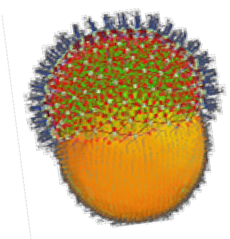
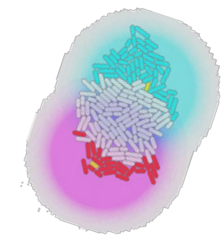
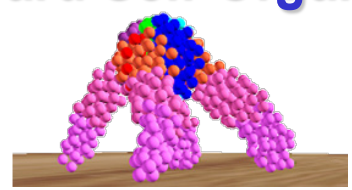
VUB AI-Lab / ULB IRIDIA, Winter 2015
"Current Trends in Artificial Intelligence" Course Series



Complex Systems, Bio-Inspiration and Morphogenetic Engineering:



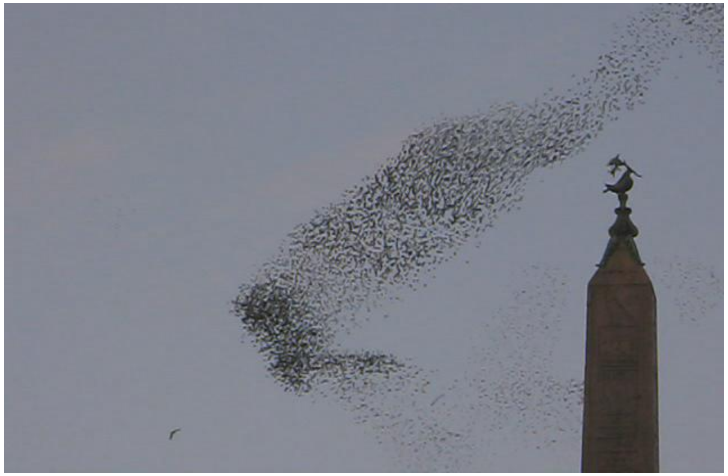
New Avenues Toward Self-Organized Architecture



René Doursat
http://doursat.free.fr

Systems that are self-organized *and* architectured

Flock of starlings above Rome
http://en.wikipedia.org/wiki/Flocking_(behavior)



free self-organization

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

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

Citroën Picasso

architecture, design

meta-design the agents

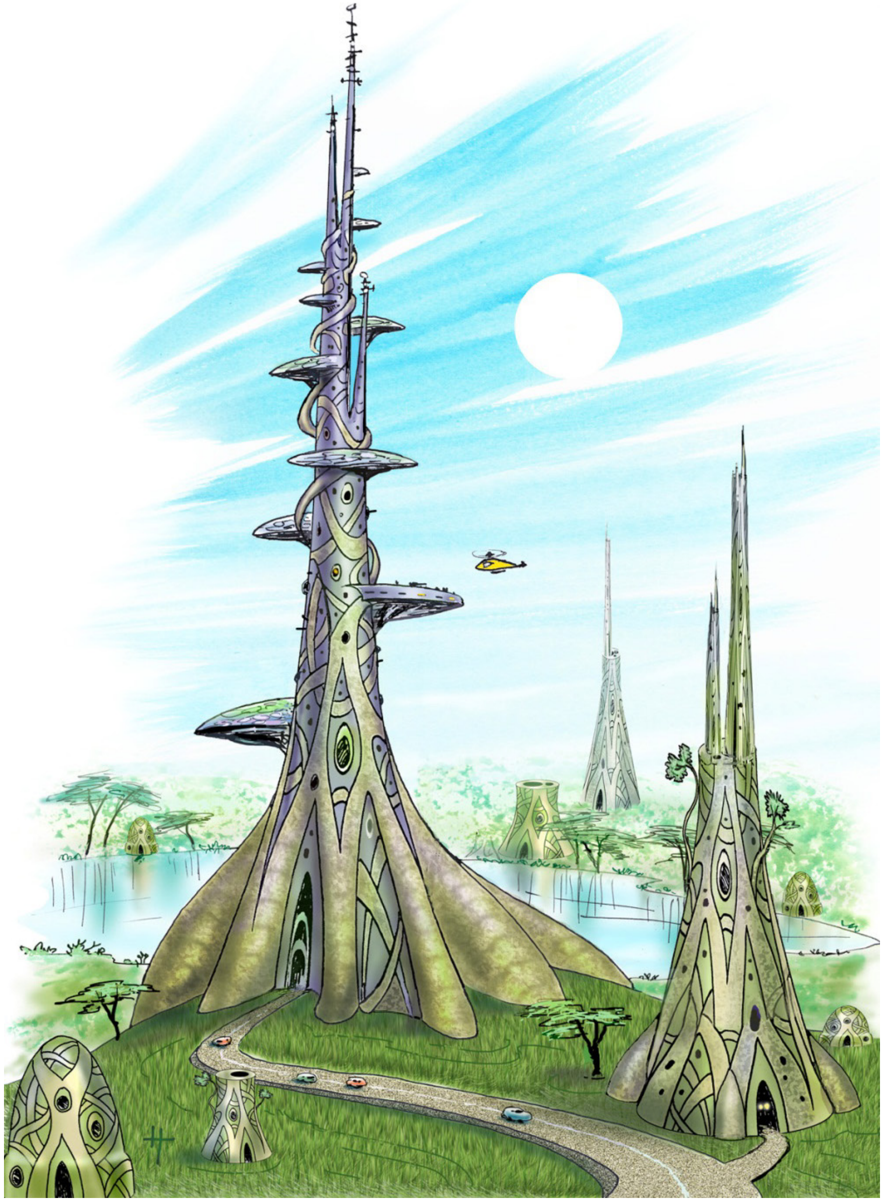
decompose the system

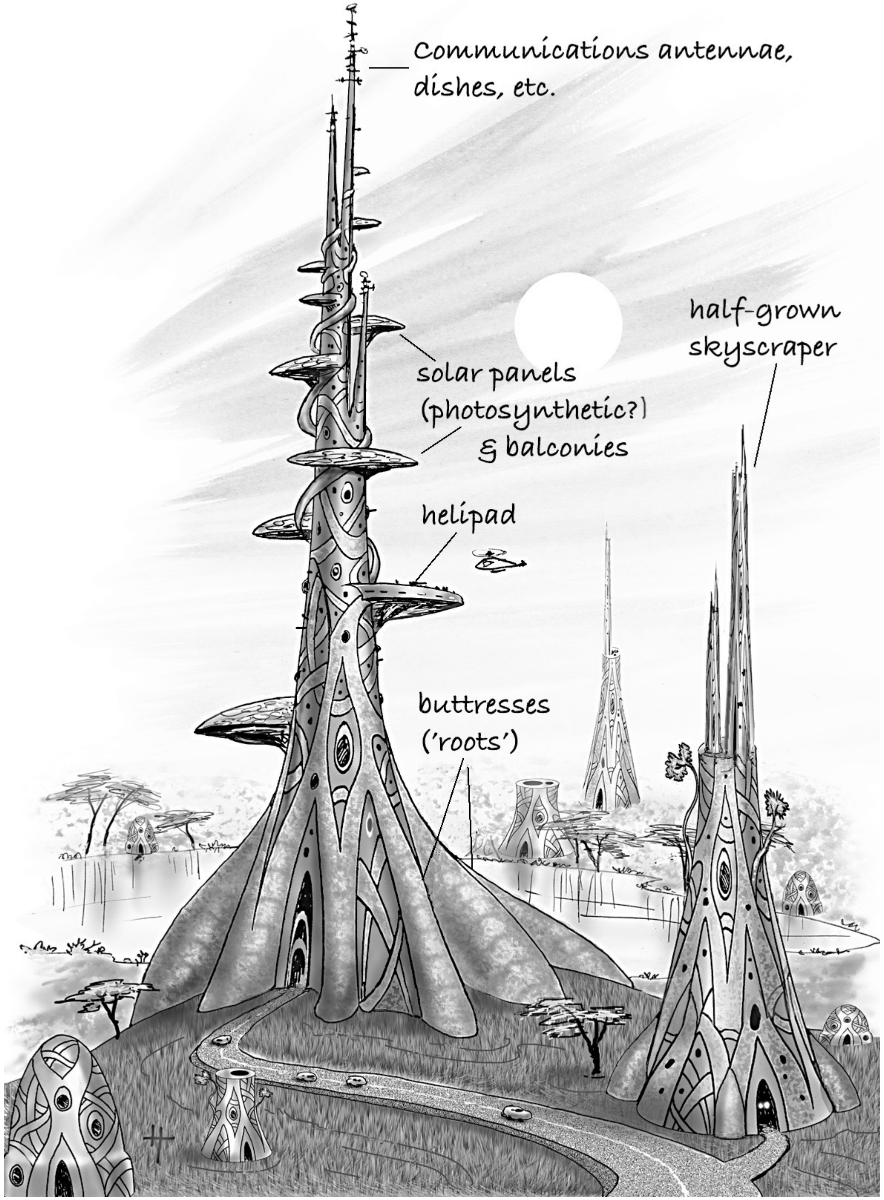
Citroën TV ad

self-organized architecture / architectured self-organization

Ex1: SYMBRION: Symbiotic Evolutionary Robot Organisms
(S. Kernbach, T. Schmickl, A. Winfield et al.)

Ex2: SWARMORPH: Morphogenesis with Self-Assembling Robots
(M. Dorigo, R. O'Grady et al., IRIDIA, ULB)



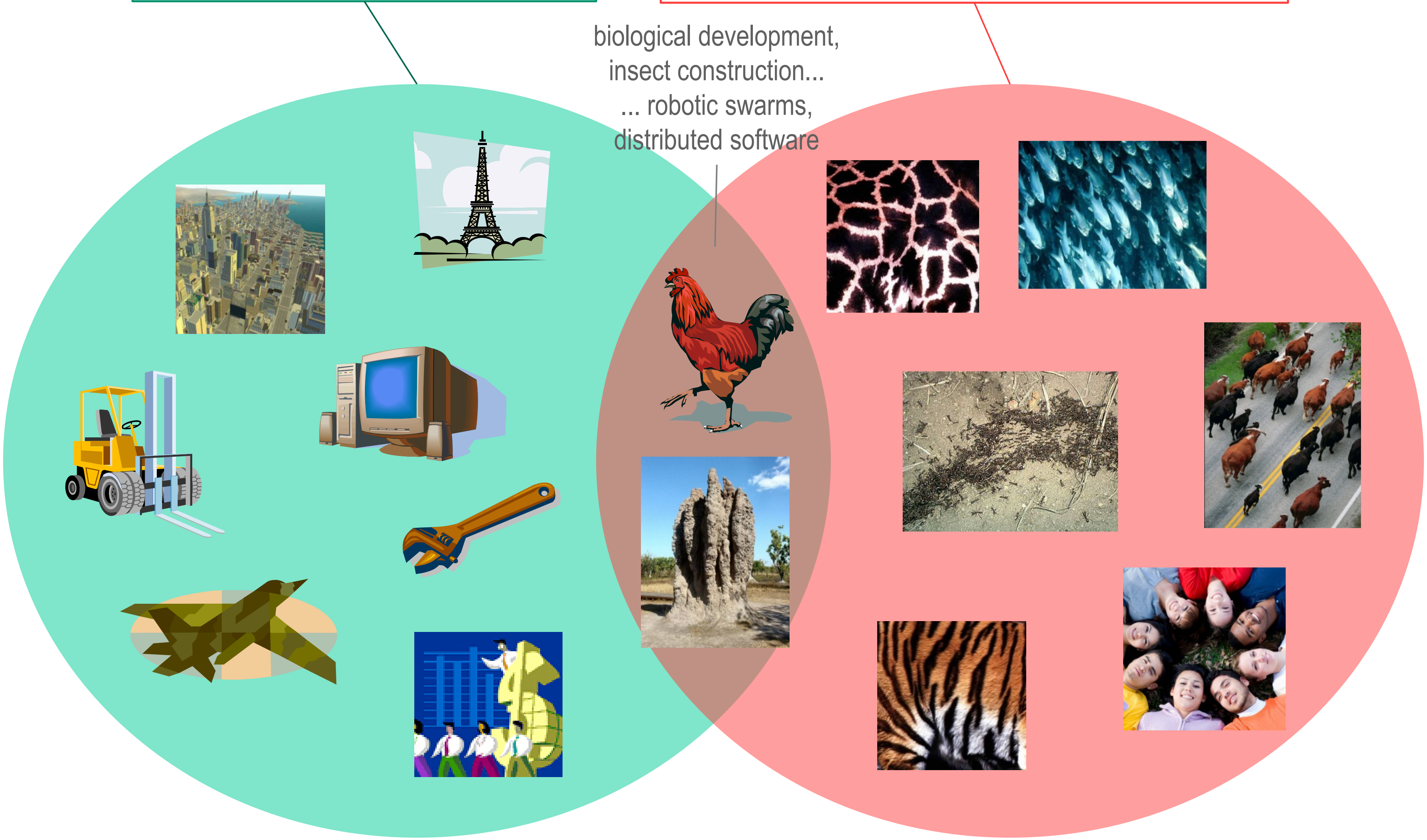


Ex3: Project "GroCyPhy": Growing Cyber-Physical Systems (S. Stepney, J. Miller et al., York)

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

"Skyscraper Garden" © David A. Hardy/www.astroart.org 2012

ARCHITECTURE & SELF-ORGANIZATION



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

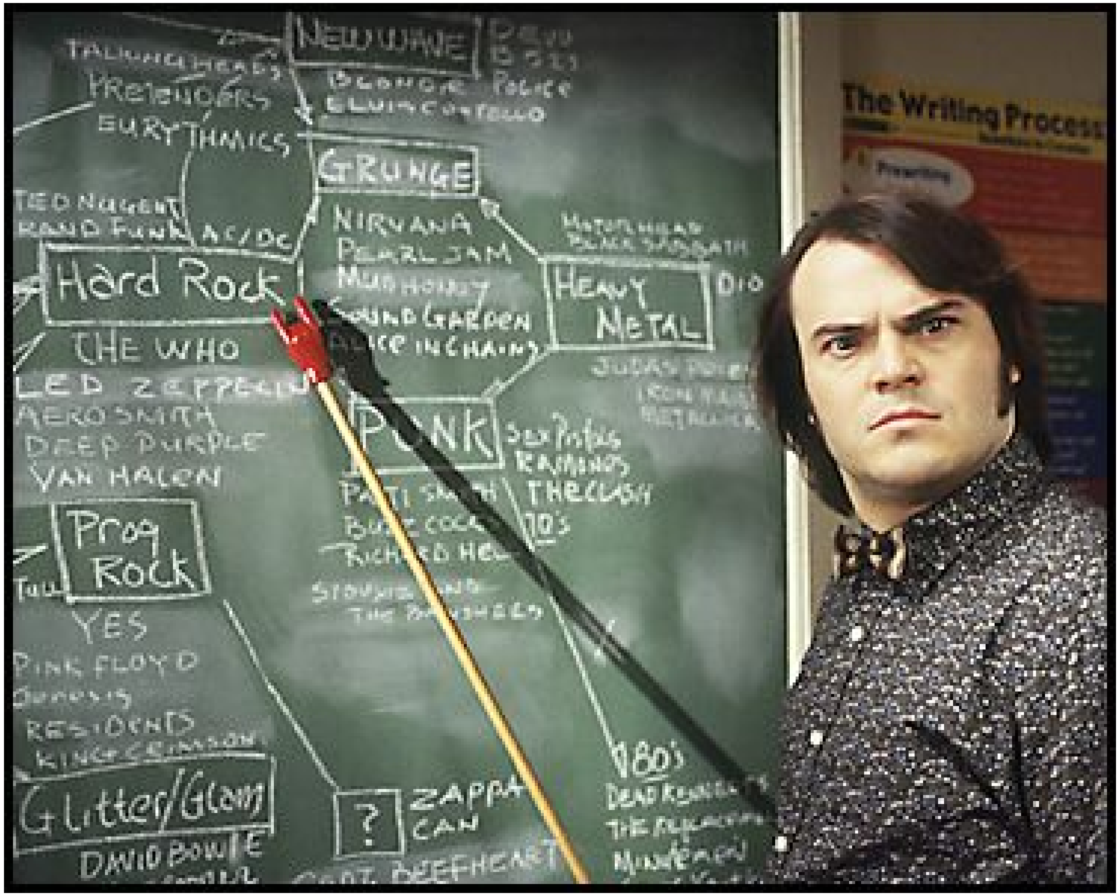
collective motion, swarm intelligence, pattern formation, complex (social) networks, spatial communities

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

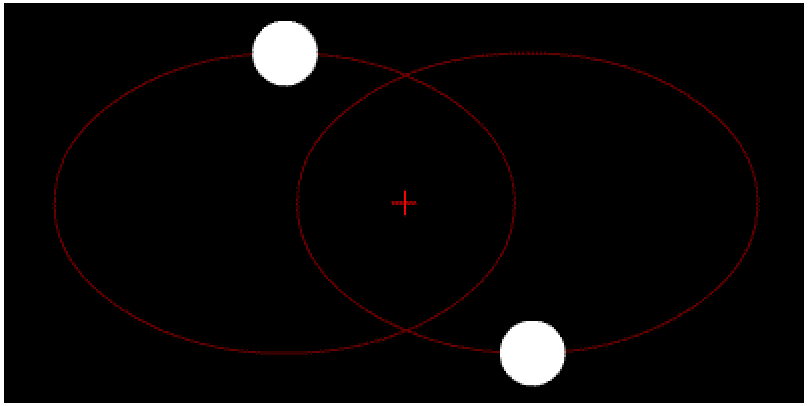
1. What Are Complex Systems?

- **Few agents, "simple" emergent behavior**

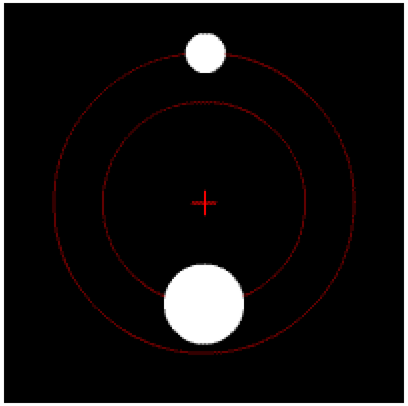
  → *ex: two-body problem*

  ✓ fully solvable and ***regular*** trajectories for inverse-square force laws (e.g., gravitational or electrostatic)

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



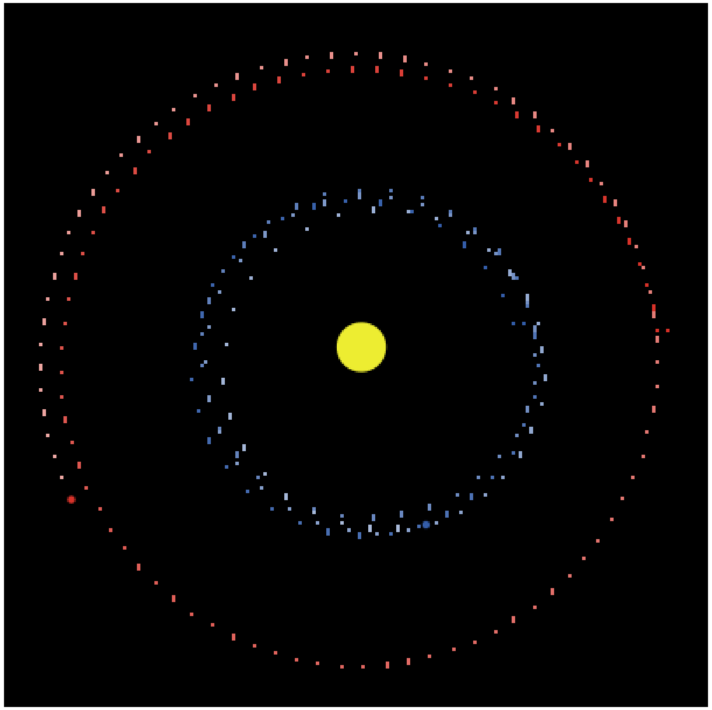
Two bodies with similar mass
Wikimedia Commons



