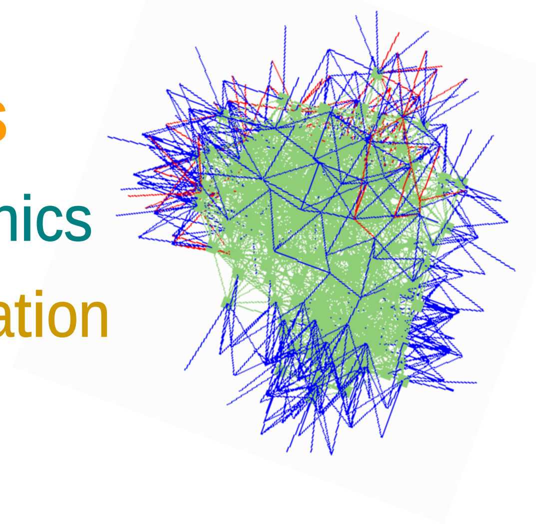


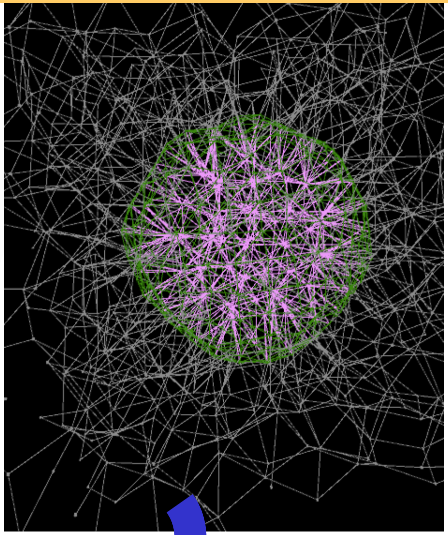
after David Kingsley, in Carroll, S. B. (2005) *Endless Forms Most Beautiful*, p125



4. Morphogenetic Engineering: Devo-MecaGen

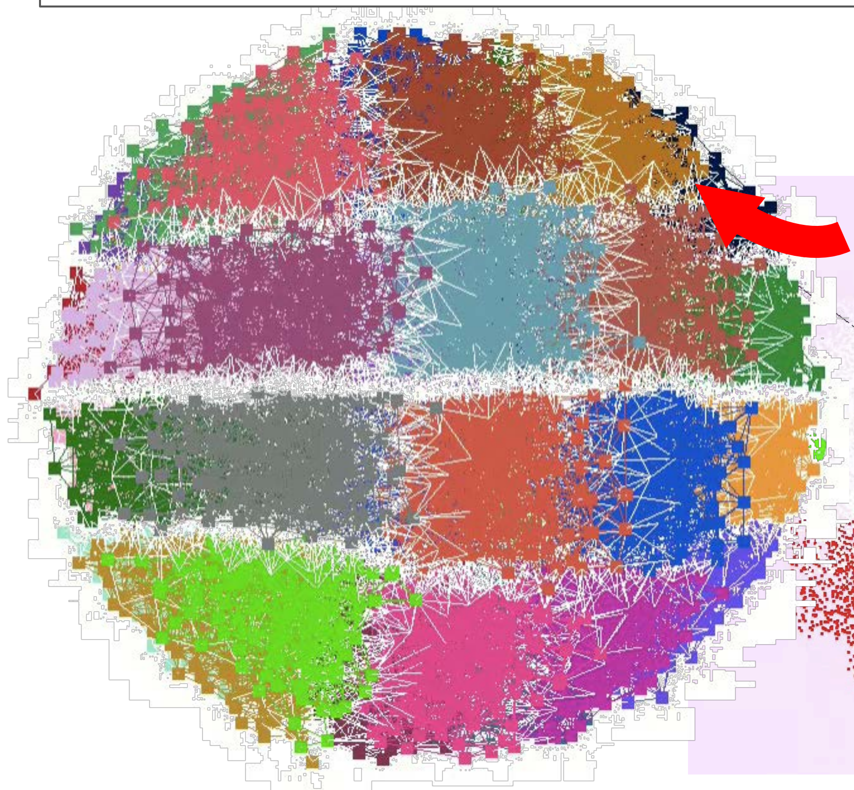
- Multi-agent embryogenesis
  - ✓ 3D particle-based mechanics
  - ✓ kinetic-based gene regulation

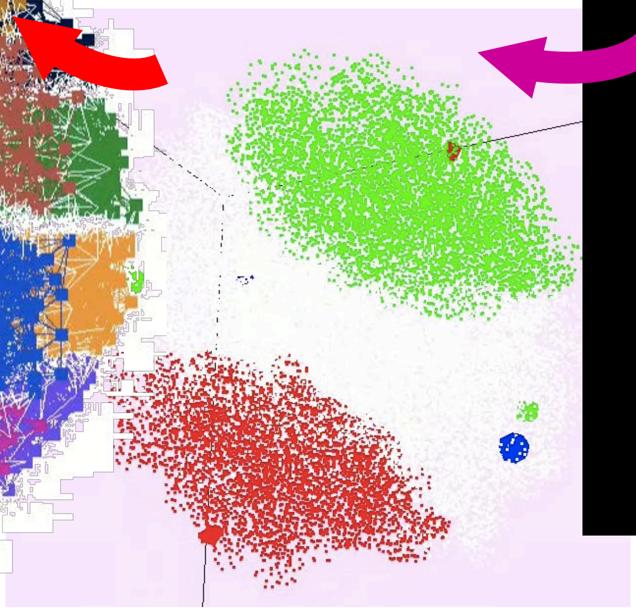


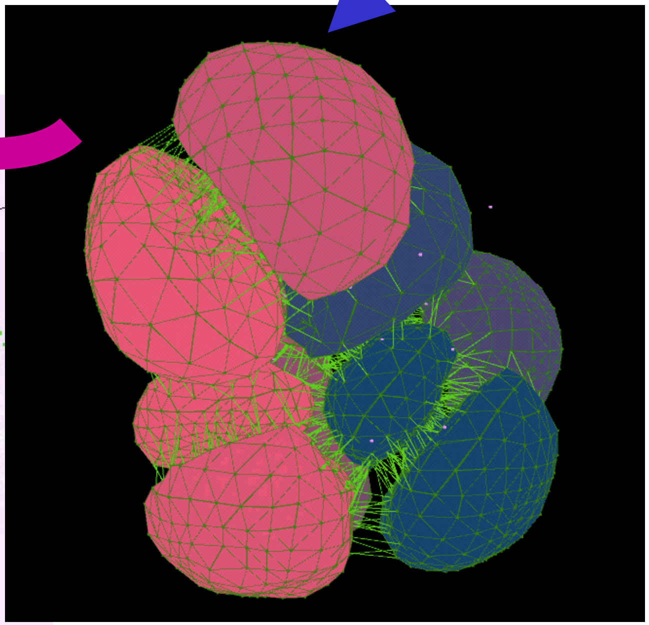


PhD student: **Julien Delile** (FdV, DGA), co-supervised by
- **Nadine Peyriéras**, CNRS Gif s/Yvette
- (**Stéphane Doncieux**, LIP6)