Two bodies with different mass
Wikimedia Commons

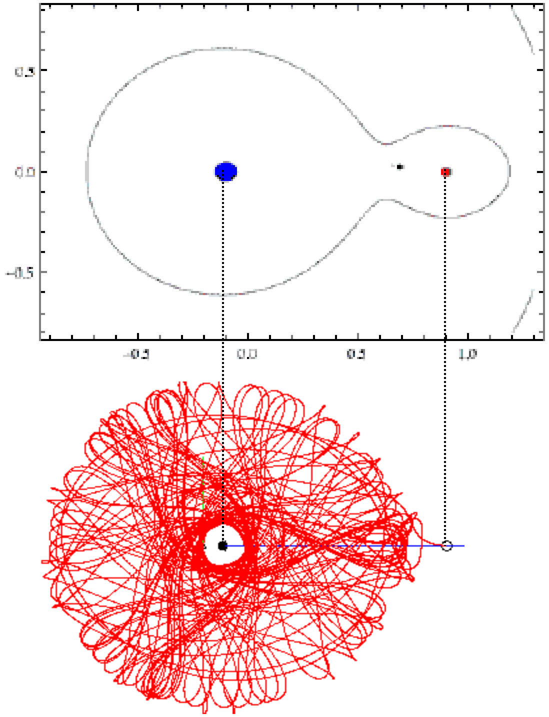
- **Few agents, complex emergent behavior**
  - → *ex: three-body problem*
  - ✓ generally no exact mathematical solution (even in "restricted" case $m_1 \langle\langle\ m_2 \approx m_3$): must be solved numerically → ***chaotic*** trajectories

NetLogo model: /Chemistry & Physics/Mechanics/Unverified



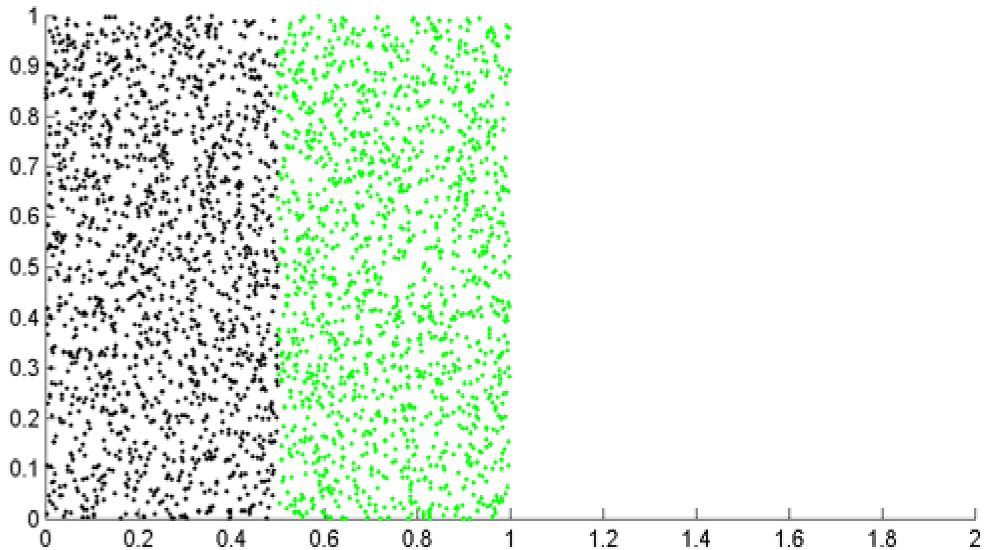
Transit orbit of the planar circular restricted problem

Scholarpedia: Three Body Problem & Joachim Köppen Kiel's applet



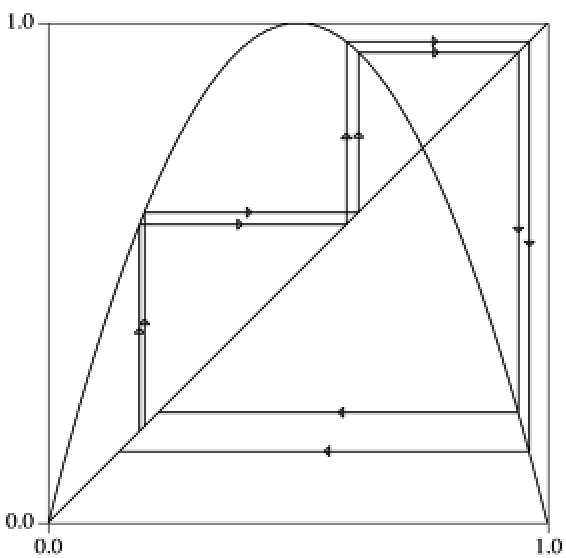
1. What Are Complex Systems?

- **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

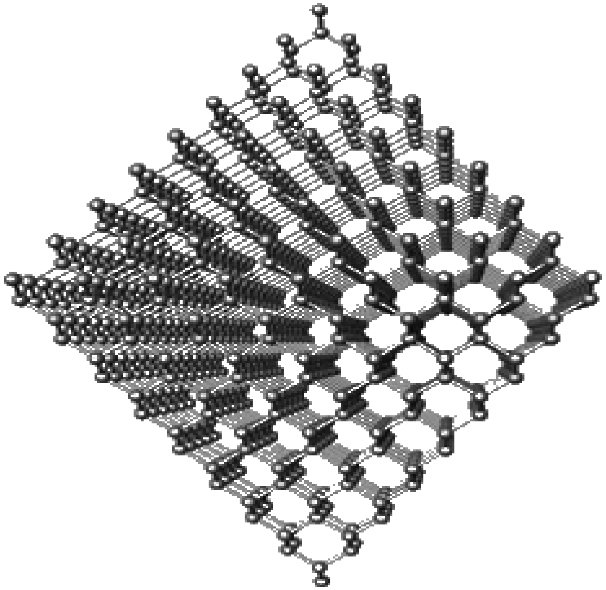
Craig L. Zirbel, Bowling Green State University, OH



Logistic map

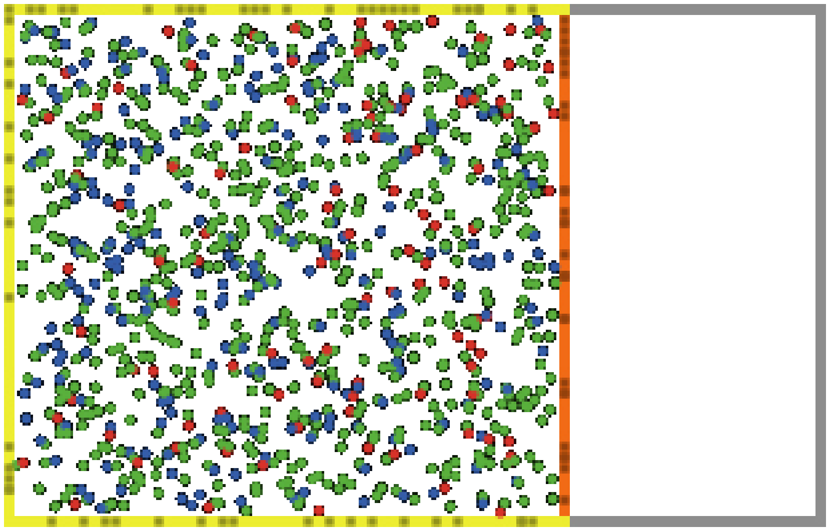
1. What Are Complex Systems?

- **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

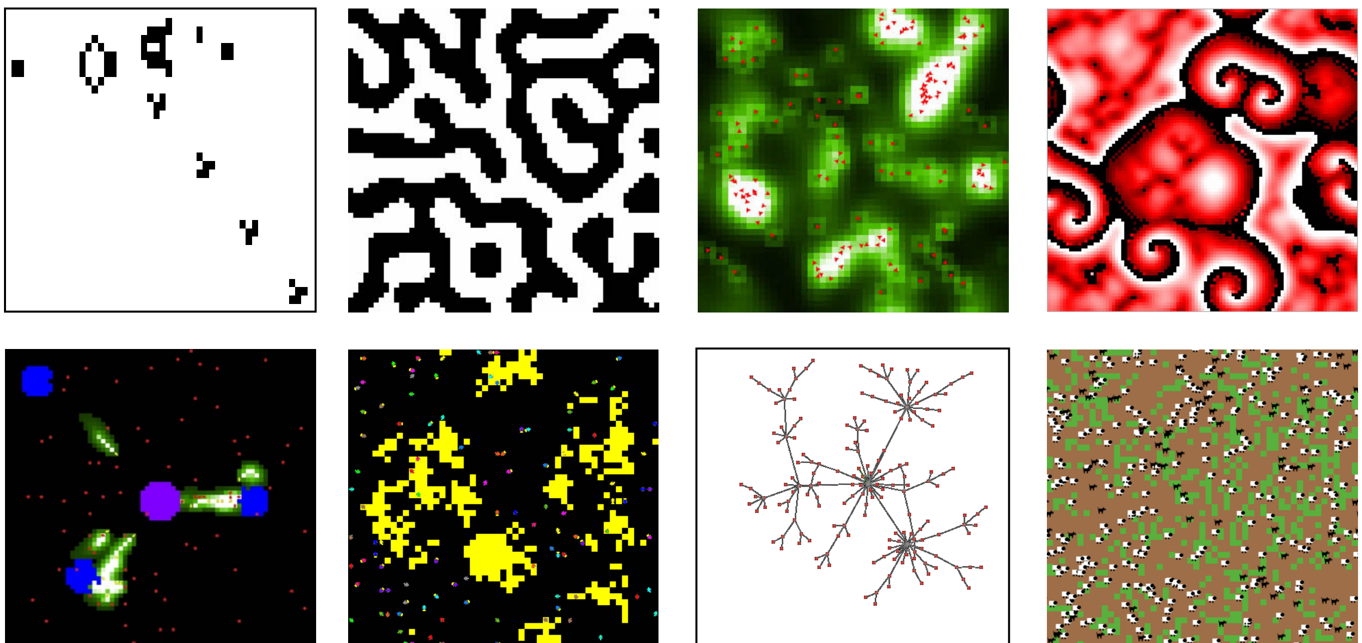


1. What Are Complex Systems?

➢ **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

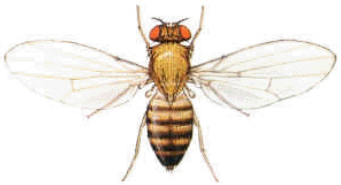
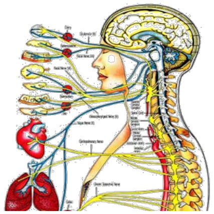


1. What Are Complex Systems?

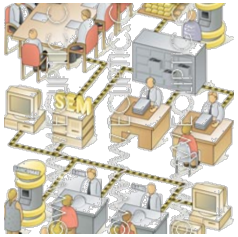
- **Many agents, complicated rules, complex emergent behavior**
  - → *natural ex: organisms (cells), societies (individuals + techniques)*
  - ✓ agent rules become more "complicated", e.g., ***heterogeneous*** depending on the element's ***type*** and/or ***position*** in the system
  - ✓ behavior is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

biological development & evolution

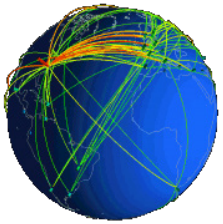


termite mounds



companies



techno-networks

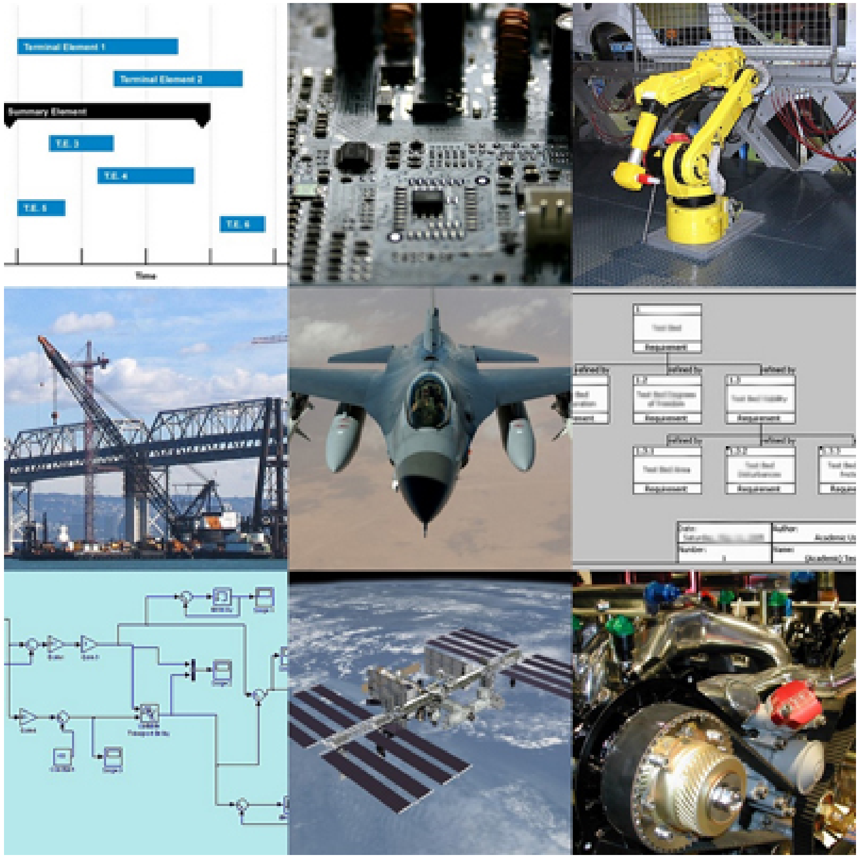
cities

1. What Are Complex Systems?

➢ **Many agents, complicated rules, “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

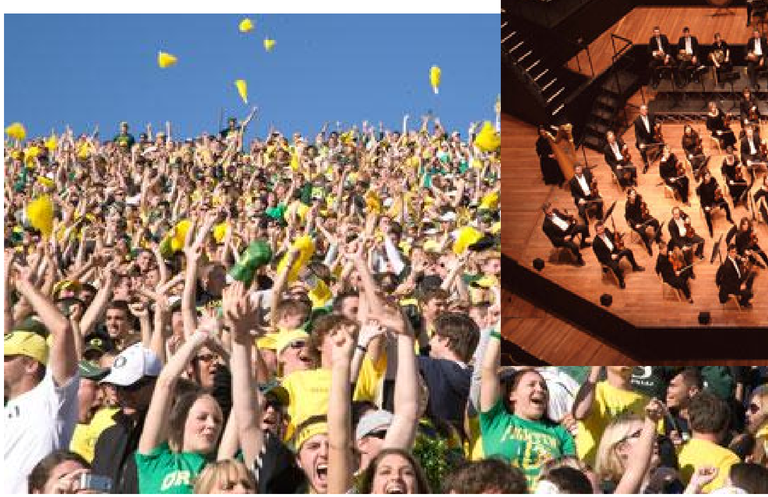


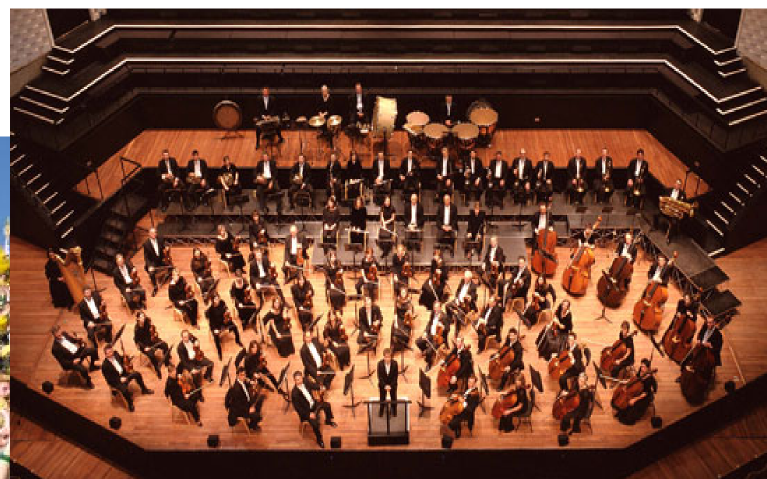
Systems engineering

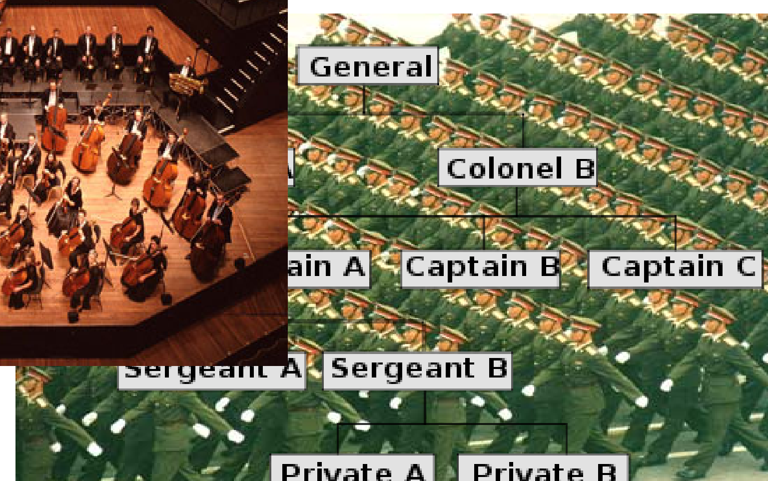
Wikimedia Commons, http://en.wikipedia.org/wiki/Systems_engineering

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

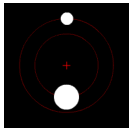
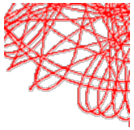
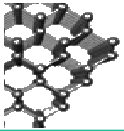
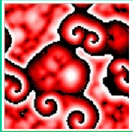
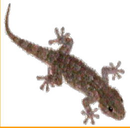






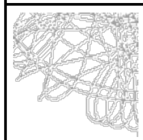
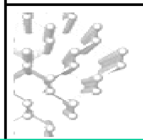
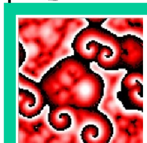
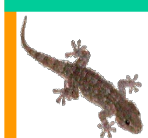
1. What Are Complex Systems?

➢ 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*
 machines, crowds with leaders	*many*	*complicated*	*deterministic/ centralized*	*COMPLICATED – not self-organized*

1. What Are Complex Systems?

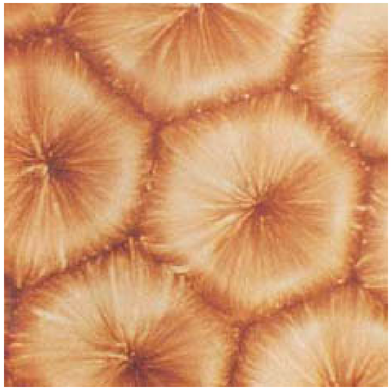
➢ Recap: complex systems in this course

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*
 machines, crowds with leaders	*many*	*complicated*	*deterministic/ centralized*	*COMPLICATED – not self-organized*

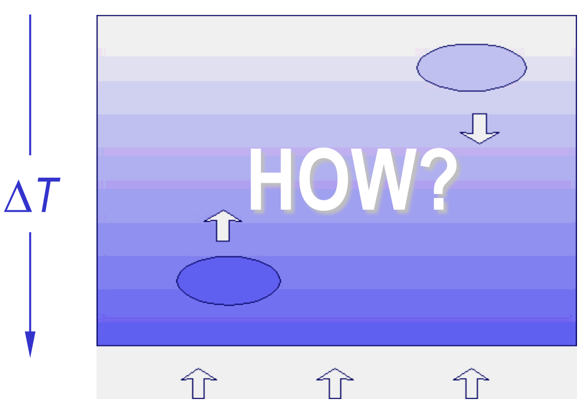
1. What Are Complex Systems?