simulations by
Julien Delile



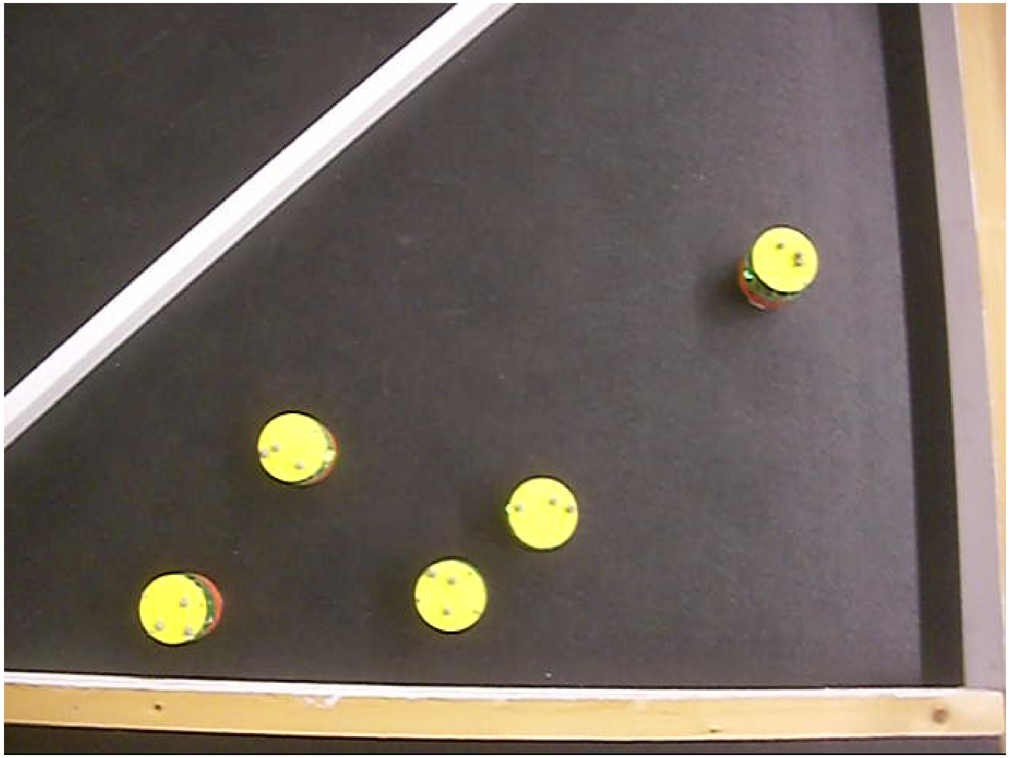


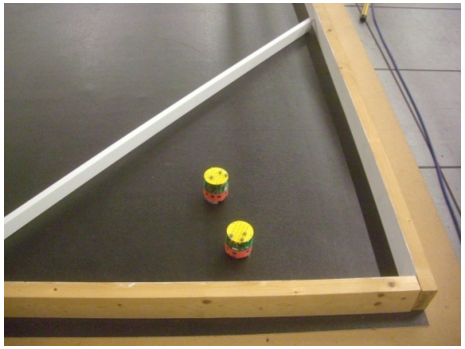


4. Morphogenetic Engineering: Devo-Bots

- 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

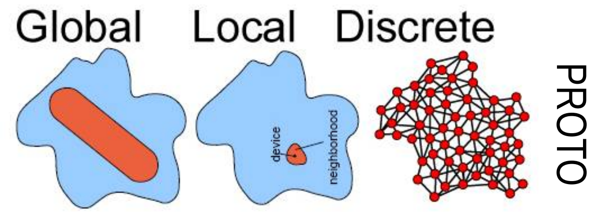




4. Morphogenetic Engineering: Devo-SynBioTIC

➢ 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

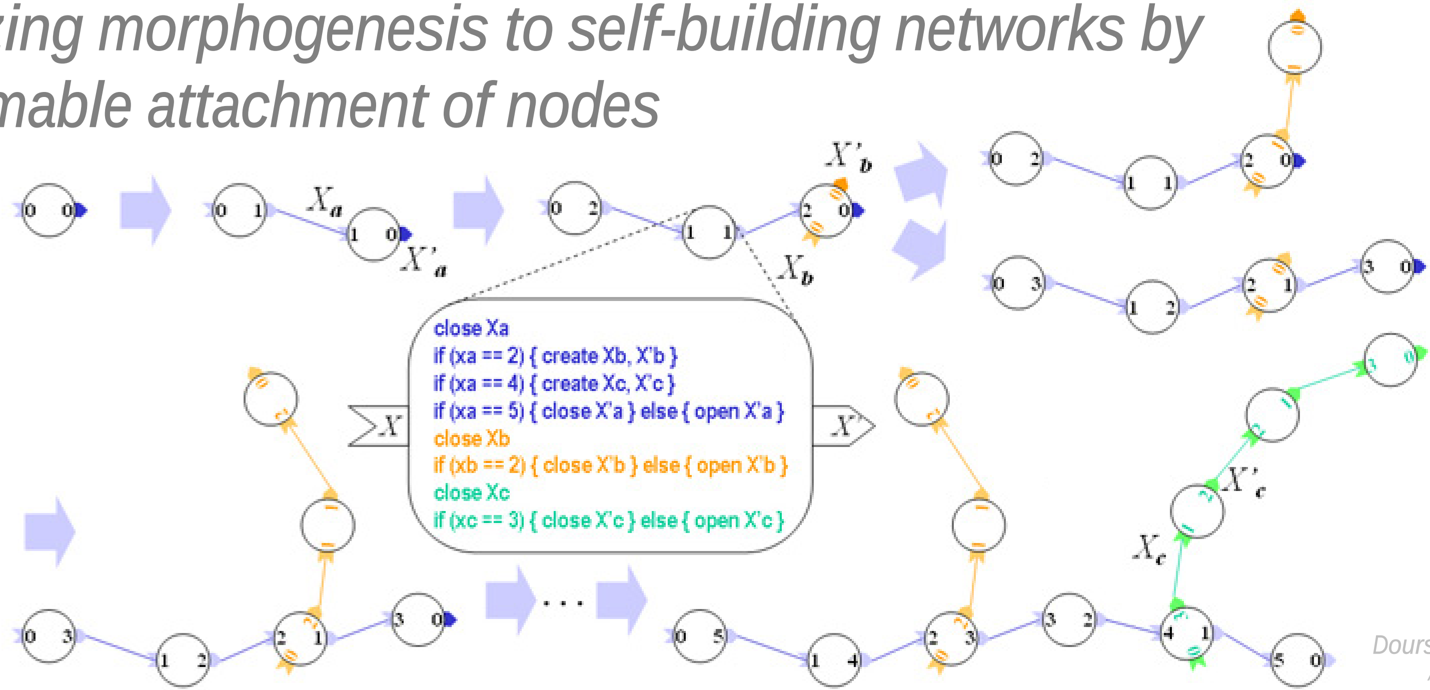
[Même] si pour l'instant la biologie synthétique se focalise sur la « programmation d'une seule