Physical pattern formation: Convection cells

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

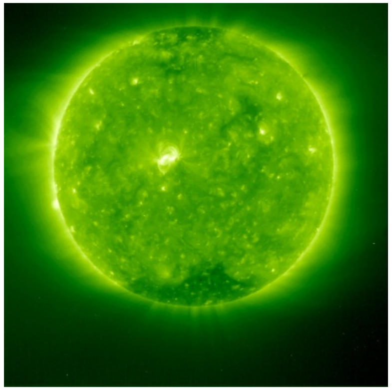


Convection cells in liquid (detail)
(Manuel Velarde, Universidad Complutense, Madrid)

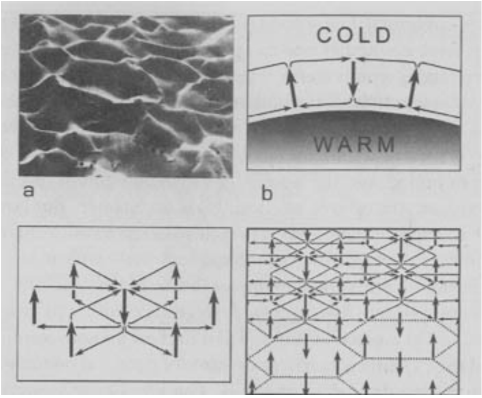


Schematic convection dynamics
(Arunn Narasimhan, Southern Methodist University, TX)

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



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



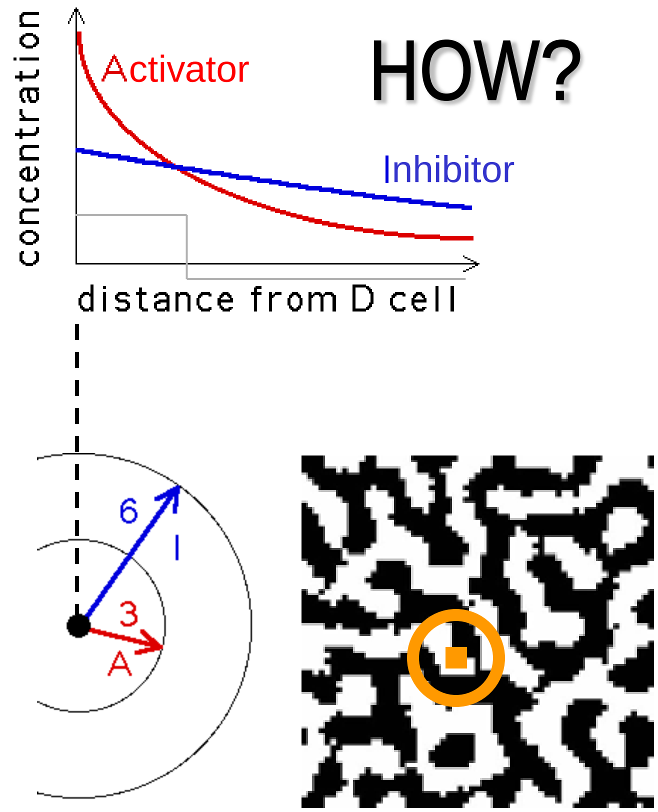
Hexagonal arrangement of sand dunes
(Solé and Goodwin, “Signs of Life”, Perseus Books)

- 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

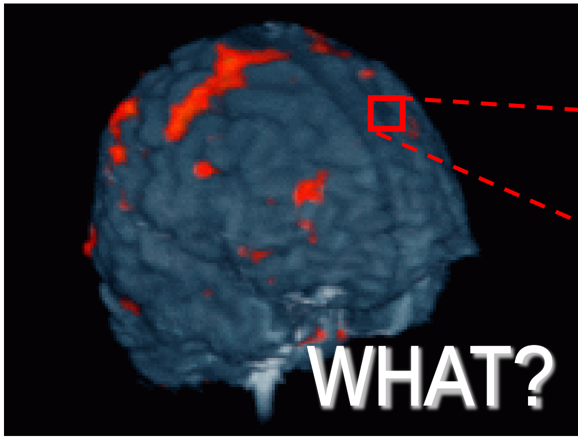
Mammal fur, seashells, and insect wings
(Scott Camazine, http://www.scottcamazine.com)



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

Spatiotemporal synchronization: Neural networks

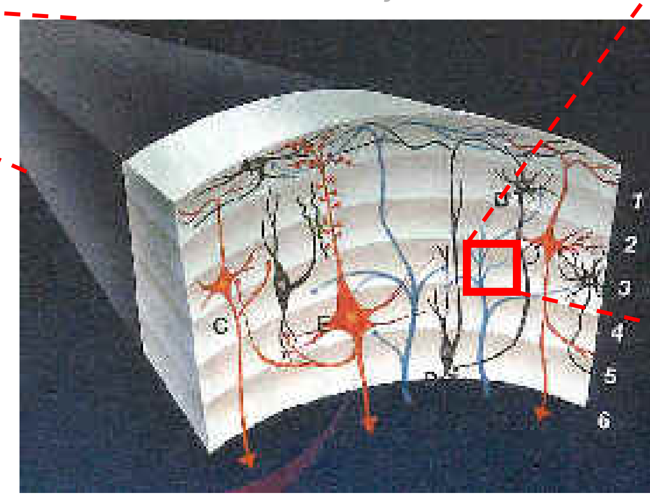


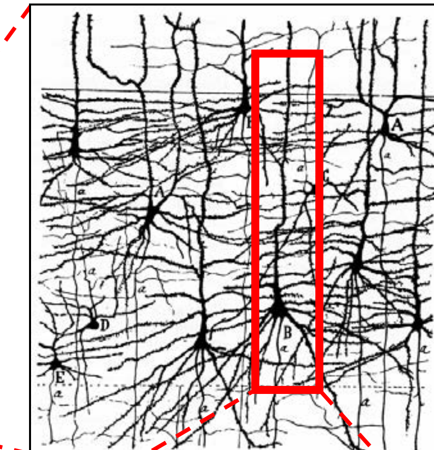
Animation of a functional MRI study
(J. Ellermann, J. Strupp, K. Ugurbil, U Minnesota)

- 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

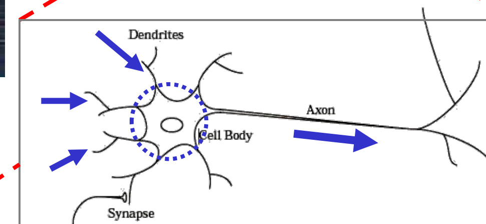
HOW?

Cortical layers

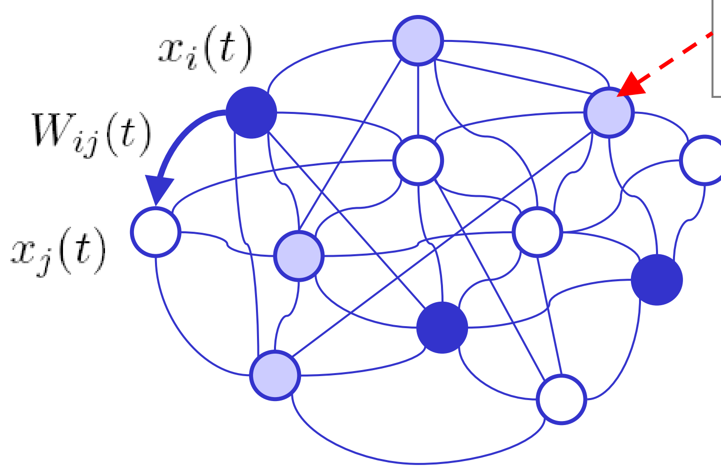


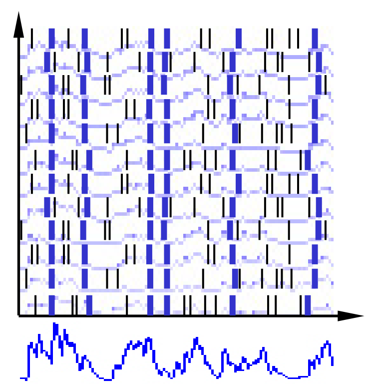


Pyramidal neurons & interneurons
(Ramón y Cajal 1900)



Schematic neural network





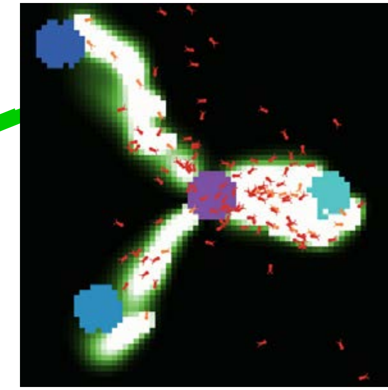
1. What are Complex Systems?

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

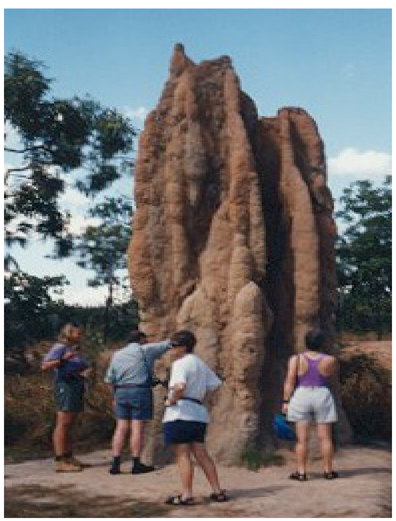
http://taos-telecommunity.org/epow/epow-archive/archive_2003/EPOW-030811_files/matabele_ants.jpg

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

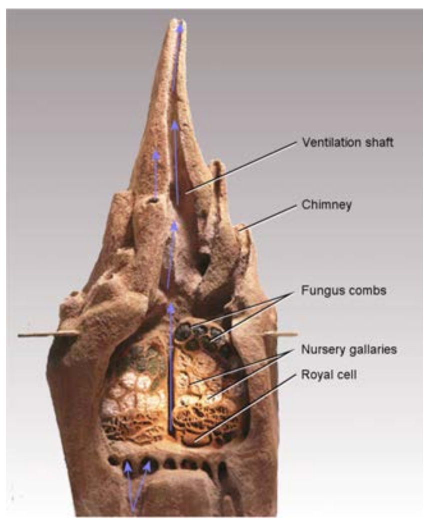
Harvester ant
(Deborah Gordon, Stanford University)



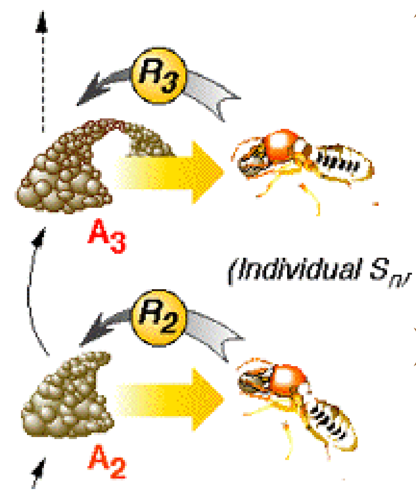
HOW?



Termite mound
(J. McLaughlin, Penn State University)



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



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

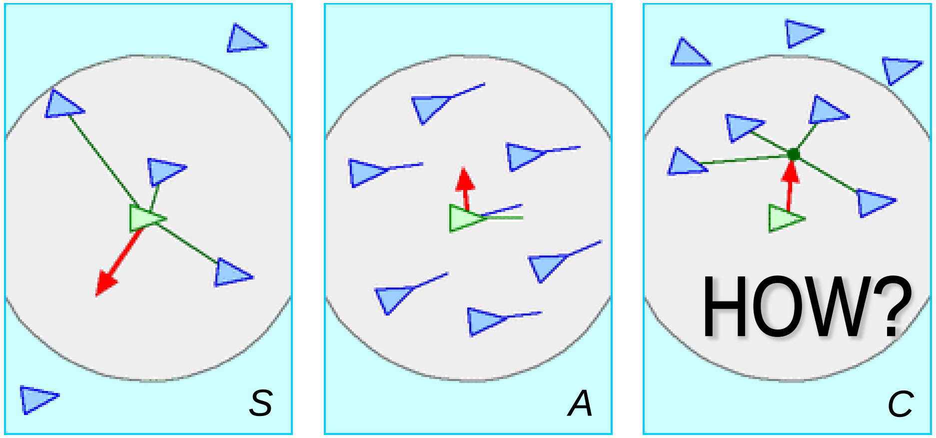
- ants form trails by following and reinforcing each other's pheromone path
- termite colonies build complex mounds by "stigmergy"

1. What are Complex Systems?

Collective motion: flocking, schooling, herding

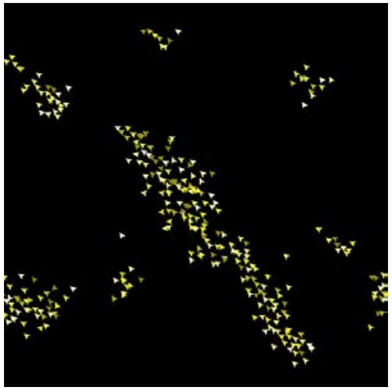
Fish school
(Eric T. Schultz, University of Connecticut)

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



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

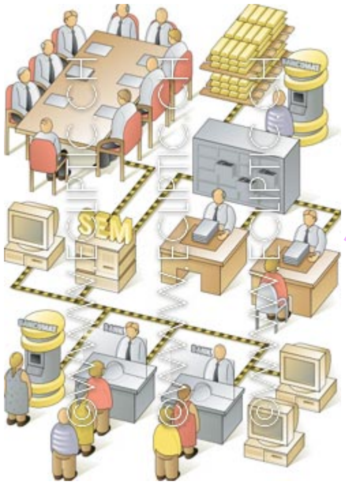
- coordinated collective movement of dozens or 1000s of individuals (confuse predators, close in on prey, improve motion efficiency, etc.)
- each individual adjusts its position, orientation and speed according to its nearest neighbors



1. What are Complex Systems?

Complex networks and morphodynamics: human organizations

organizations

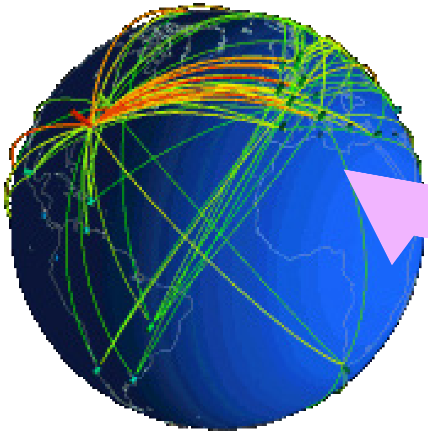


(Thomas Thü Hürlimann, http://ecliptic.ch)

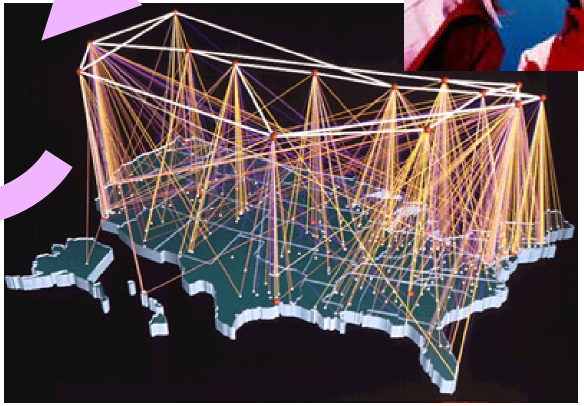
urban dynamics

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

global connectivity

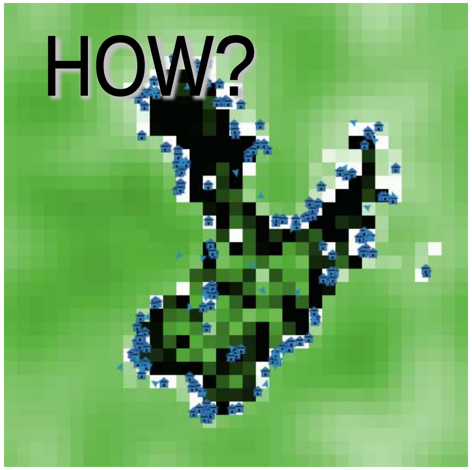


techno-social networks



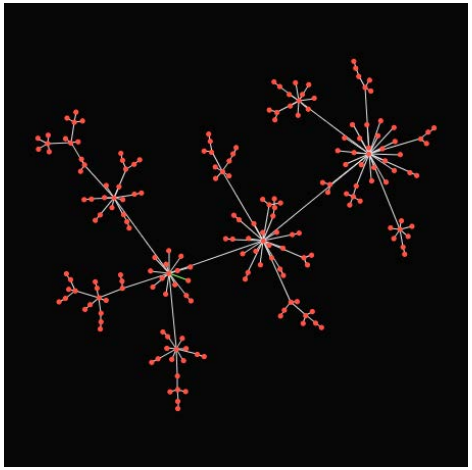
NSFNet Internet (w2.eff.org)

cellular automata model



NetLogo urban sprawl simulation

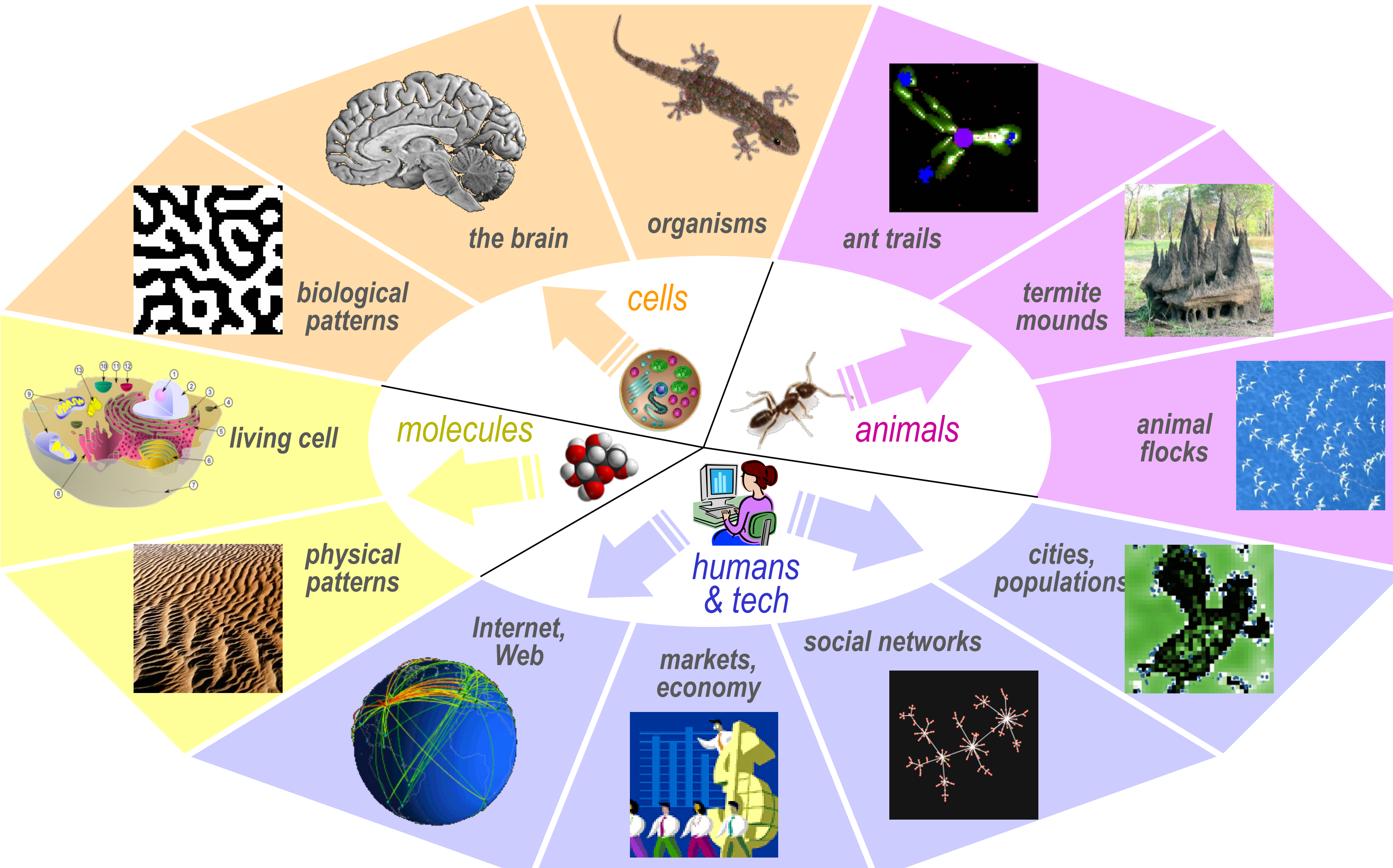
“scale-free” network model



NetLogo preferential attachment simulation

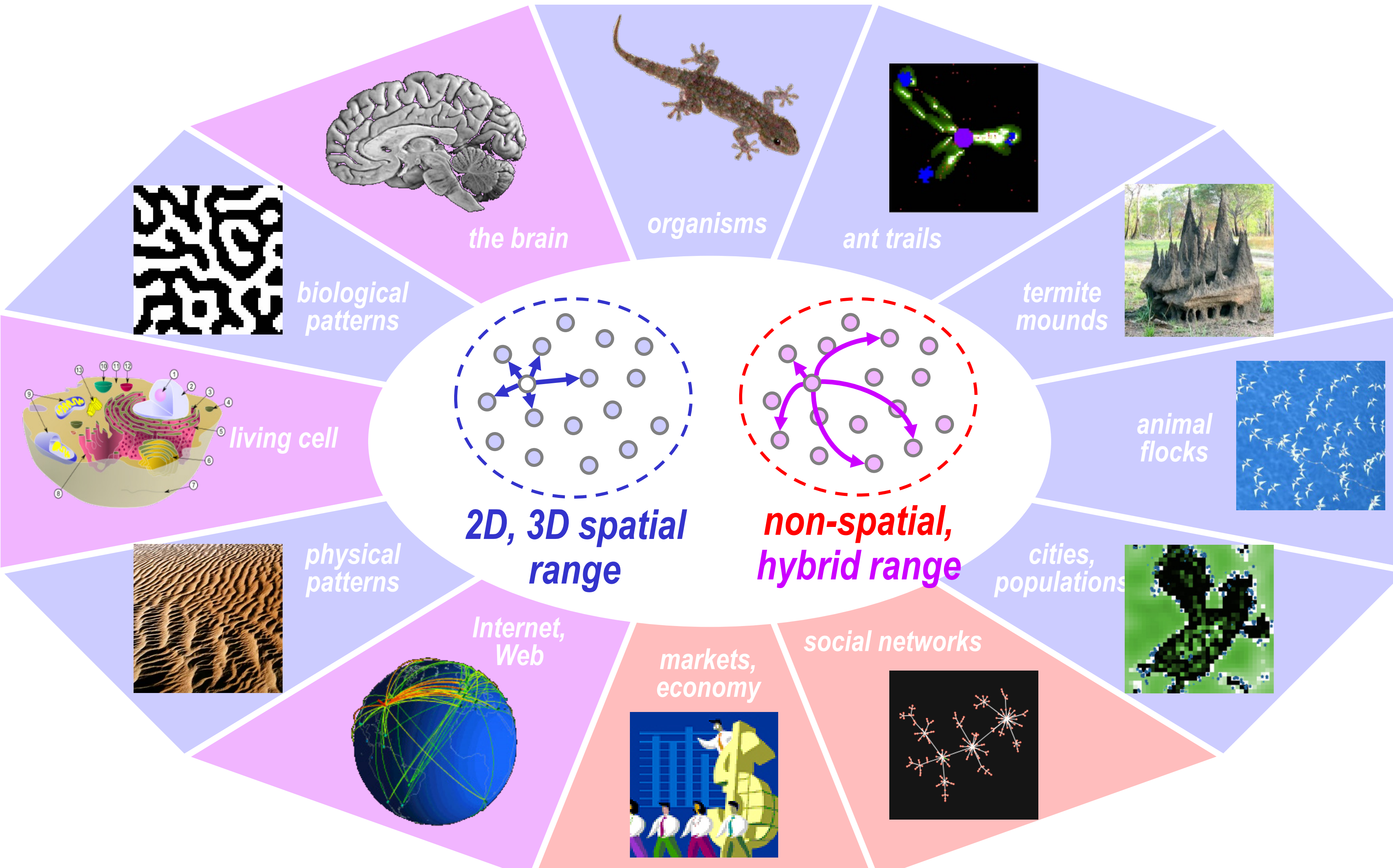
1. What Are Complex Systems?