bactérie », le développement de biosystèmes un tant soit peu complexe reposera sur le fonctionnement intégré de colonies bactériennes et donc sur la prise en compte d'interactions spatiales au sein d'une population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

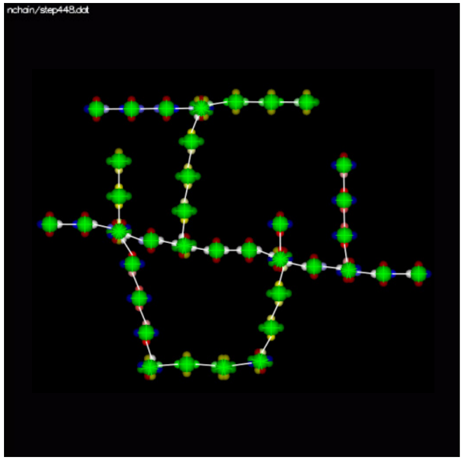
Projet SynBioTIC, 2010

4. Morphogenetic Engineering: ProgNet

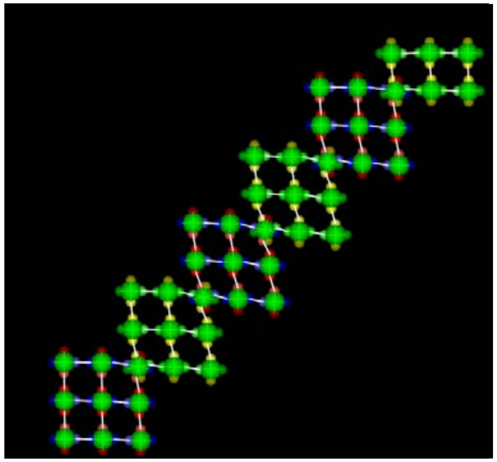
Generalizing morphogenesis to self-building networks by programmable attachment of nodes