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



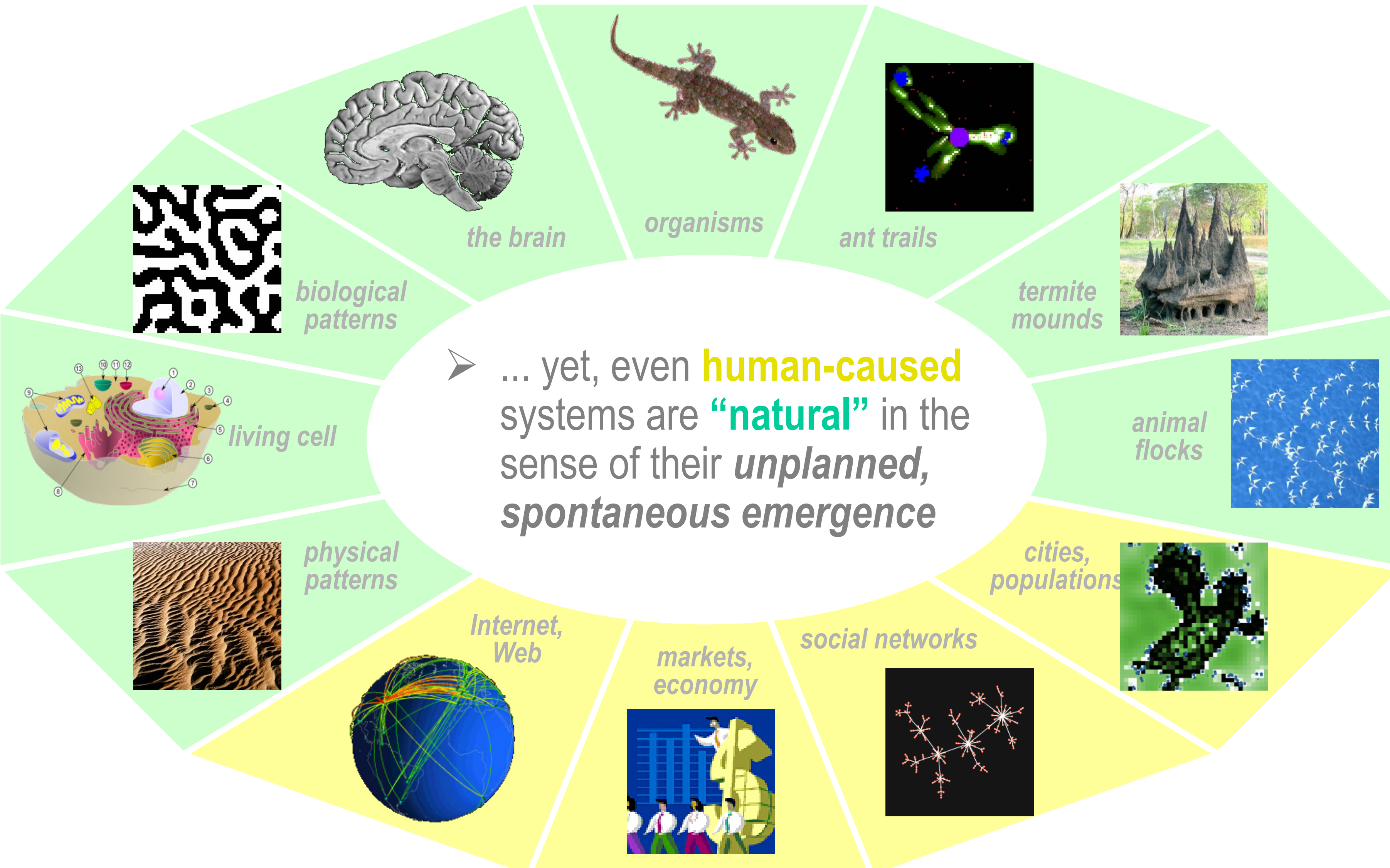
1. What Are Complex Systems?

Categories of complex systems by range of interactions



1. What Are Complex Systems?

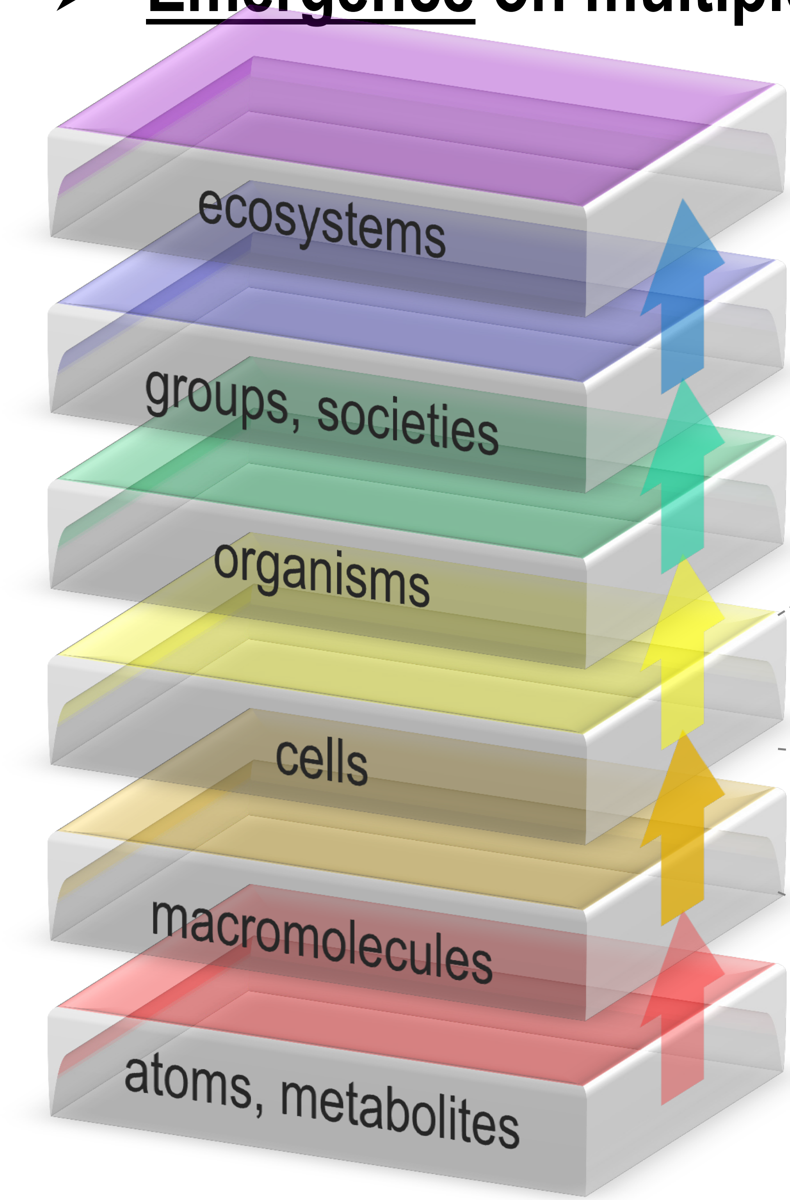
Natural ***and human-caused categories of complex systems***



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

1. What Are Complex Systems?

➢ <u>Emergence</u> on multiple levels of self-organization

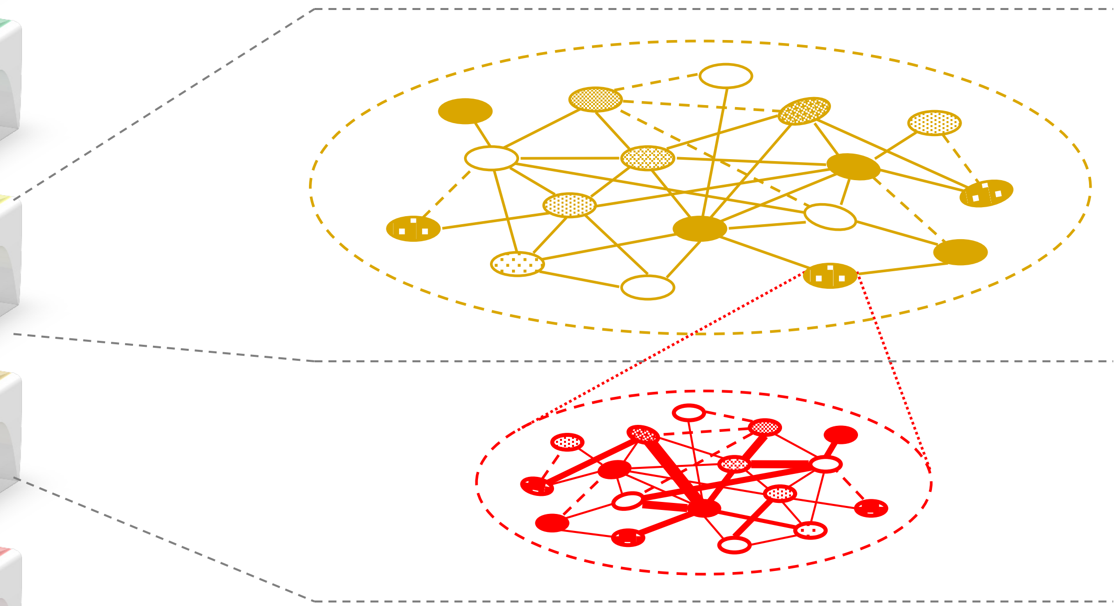


"complex systems" =

a) large number of elementary agents interacting locally

b) simple individual behaviors creating a complex emergent collective behavior

c) decentralized dynamics: no blueprint or architect



1. What Are Complex Systems?

- Decentralization
- Emergence
- Self-organization

2. CS Science & Eng: Toward Bio-Inspiration

Or how to control spontaneity

2. CS Science & Eng: Toward Bio-Inspiration

- **Emergence**
  - ✓ the system has properties that the elements do not have
  - ✓ these properties cannot be easily inferred or deduced
  - ✓ different properties can emerge from the same elements

- **Self-organization**
  - ✓ the system's "order" increases without external intervention
  - ✓ this originates purely from interactions among the agents (possibly via cues in the environment)

- ***Counter-examples of emergence without self-organization***
  - ✓ *ex: well-informed leader (orchestra conductor, military officer)*
  - ✓ *ex: global plan (construction area), full instructions (program)*

2. CS Science & Eng: Toward Bio-Inspiration

- **Positive feedback, circularity**
  - ✓ creation of structure by amplification of fluctuations (homogeneity is unstable)
    - ex: termites bring pellets of soil where there is a heap of soil
    - ex: cars speed up when there are fast cars in front of them
    - ex: the media talk about what is currently talked about in the media

- **Decentralization**
  - ✓ the “invisible hand”: order without a leader
    - ex: the queen ant is not a manager
    - ex: the first bird in a V-shaped flock is not a leader
  - ✓ distribution: each agent carry a small piece of the global information
  - ✓ ignorance: agents don’t have explicit group-level knowledge/goals
  - ✓ parallelism: agents act simultaneously

2. CS Science & Eng: Toward Bio-Inspiration

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)

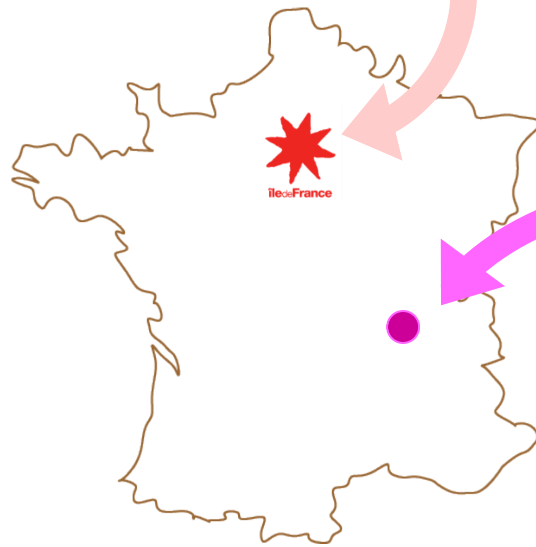
multitude, statistics: large-scale properties of systems
- **graph theory & networks**
- **statistical physics**
- **agent-based modeling**
- **distributed AI systems**

COMPLEX SYSTEMS

INSTITUT DES SYSTEMES COMPLEXES
Paris Ile-de-France

4th French Complex Systems Summer School, 2010

National



Lyon Rhône-Alpes

Resident Researchers (2010)

Pierre Baudot

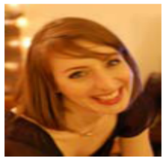
Information Theory - Adaptation - Topology – Thermodynamics of perception.

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

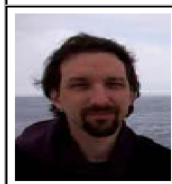
Nonequilibrium statistical mechanics (Active matter, collective motion, flockng, nonequilibrium wetting, directed percolation, long range interactions) - Dynamical system theory (Lyapunov exponents, Lyapunov vectors, synchronization, stable chaos, spatiotemporal chaos, structural stability, hyperbolicity).

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

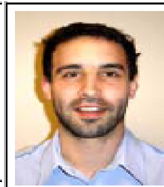
Complex network analysis and simulation - Social networks - Evolutionary search for multi-agent models, Genetic programming applied to programmable networks - Bio-inspired algorithms.

social networks

Bivas Mitra

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

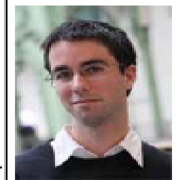
peer-to-peer networks



Romain Reuillon

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

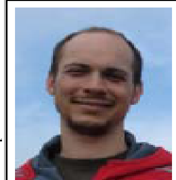
high performance computing



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

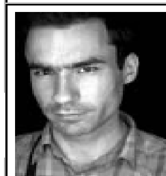
Grid Computing,Bioemergences Platform (workflow), Mophodynamics reconstruction, Images processing algorithms.

embryogenesis

David Chavalarias

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

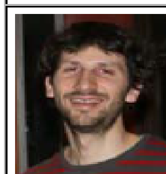
web mining / social intelligence



Srdjan Ostojic

Neuroscience théoriques - Spiking Neurons - Dynamiques Stochastic-ques.

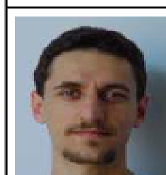
spiking neural dynamics



Andrea Perna

Morphogenesis, Collective behavior, Spatial patterns, Spatial networks.

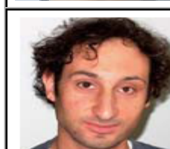
spatial networks / swarm intelligence



Fernando Peruani

Biophysique – Active Matter – Complex Networks.

active matter / complex networks



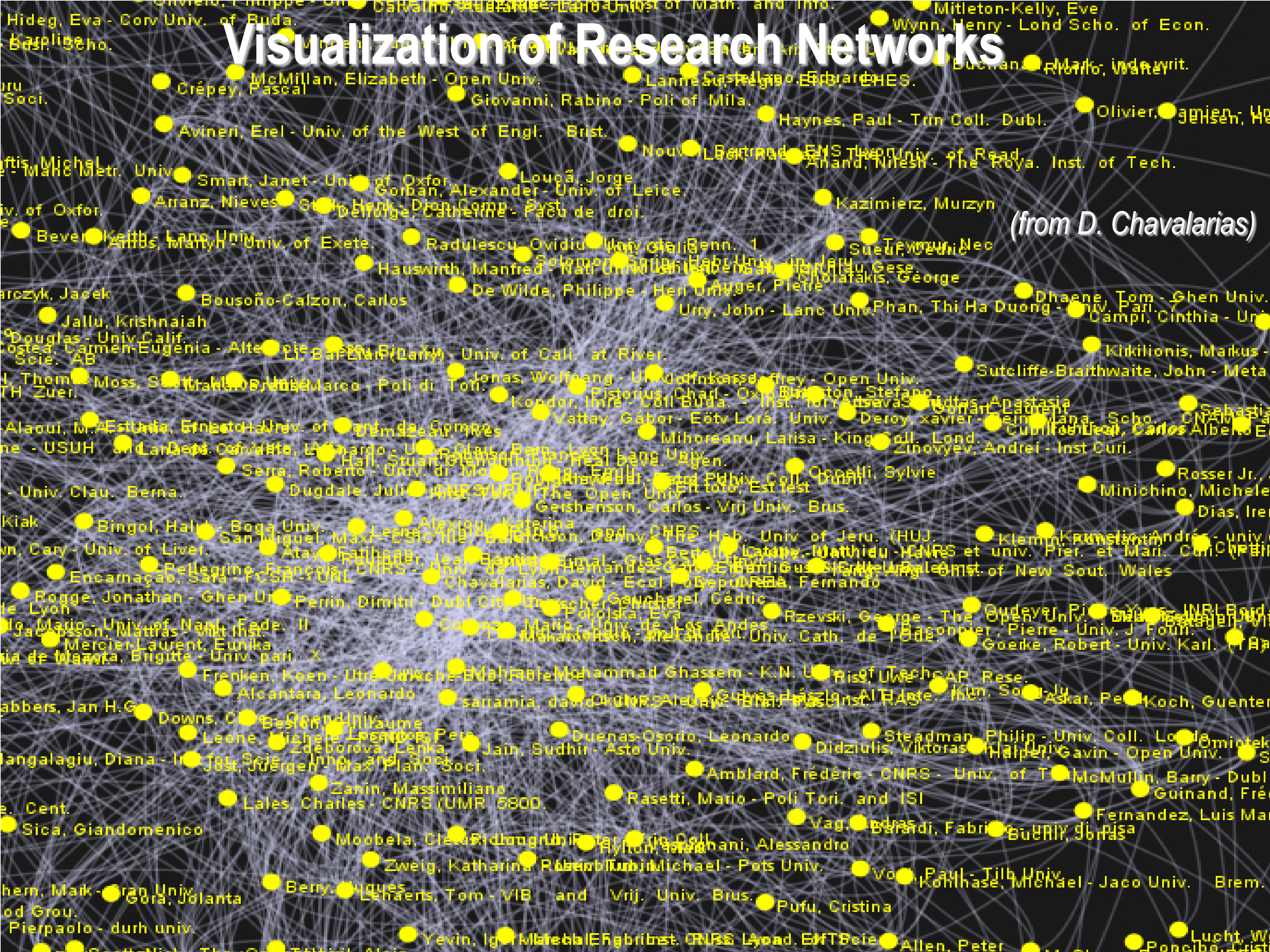
Francesco d'Ovidio

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

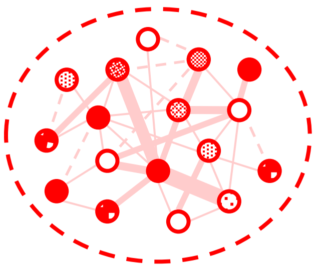
Visualization of Research Networks



(from D. Chavalarias)