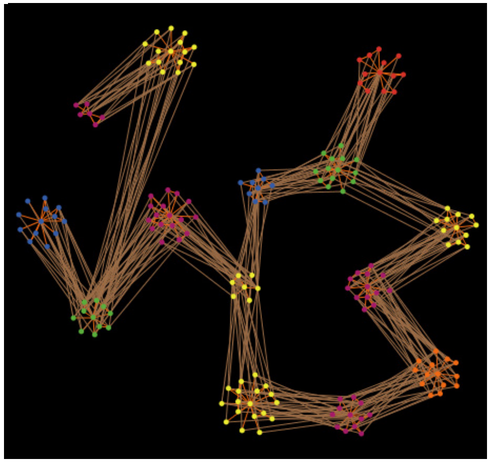
Doursat & Ulieru (2008)
Autonomics 2008, Turin



single-node
composite branching

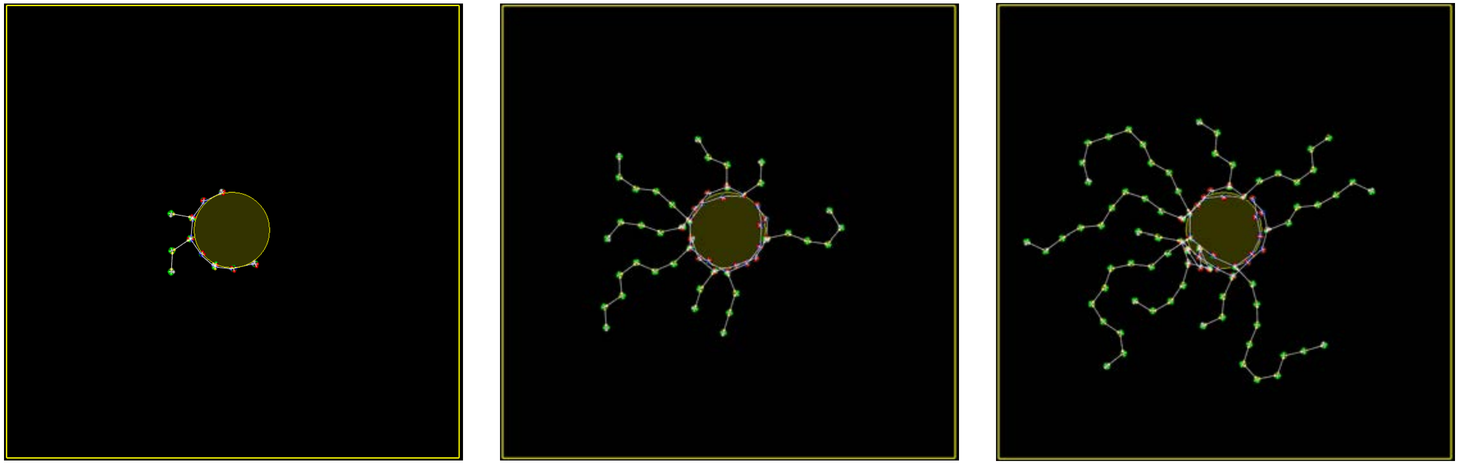


iterative lattice pile-up

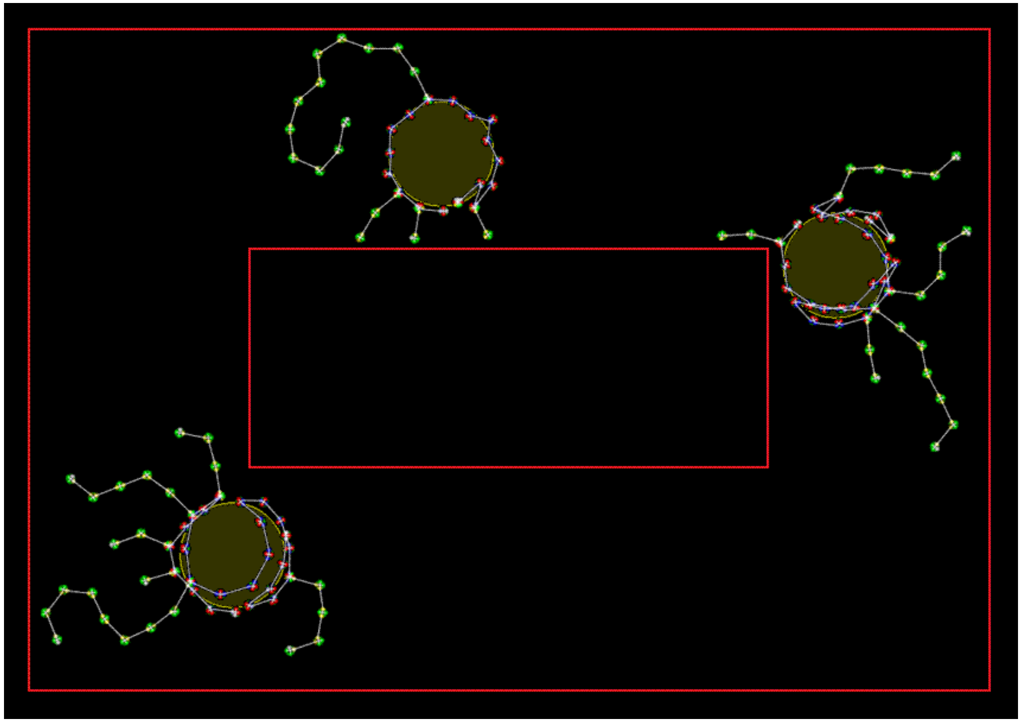


clustered