2. CS Science & Eng: Toward Bio-Inspiration

➢ Between natural and engineered emergence



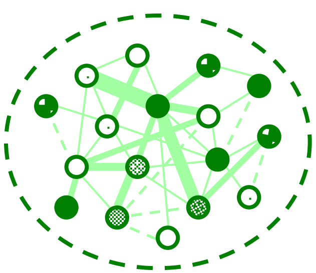
CS science: observing and understanding "natural", spontaneous emergence (including human-caused)

→ *Agent-Based Modeling (ABM)*

But CS computation is not without paradoxes:

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

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



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

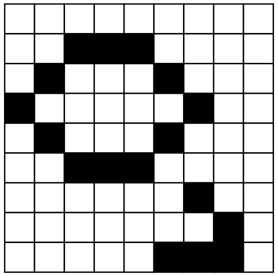
→ *Multi-Agent Systems (MAS)*

2. CS Science & Eng: Toward Bio-Inspiration

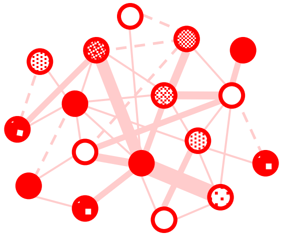
➢ People: the ABM modeling perspective of the social sciences

- ✓ ***agent-*** (or individual-) ***based modeling*** (ABM) arose from the need to model systems that were too complex for analytical descriptions

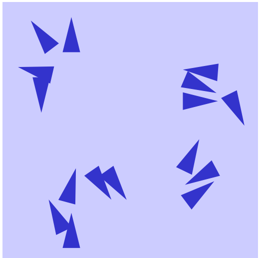
- ✓ main origin: cellular automata (CA)
  - von Neumann self-replicating machines → Ulam's "paper" abstraction into CAs → Conway's *Game of Life*
  - based on ***grid*** topology



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



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



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

2. CS Science & Eng: Toward Bio-Inspiration

➢ ICT: the MAS multi-agent perspective of computer science

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

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

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

- **Getting ready to organize spontaneity**

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

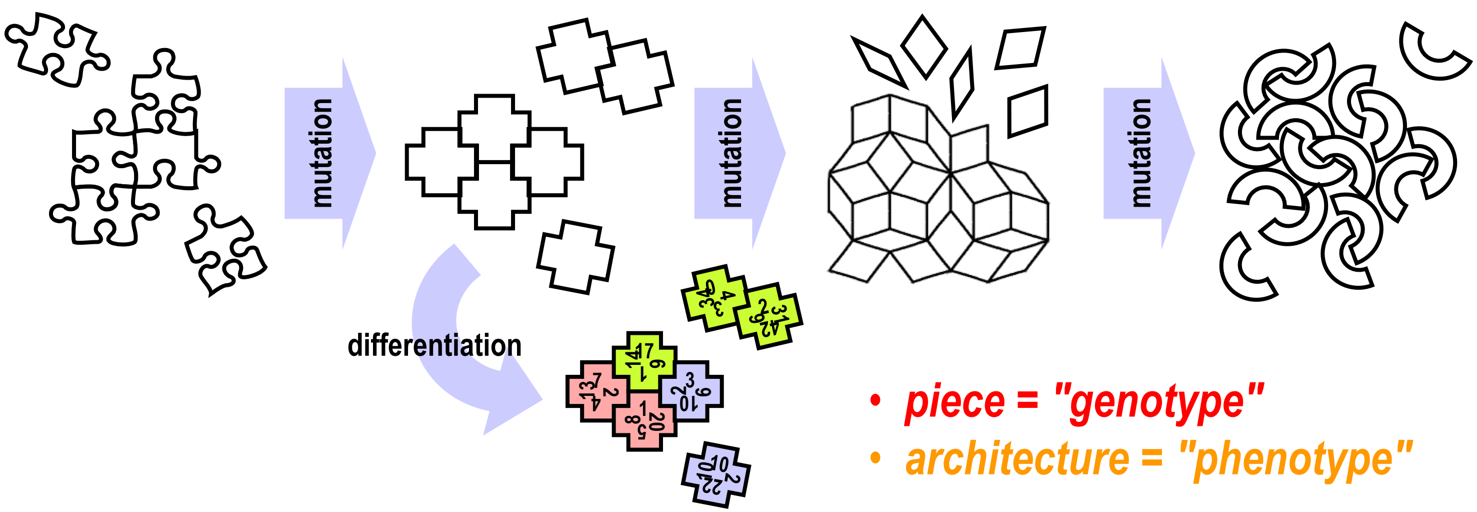
✓ Instead of assembling a construction yourself, shape its building blocks in a way that they self-assemble for you—and come up with new solutions

b) Design and program the pieces

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

c) Add evolution

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



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

2. CS Science & Eng: Toward Bio-Inspiration

- **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

2. CS Science & Eng: Toward Bio-Inspiration

- **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

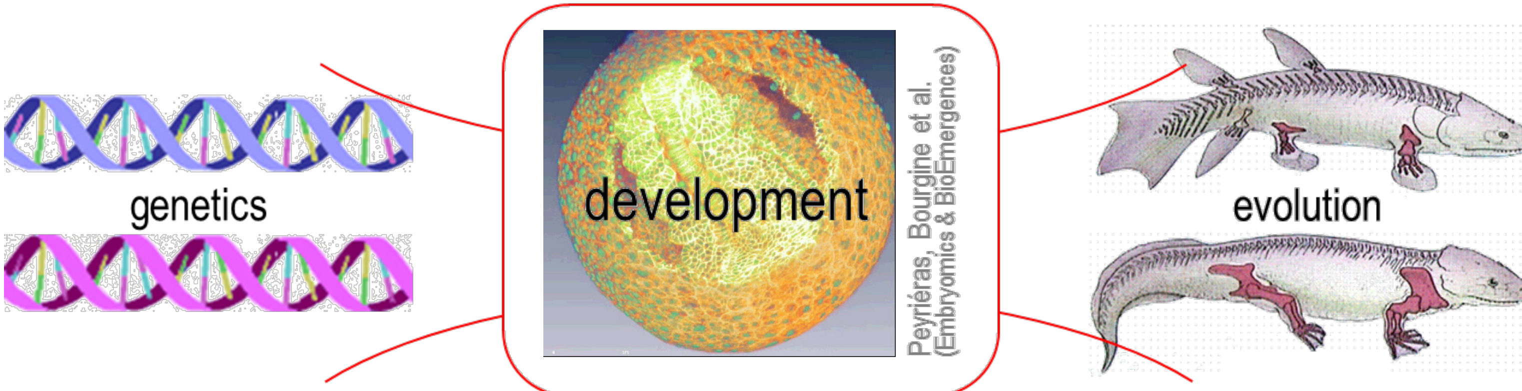
ant colony optimization (ACO) applied to graph theoretic & networking problems

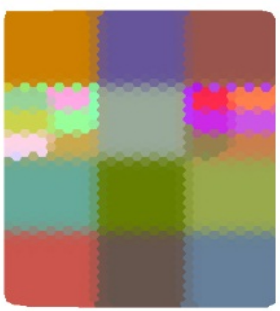
genetic algorithms (GAs), evolutionary computation for search & optimization

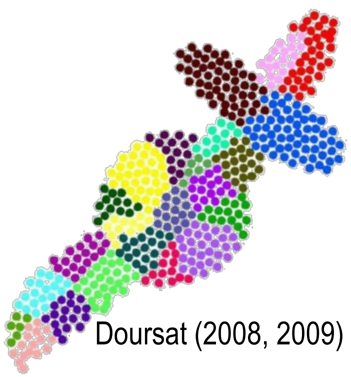
TOMORROW: implemented in bioware, nanoware, etc.

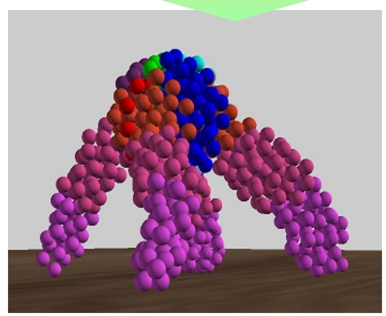
2. CS Science & Eng: Toward Bio-Inspiration

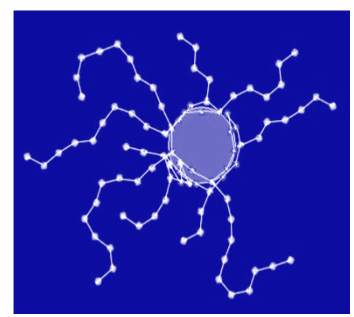
- **A new line of bio-inspiration: *biological morphogenesis***
  - ✓ designing multi-agent models for decentralized systems engineering

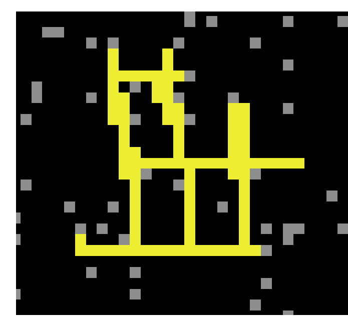



Doursat (2006)


Doursat (2008, 2009)


Doursat, Sanchez, Fernandez
Kowaliw & Vico (2012)

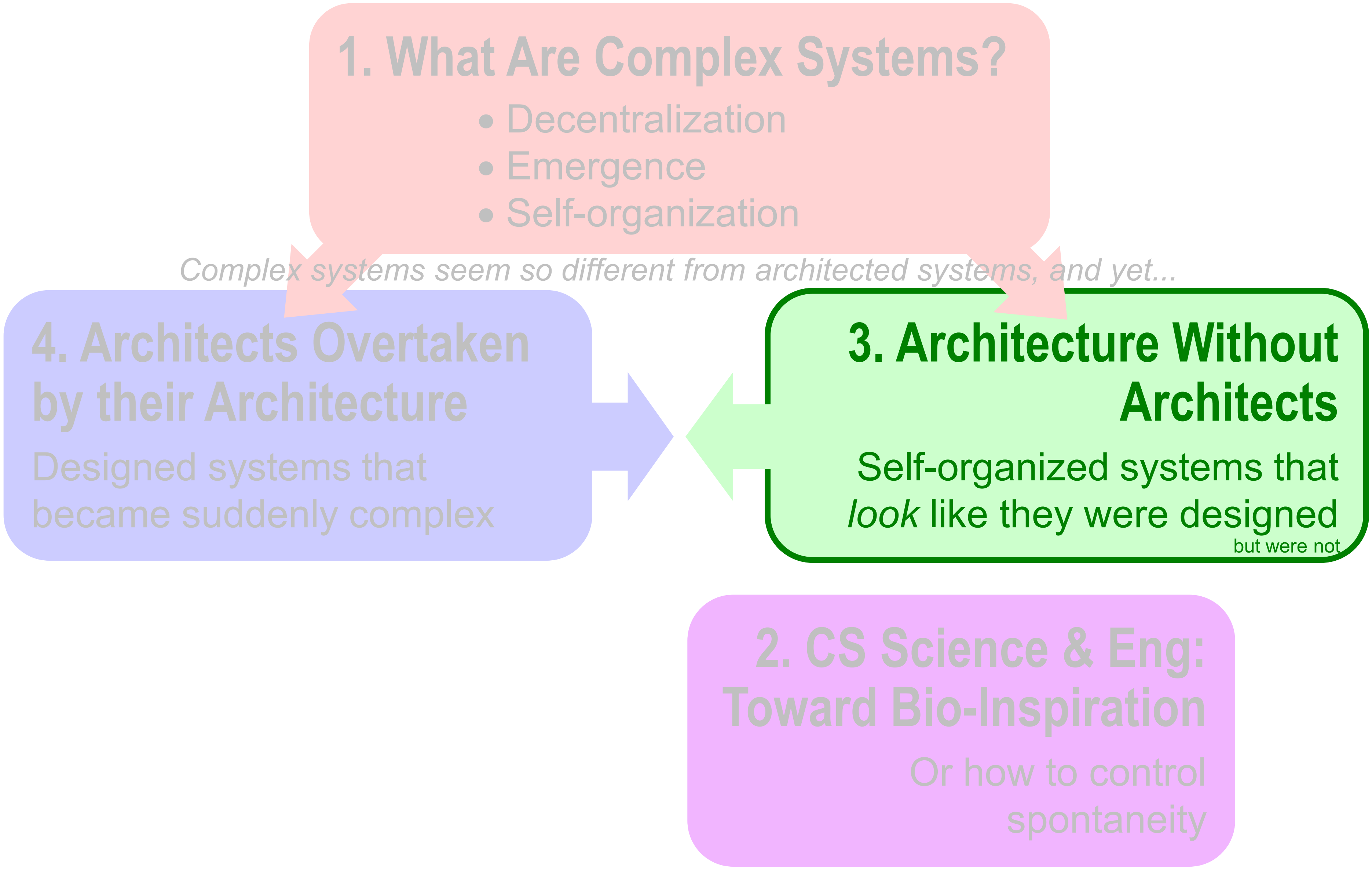

Doursat & Ulieru (2009)


Doursat, Fourquet,
Dordea & Kowaliw (2012)

Embryomorphic Engineering

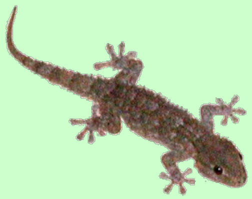
whether simulated in a Turing machine...	... or embedded in bioware, nanoware...

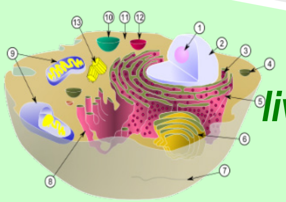
ARCHITECTURE & SELF-ORGANIZATION



3. Architecture Without Architects

- "Simple"/random vs. **architectured** complex systems

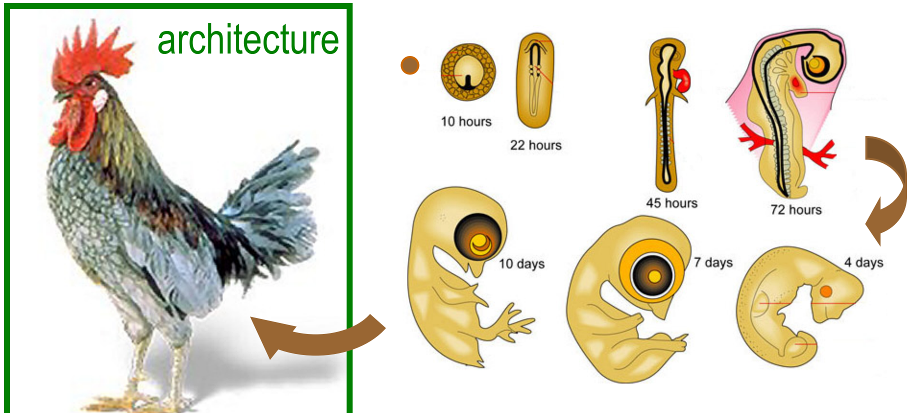




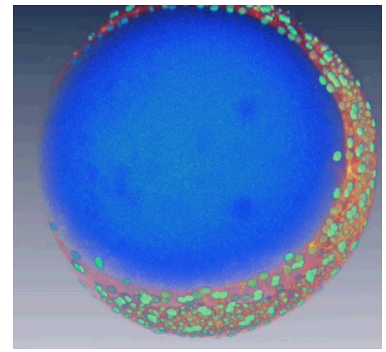
- biology strikingly demonstrates the possibility of **combining pure self-organization and elaborate architecture**, i.e.:
  - ✓ a non-trivial, sophisticated morphology
    - ***hierarchical*** (multi-scale): regions, parts, details
    - ***modular***: reuse of parts, quasi-repetition
    - ***heterogeneous***: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

3. Architecture Without Architects

➢ Ex: Morphogenesis – Biological development



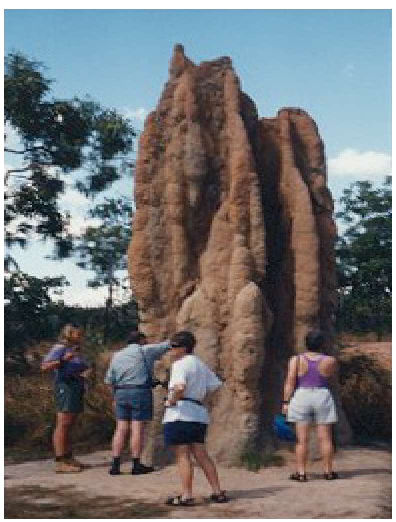
www.infovisual.info



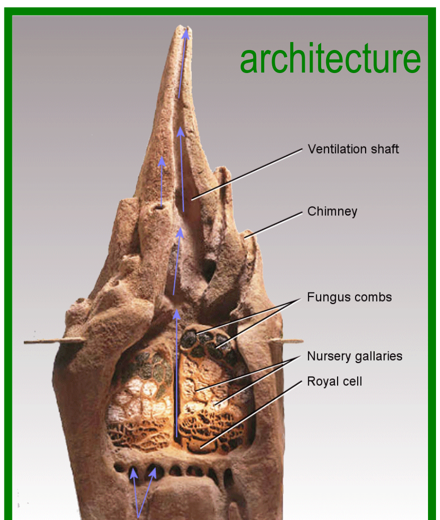
Nadine Peyriéras, Paul Bourgine et al.
(Embryomics & BioEmergences)

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

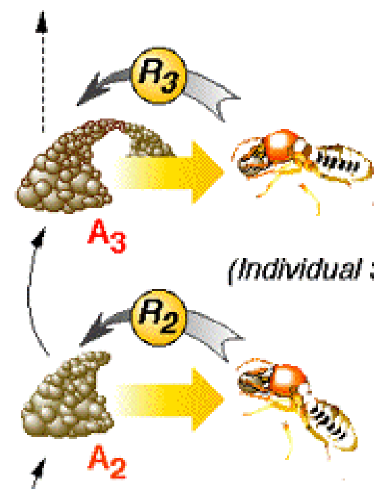
➢ Ex: Swarm intelligence – Termite mounds



Termite mound
(J. McLaughlin, Penn State University)



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

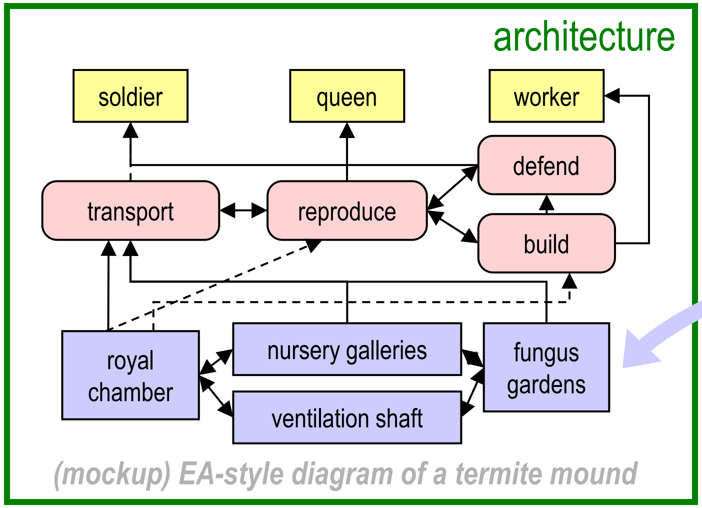


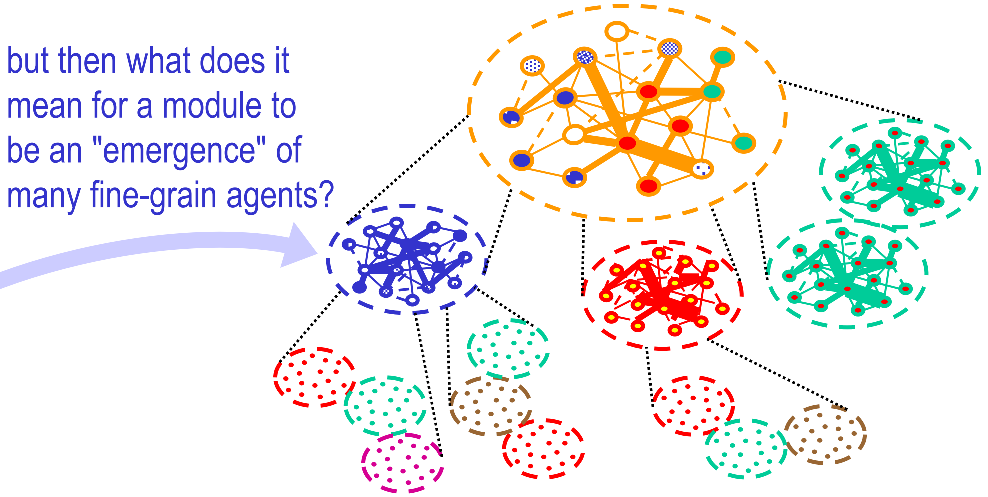
Termite stigmergy
(after Paul Grassé; from Solé and Goodwin, "Signs of Life", Perseus Books)