composite branching

4. Morphogenetic Engineering: ProgNet

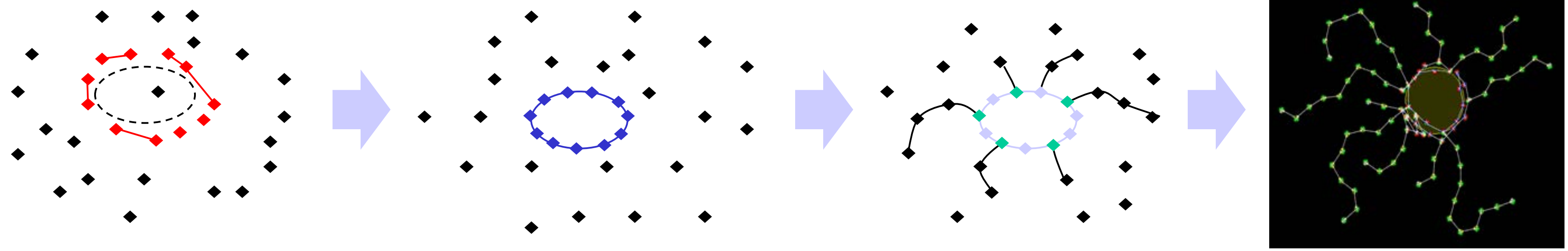


Order influenced (not imposed) by the environment



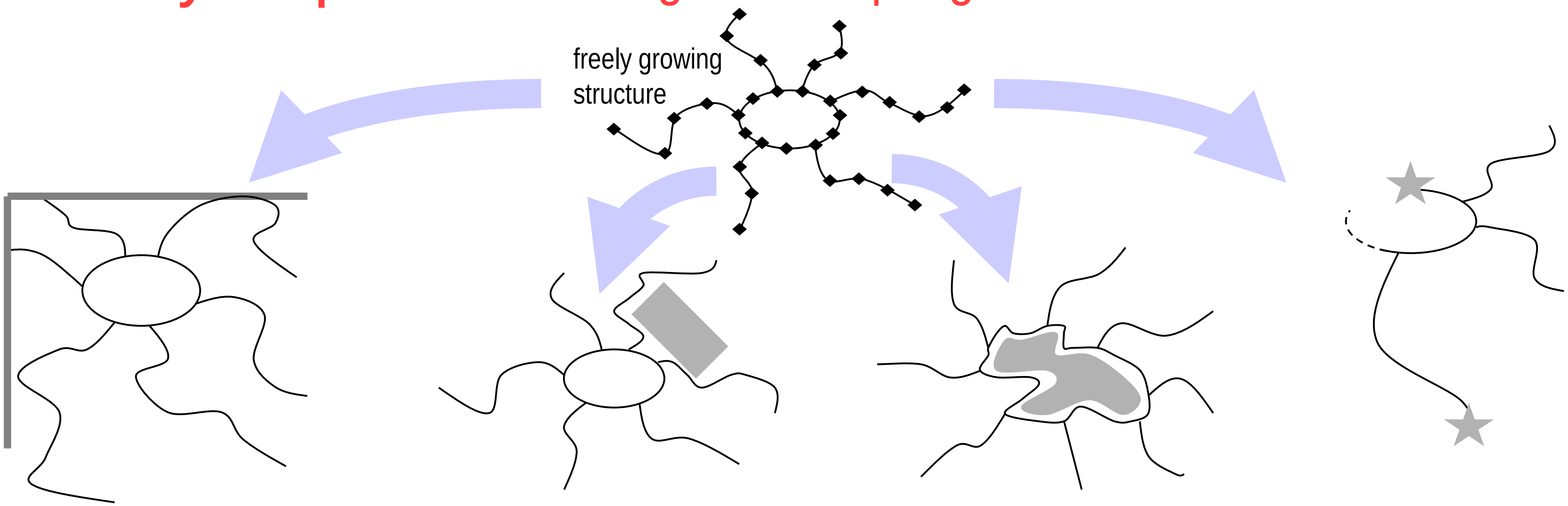
with Mihalea Ulieru and Adam MacDonald

Development: growing an intrinsic architecture

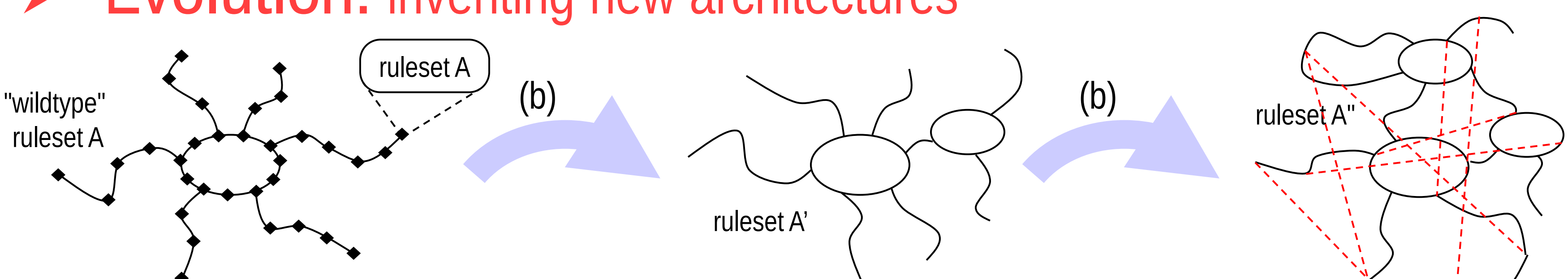


Ulieru & Doursat (2010) ACM TA
simulation by Adam MacDonald, UNB

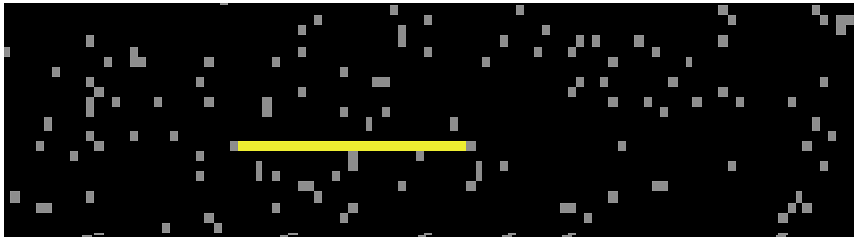
➢ Polymorphism: reacting and adapting to the environment