- 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*

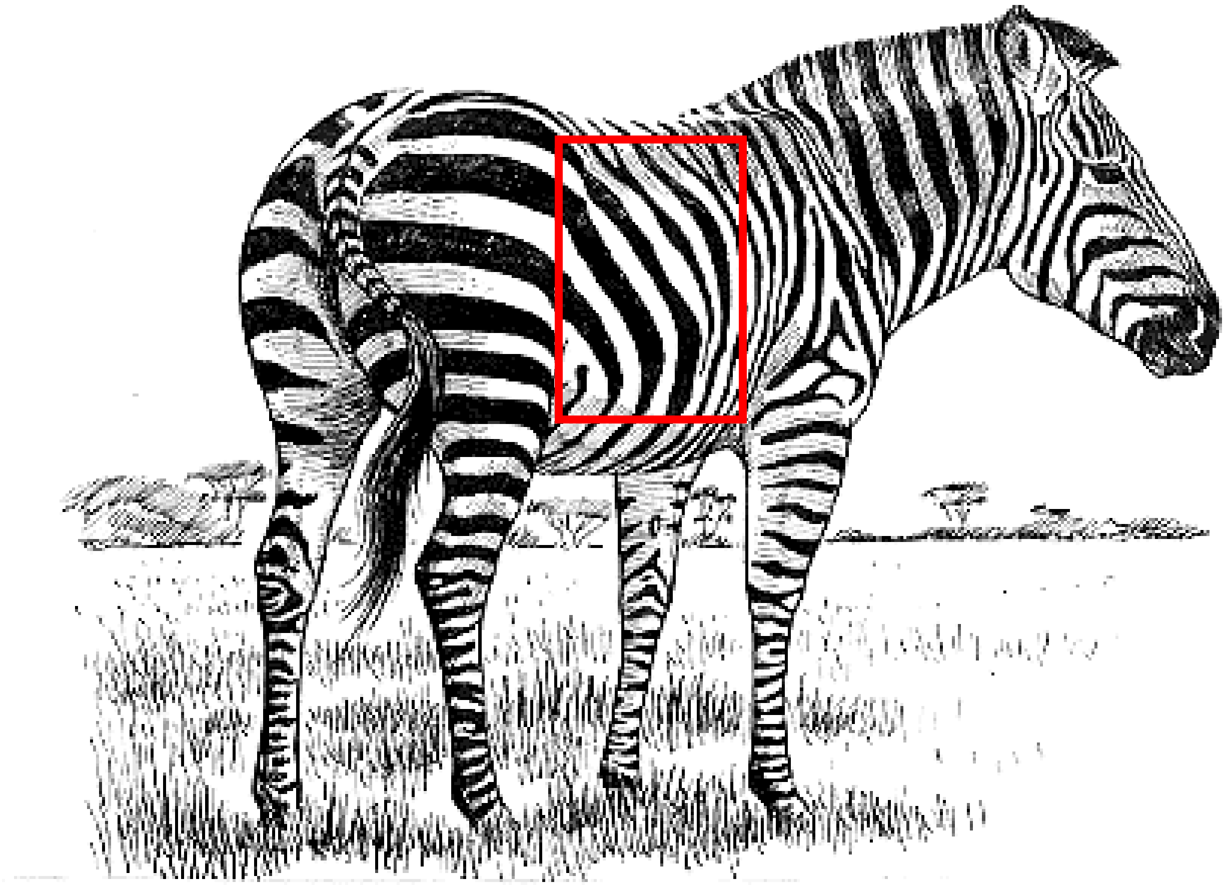




→ *cells and social insects have successfully "aligned business and infrastructure" for millions of years without any architect telling them how to*

3. Architecture Without Architects

Pattern Formation → Morphogenesis



“The stripes are easy, it’s the horse part that troubles me”

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

3. Architecture Without Architects

- From "statistical" to "morphological" complex systems

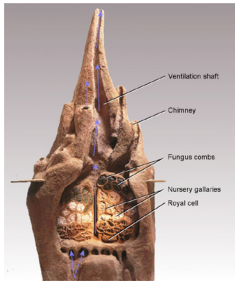
more intrinsic sophisticated architecture, less randomness

Natural Systems

social insects:
collective constructions

ant trail

network of ant trails



termite mound

ant nest

inert matter:
pattern formation

cells: biological
morphogenesis

cells

termites

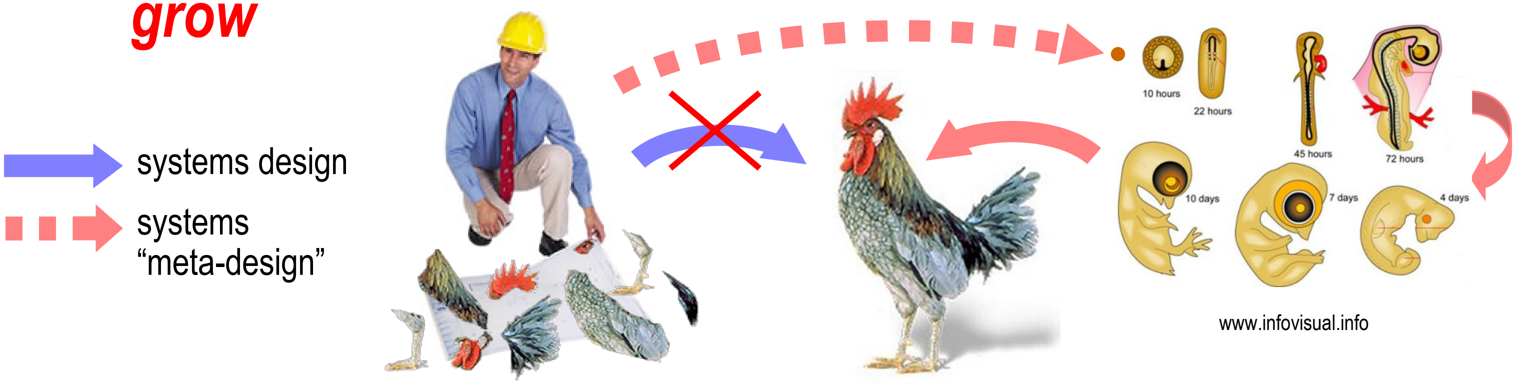
ants

grains of sand
+ warm air

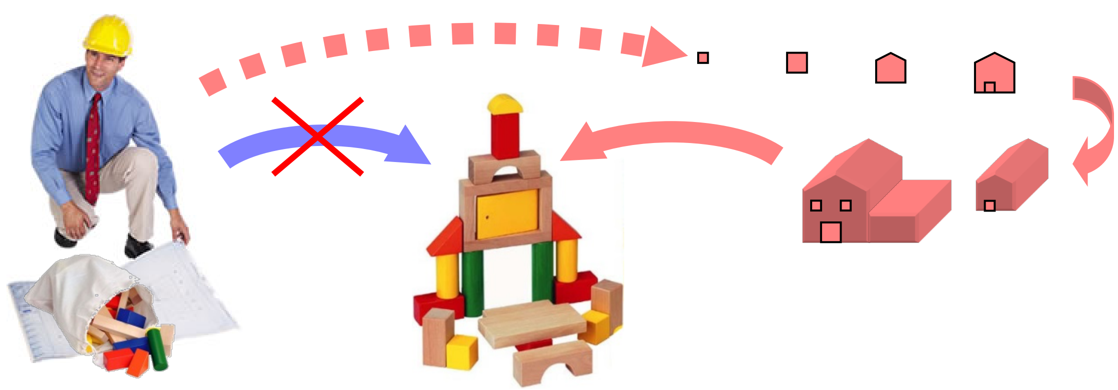
3. Architecture Without Architects

➢ From centralized heteromy to decentralized autonomy

- ✓ artificial systems *are built* exogenously, organisms endogenously ***grow***



- ✓ thus, future (SASO) engineers should "step back" from their creation and only set ***generic*** conditions for systems to self-assemble and evolve



ARCHITECTURE & SELF-ORGANIZATION

1. What Are Complex Systems?

- Decentralization
- Emergence
- Self-organization

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

4. Architects Overtaken by their Architecture

Designed systems that became suddenly complex

3. Architecture Without Architects

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

2. CS Science & Eng: Toward Bio-Inspiration

Or how to control spontaneity

4. Architects Overtaken by their Architecture

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

by their unplanned, spontaneous emergence and adaptivity... | **... arising from a multitude of traditionally designed artifacts**

geography: cities, populations ⇐ houses, buildings

people: social networks ⇐ address books

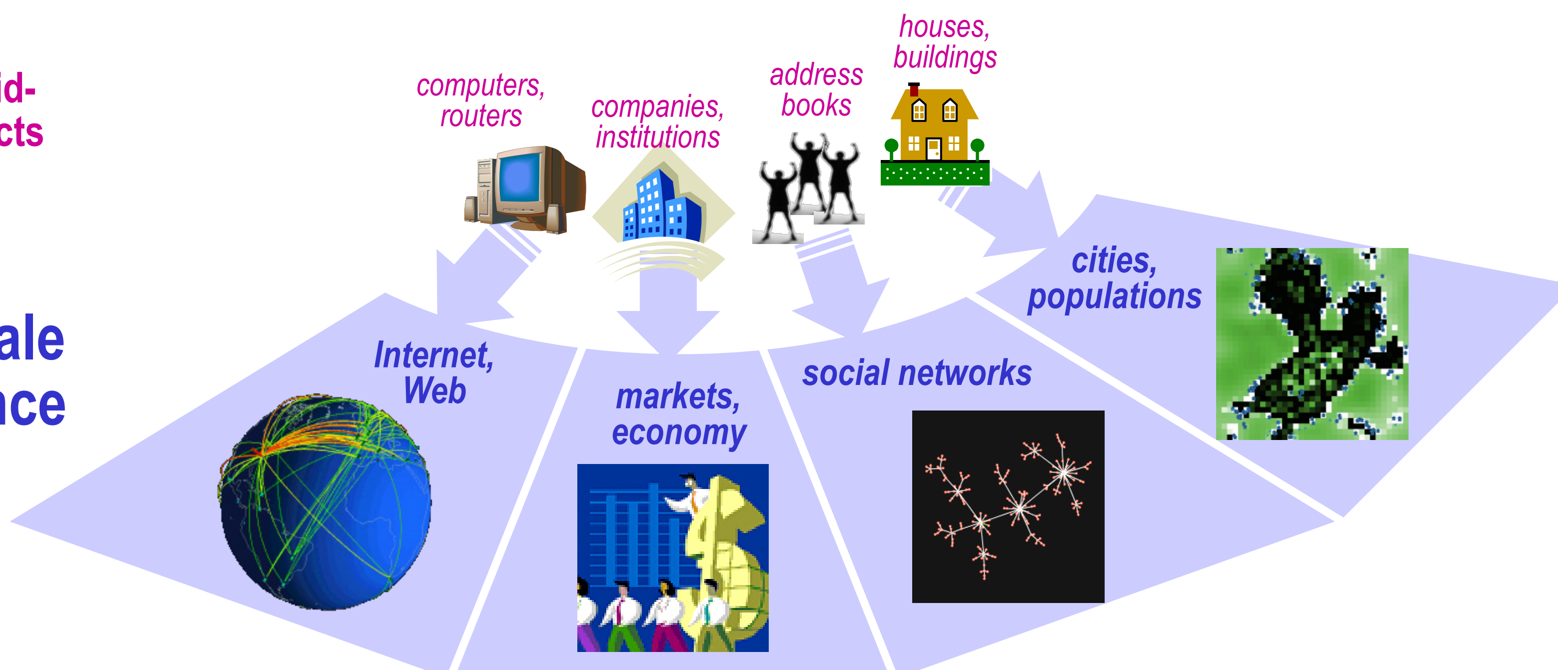
wealth: markets, economy ⇐ companies, institutions

technology: Internet, Web ⇐ computers, routers

---

small to mid-scale artifacts

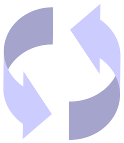
large-scale emergence

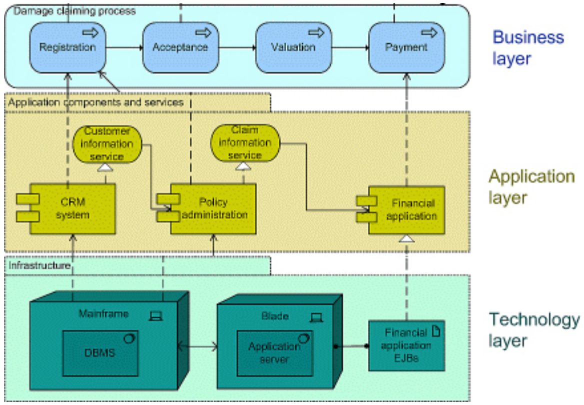


4. Architects Overtaken by their Architecture

➢ 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

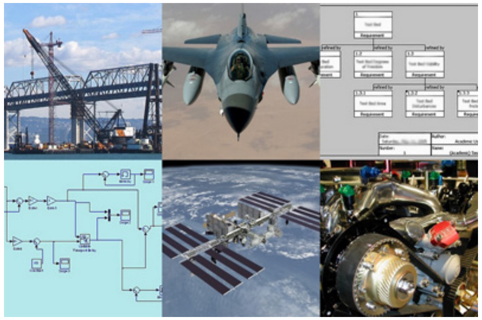




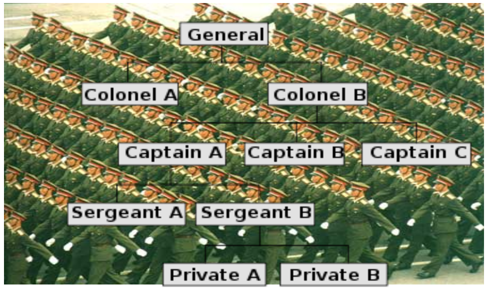
ArchiMate EA example

➢ 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



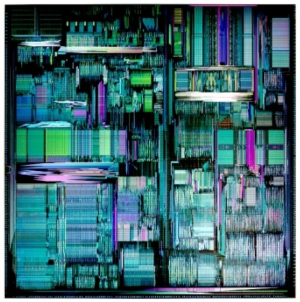
Systems engineering
Wikimedia Commons



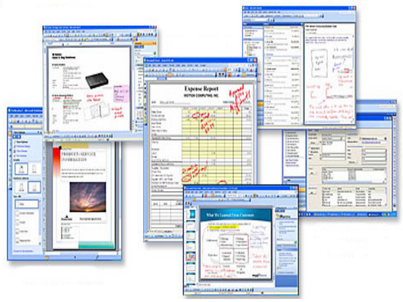
4. Architects Overtaken by their Architecture

➢ Burst to large scale: *de facto* complexification of ICT systems

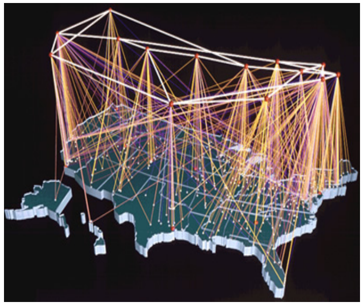
✓ ineluctable breakup into, and ***proliferation*** of, modules/components



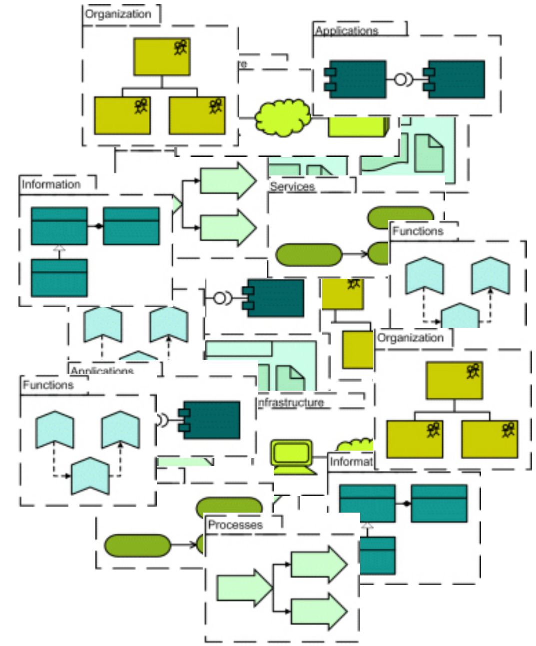
in hardware,

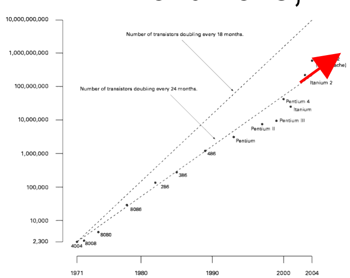


software,

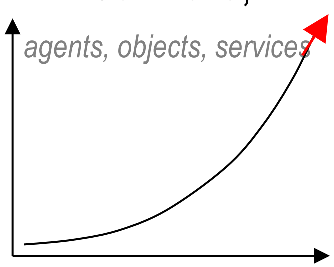


networks...

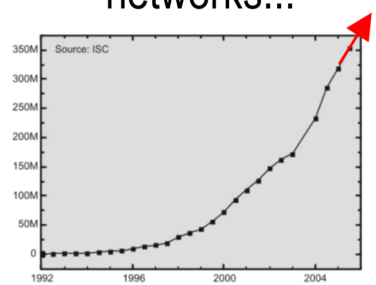




number of transistors/year



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:*

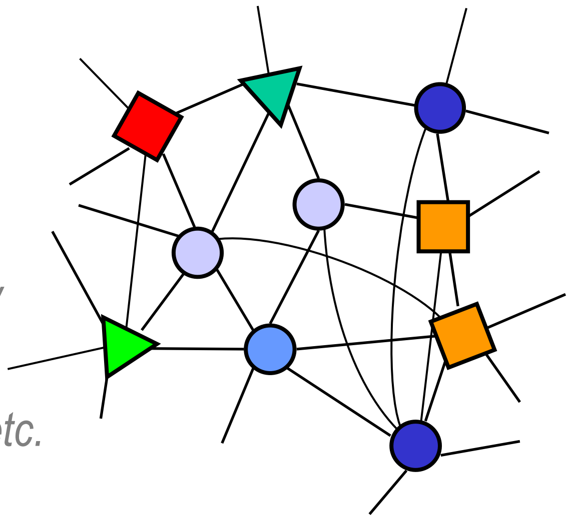
- cannot place every part anymore
- cannot foresee every event anymore
- cannot control every process anymore ... but do we still *want* to?