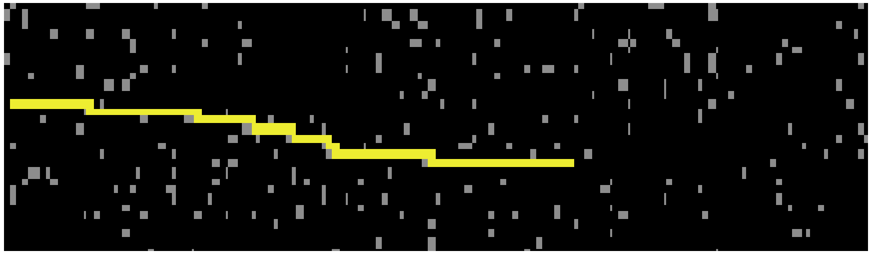
➢ Evolution: inventing new architectures



4. Morphogenetic Engineering: ProgNet



Starting rules :
open left port, open right port

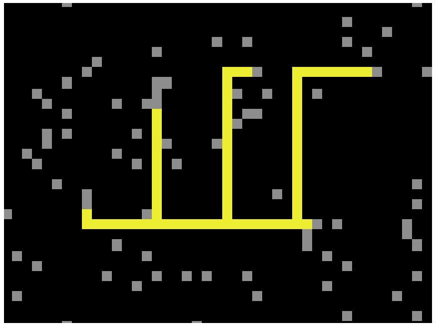


Afer 20 mutations :
New set of rules :

open left port
if a rock is on the left then open top port
if a rock is on the right then close top port

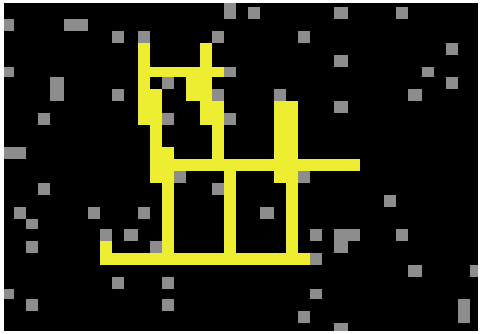
- Mutations of the rules
  - Creation
  - Deletion
  - Modification
  - Order change
  - Constants' change

with David Fourquet



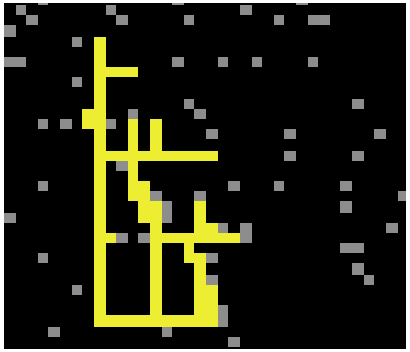
N=0

if left gradient = 0 open right port
if right gradient = 0 modulo (periodicity) open top port
if top gradient > 0 close right port
if top gradient = width open right port
if right gradient >= length close right port
if top gradient >= width close top port
length = 20 , width = 10, periodicity = 5



N = 100 mutations

if top gradient = 0 mod (width) open right port
if right gradient = 0 modulo (periodicity) open top port
if top gradient = width close top port
if right gradient = length close right port
if rock on top open left port
if bottom gradient > new_cst and rock at right open left port
length = 20 , width = 8, periodicity = 5, new_cst = 9



N = 300 mutations

if top gradient = 0 mod (width) open right port
if right gradient = 0 modulo (periodicity) open top port
if rock on the left open top port
if rock on the right open left port
width = 8, periodicity = 5

4. Morphogenetic Engineering: ECSTASY

➢ 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 (ME)

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.

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, 2012, 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. Bio-Inspiration and Artificial Evo-Devo

Or how to control spontaneity