4. 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
    - energy & environment
    - education
    - defense & security
    - business
    - 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

1. What Are Complex Systems?

- Decentralization
- Emergence
- Self-organization

2. CS Science & Eng: Toward Bio-Inspiration

Or how to control spontaneity

3. Architecture Without Architects

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

but were not

4. Architects Overtaken by their Architecture

Designed systems that became suddenly complex

5. Morphogenetic Engineering

From cells and insects to robots and networks

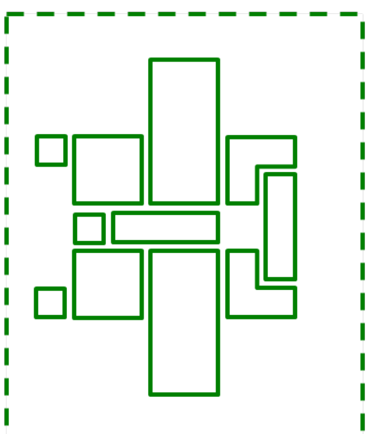
5. Morphogenetic Engineering

Artificial Systems

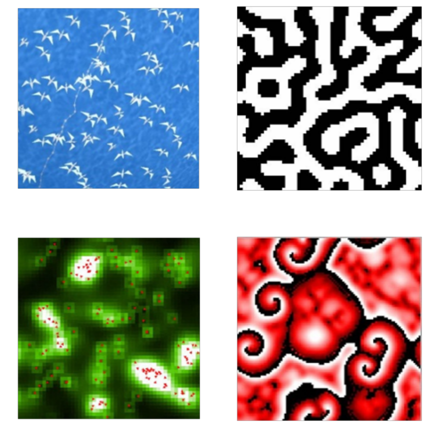
Natural Systems

(d)

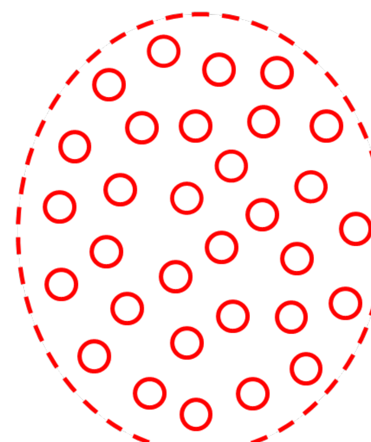
Architectured Systems
Showing *no* Self-Organization



(a)



Self-Organized Systems
Showing *no* Architecture



Doursat, Sayama & Michel (2012, 2013)

5. Morphogenetic Engineering

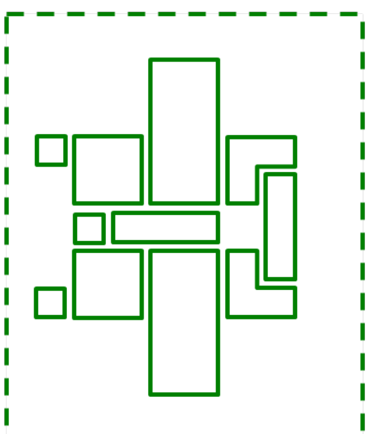
Artificial Systems

more architecture,
less randomness

Natural Systems

(d)

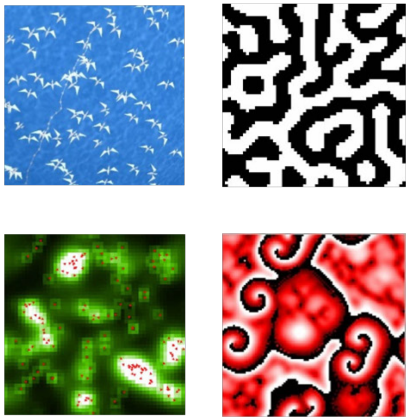
Architectured Systems
Showing *no* Self-Organization



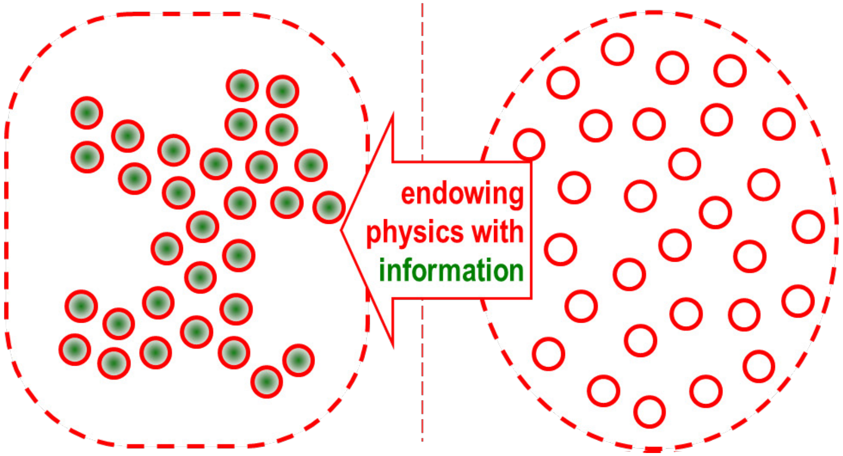
(b)

Self-Organized Systems
Showing an Architecture

(a)



Self-Organized Systems
Showing *no* Architecture



Doursat, Sayama & Michel (2012, 2013)

5. Morphogenetic Engineering

Artificial Systems — more self-organization, less design

Natural Systems

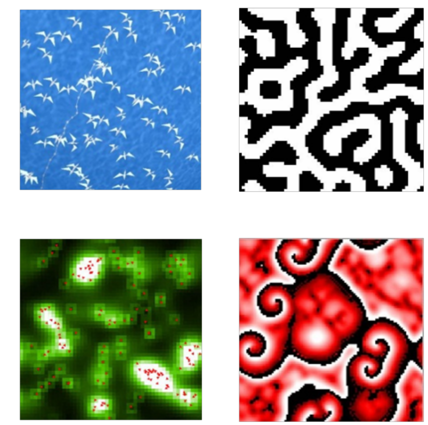
(d)

Architectured Systems
Showing *no* Self-Organization

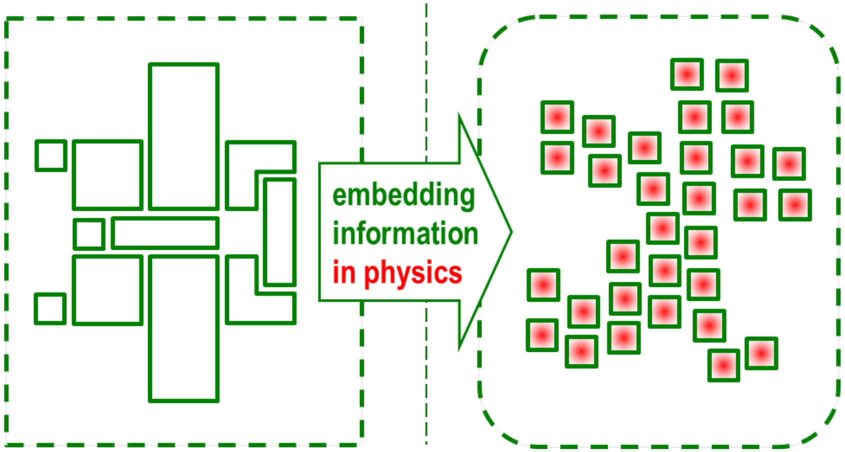
(c)

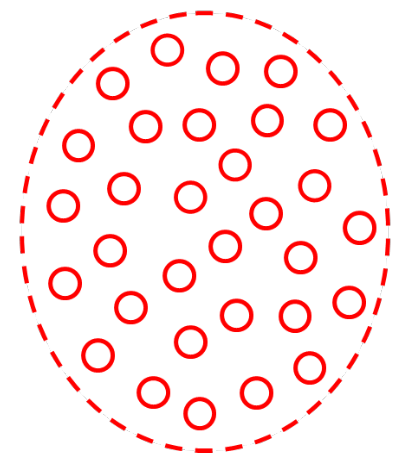
Architectured Systems
Showing Self-Organization

(a)



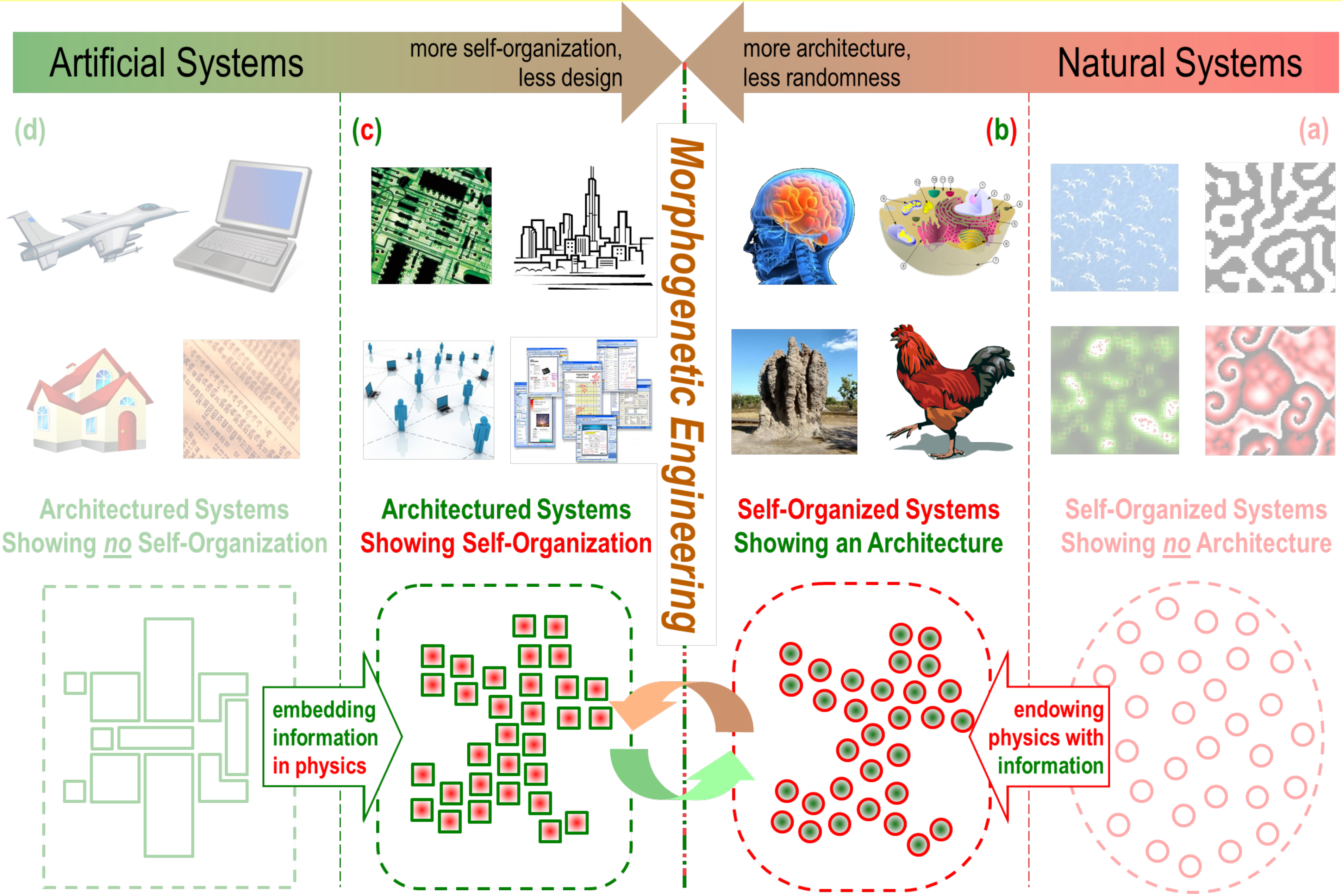
Self-Organized Systems
Showing *no* Architecture





Doursat, Sayama & Michel (2012, 2013)

5. Morphogenetic Engineering



Doursat, Sayama & Michel (2012, 2013)

5. Morphogenetic Engineering

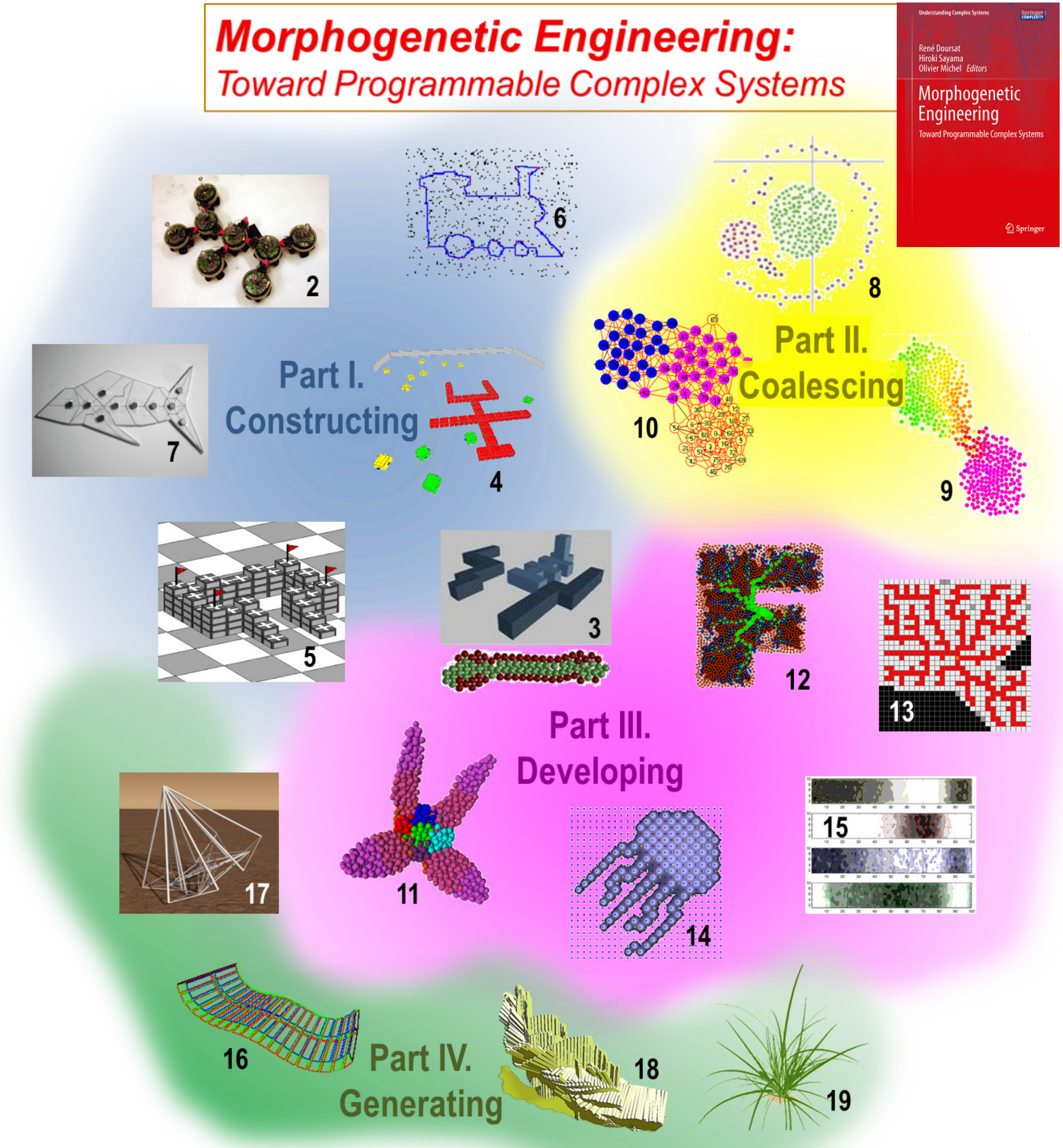
Morphogenetic Engineering (ME) is about designing the agents of self-organized architectures... *not the architectures directly*

- **ME brings a new focus in complex systems engineering**
  - ✓ exploring the artificial design and implementation of **decentralized systems capable of developing elaborate, heterogeneous morphologies** without central planning or external lead

- **Related emerging ICT disciplines and application domains**
  - ✓ *amorphous/spatial computing* (MIT, Fr.)
  - ✓ *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.

- **ME Workshops (MEW) and book**
  - ○ 1st MEW, Complex Systems Institute Paris, 2009
  - ○ 2nd MEW (Special Session), ANTS 2010, ULB Bruxelles
  - ○ 3rd MEW, ECAL 2011, Paris
  - ○ Springer Book, 2012
  - ○ 4th MEW, Alife 2014, New York
  - ○ 5th MEW, ECAL 2015, York, UK

Morphogenetic Engineering:
Toward Programmable Complex Systems



Doursat, Sayama & Michel, eds. (Springer, 2012)

Chap 2 – **O'Grady, Christensen & Dorigo**
Chap 3 – **Jin & Meng**
Chap 4 – **Liu & Winfield**
Chap 5 – **Werfel**
Chap 6 – **Arbuckle & Requicha**
Chap 7 – **Bhalla & Bentley**

Chap 8 – **Sayama**
Chap 9 – **Bai & Breen**
Chap 10 – **Nembrini & Winfield**

Chap 11 – **Doursat, Sanchez, Dordea, Fourquet & Kowaliw**
Chap 12 – **Beal**
Chap 13 – **Kowaliw & Banzhaf**
Chap 14 – **Cussat-Blanc, Pascalie, Mazac, Luga & Duthen**
Chap 15 – **Montagna & Viroli**

Chap 16 – **Michel, Spicher & Giavitto**
Chap 17 – **Lobo, Fernandez & Vico**
Chap 18 – **von Mammen, Phillips, Davison, Jamniczky, Hallgrimsson & Jacob**
Chap 19 – **Verdenal, Combes & Escobar-Gutierrez**

Doursat, Sayama & Michel, *Natural Computing* (2013)

Broader Review of ME

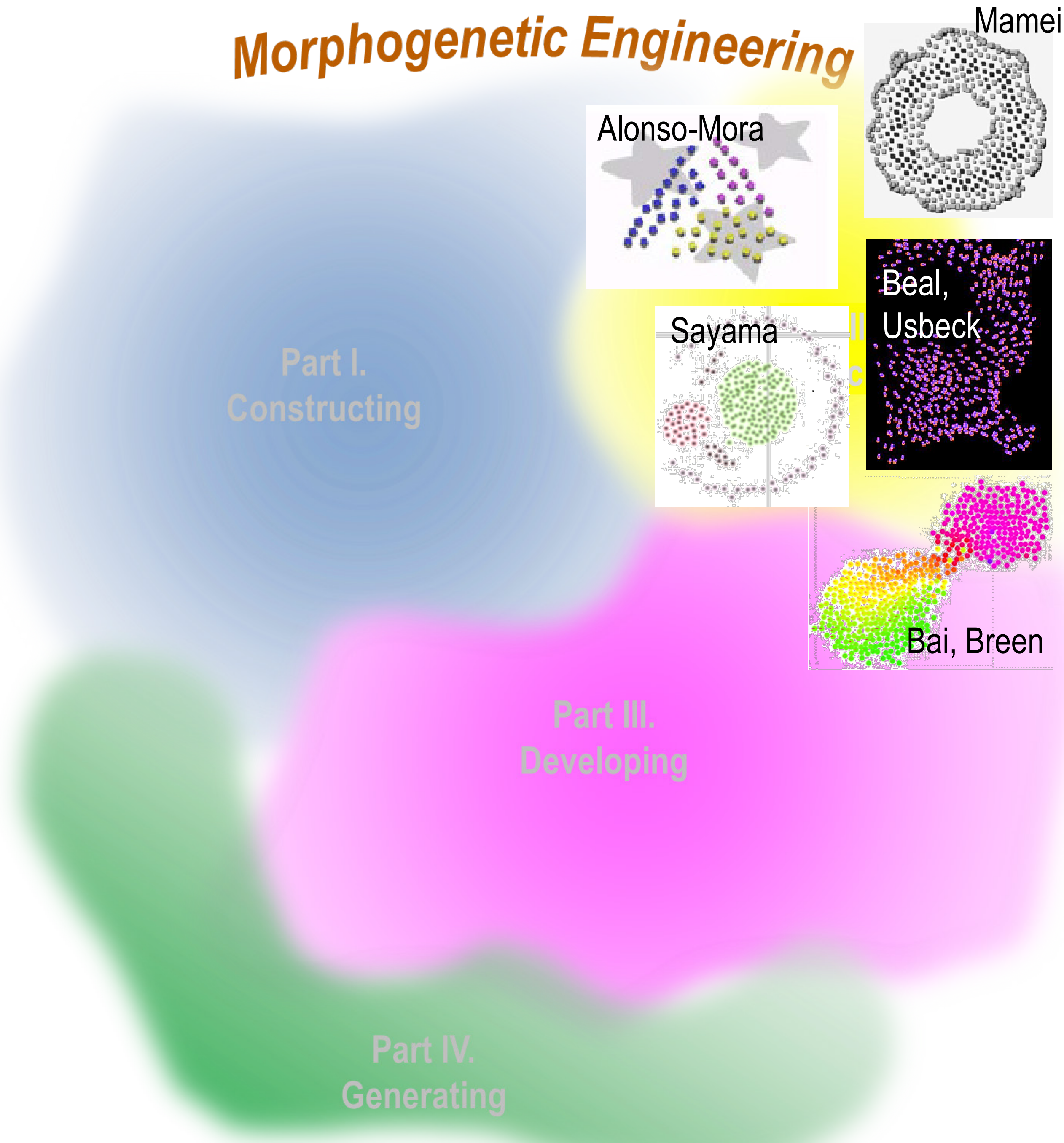
Category I. Constructing

(or "Assembling", "Fitting")

A small number of mobile agents or components attach to each other or assemble blocks to build a precise "stick-figure" structure.

... based on:

- **Self-rearranging robotic parts**
  - ex: Lipson (MOLECUBES)
  - ex: Murata (M-TRAN)
- **Self-assembling mobile robots**
  - ex: O'Grady, Dorigo (SWARMORPH)
  - ex: SYMBRION
- **Block constructions**
  - ex: Werfel (TERMES)



Doursat, Sayama & Michel, *Natural Computing* (2013)

Broader Review of ME

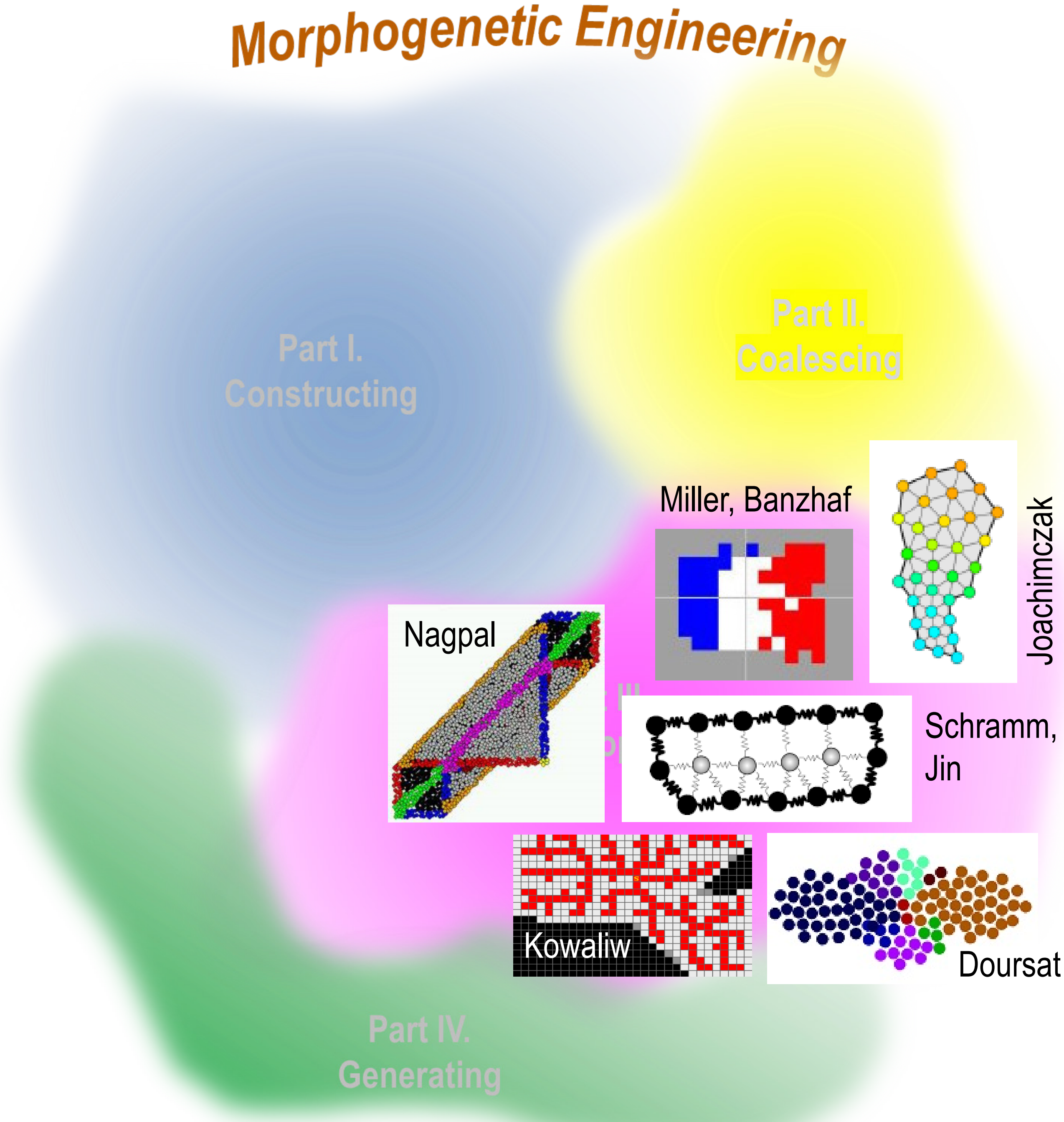
Category II. Coalescing

(or "Synchronizing", "Swarming")

A great number of mobile agents flock and make together dense clusters, whose contours adopt certain shapes.

... based on:

- **Robotic agents**
  - ex: Mamei
  - ex: Alonso-Mora
- **Software particles**
  - ex: Sayama (SWARM CHEMISTRY)
  - ex: Bai, Breen
- **Programming matter, computing in space**
  - ex: Beal, Usbeck (PROTO)
  - ex: Goldstein (CLAYTRONICS)



Doursat, Sayama & Michel, *Natural Computing* (2013)

Broader Review of ME

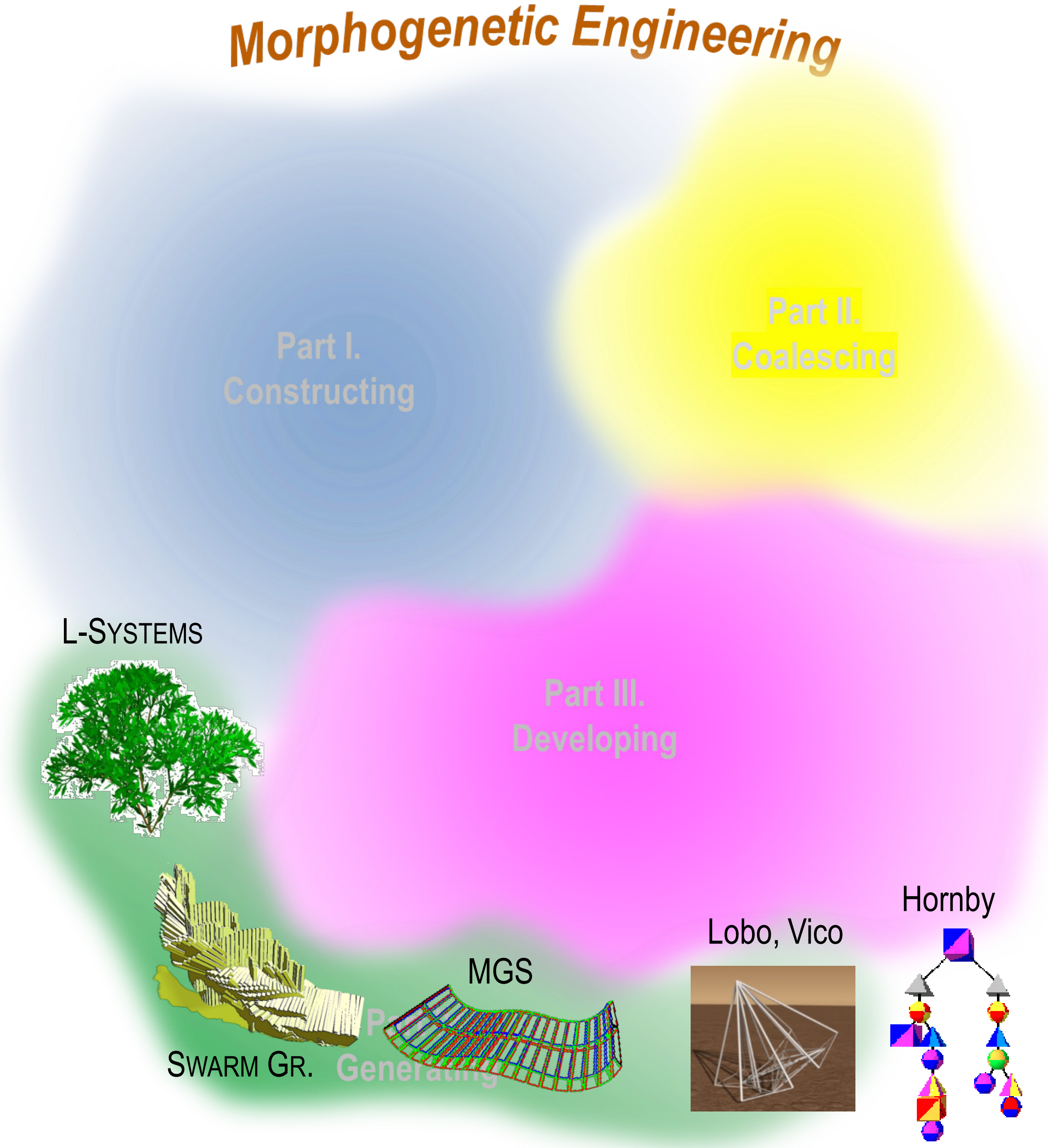
Category III. Developing

(or “Growing”, “Aggregating”)

The system expands from a single initial agent or group by division or aggregation, forming biological-like patterns or organisms.

... based on:

- **Artificial (evolutionary) development**
  - ex: Miller, Banzhaf (FRENCH FLAG)
  - ex: Doursat
- **Developmental animats**
  - ex: Joachimczak, Wrobel
  - ex: Schramm, Jin
- **Morphogenetic patterning**
  - ex: Kowaliw
  - ex: Nagpal, Coore (GPL)



Broader Review of ME

Category IV. Generating

(or “Rewriting”, “Inserting”)

The system expands by successive transformations of components in 3D space, based on a grammar of “rewrite” rules.

... based on:

- **Biologically inspired grammars**
  - ex: Lindemayer, Prusinkiewicz (L-SYSTEMS)
  - ex: Spicher, Michel, Giavitto (MGS)
- **Graph and swarm grammars**
  - ex: Sayama (GNA)
  - ex: von Mammen
- **Evolutionary grammars**
  - ex: Hornby, Pollack
  - ex: Lobo, Vico

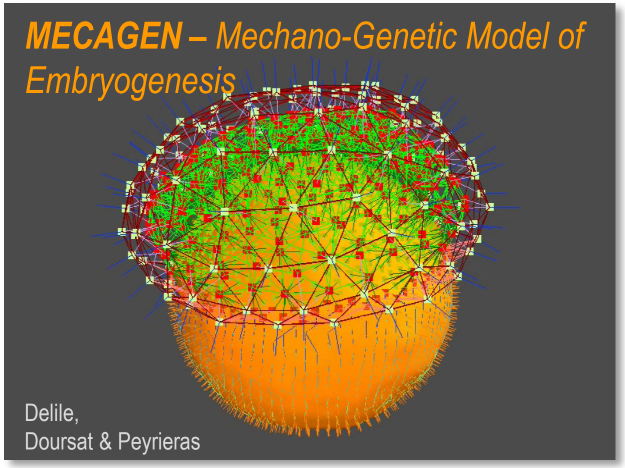
THREE STUDIES IN MORPHOGENETIC ENGINEERING

Systems that are self-organized *and* architectured

➢ Embryogenesis to Simulated Development to Synthetic Biology

*illustration of **Morphogenetic Engineering** ideas*

mutually beneficial transfers between biology & CS

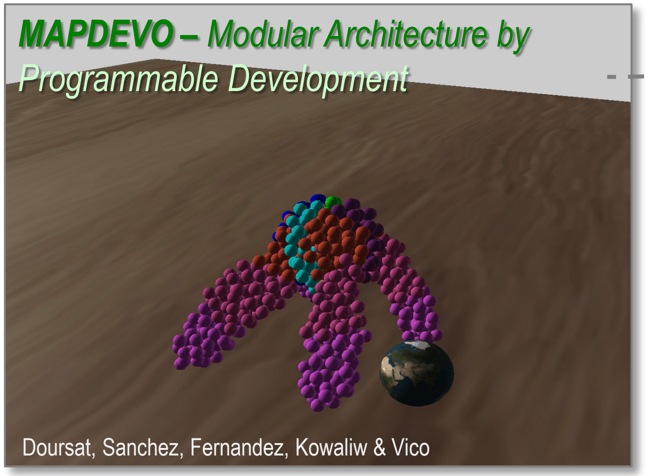


***MECAGEN** – Mechano-Genetic Model of Embryogenesis*

Delile, Doursat & Peyrieras

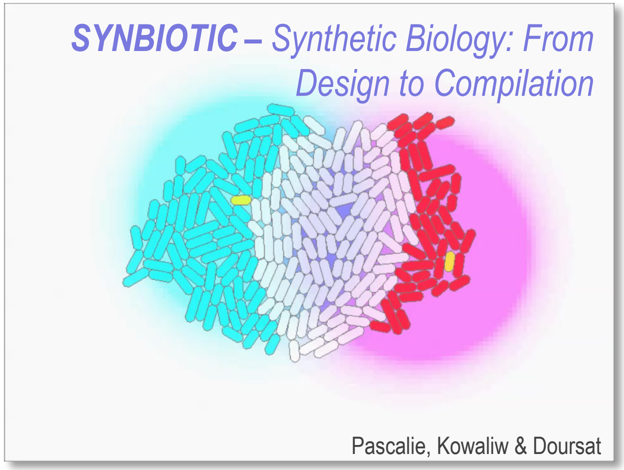
BIOMODELING (LIFE)

BIO-INSPIRED ENGINEERING (ALIFE)



***MAPDEVO** – Modular Architecture by Programmable Development*

Doursat, Sanchez, Fernandez, Kowaliw & Vico



***SYNBIOTIC** – Synthetic Biology: From Design to Compilation*

Pascalie, Kowaliw & Doursat

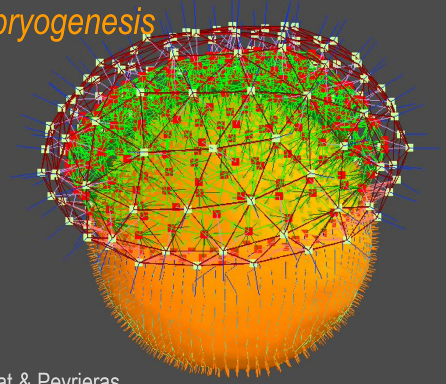
BIOENGINEERING (HYBRID LIFE)

Systems that are self-organized *and* architectured

➤ Embryogenesis to Simulated Development to Synthetic Biology

illustration of Morphogenetic Engineering ideas

***MECAGEN** – Mechano-Genetic Model of Embryogenesis*



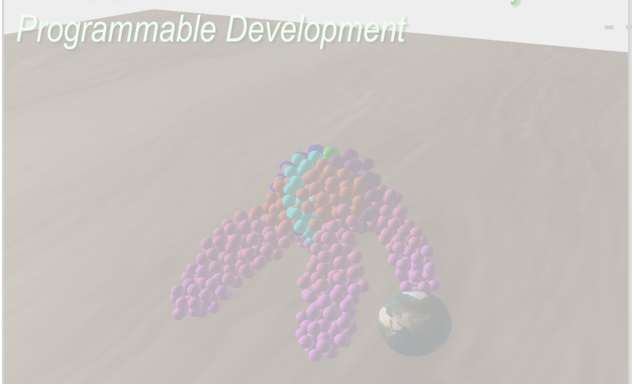
Delile, Doursat & Peyrieras

BIOMODELING (LIFE)

mutually beneficial transfers between biology & CS

BIO-INSPIRED ENGINEERING (ALIFE)

***MAPDEVO** – Modular Architecture by Programmable Development*



Doursat, Sanchez, Fernandez, Kowaliw & Vico

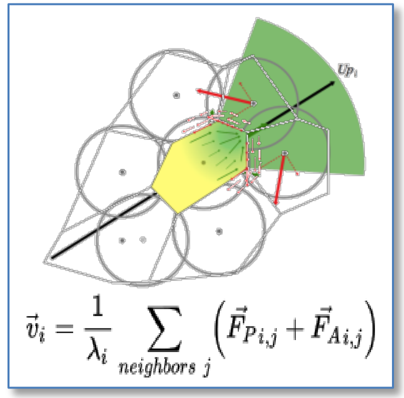
***SYNBIOTIC** – Synthetic Biology: From Design to Compilation*

Pascalie, Kowaliw & Doursat

BIOENGINEERING (HYBRID LIFE)

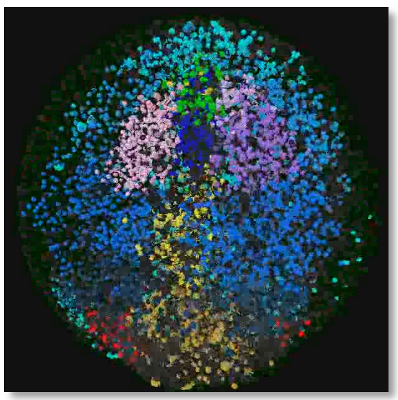
Methodology and workflow

Hypotheses



3 Agent-based Model

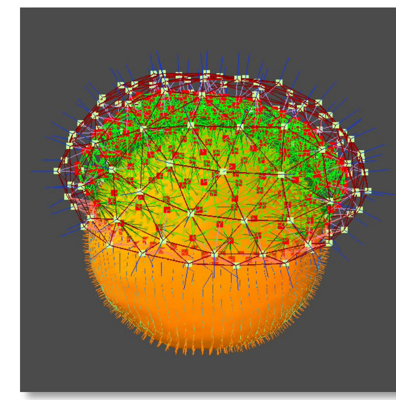
Simulation



2 Phenomenological reconstruction

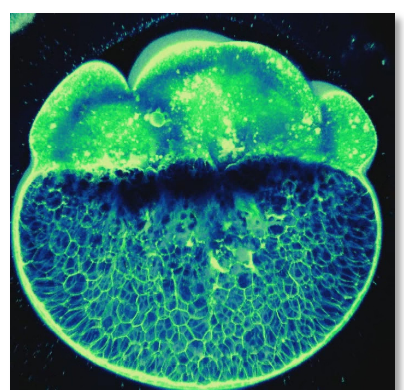
Δ

5 *Validation*



4 Computational reconstruction

Processing



1 Raw imaging data

PhD thesis: Julien Delile (ISC-PIF)
supervisors: René Doursat, Nadine Peyriéras

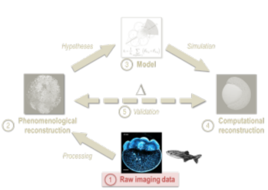
MECAGEN – *Mechano-Genetic Model of Embryogenesis*

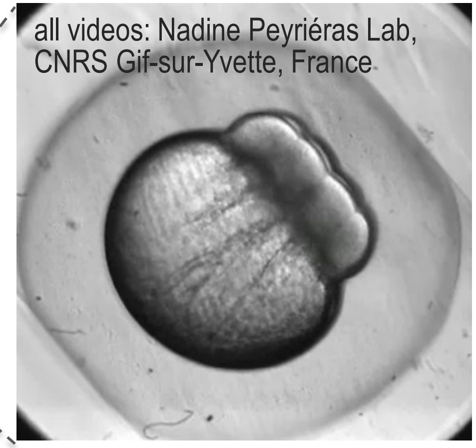
➢ Zebrafish development

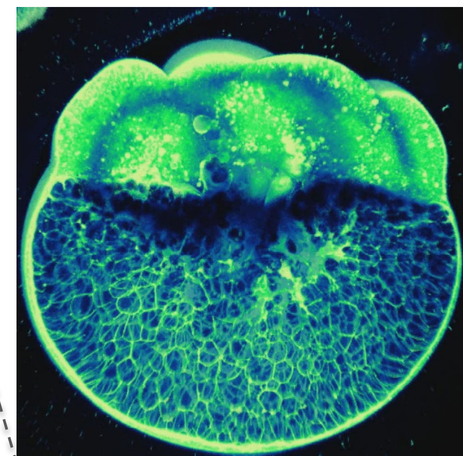
- 00.00 – 00.75 hrs **Zygote Period**
- 00.75 – 02.25 hrs **Cleavage Period**
- 02.25 – 05.25 hrs **Blastula Period**
- 05.25 – 10.33 hrs **Gastrula Period**
- 10.33 – 24 hrs **Segmentation Pd**
- 24 hrs – 48 hrs **Pharyngula Period**
- 48 hrs – 72 hrs **Hatching Period**

Larval Period

Adult

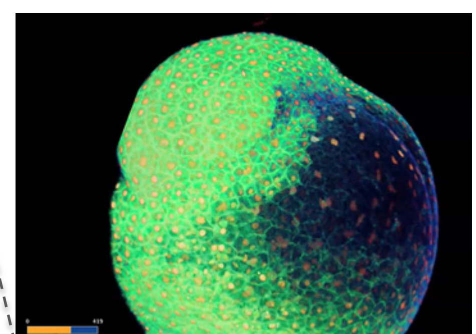






- nonlinear optics imaging method (without dyes): based on natural "Second and Third Harmonic Generation" (SHG, THG) of photons by live tissue from a laser excitation

Emmanuel Beaurepaire's Optics & Bioscience Lab at Ecole Polytechnique Paris



- biological marker imaging method: "Double Labelling" ubiquitous staining with two fluorescent proteins targeted at the cell nuclei and membranes

MECAGEN – *Mechano-Genetic Model of Embryogenesis*

➢ Phenomenological reconstruction: *BioEmergences* workflow

Filtering

3D image sequence processing

Evolutionary process on partial differential equation

Local maxima Detection

Different filtering methods
- Perona Malik
- Mean Curvature Flow
- Geodesic Mean Curvature Flow
- Gradient Anisotropic Diffusion
- Twister Segment Filtering

Detection: Nucleus

Hough transform with parallel algorithms

Mathematical Morphology

Automatic comparison of results

Segmentation

Limitation in optical re-solution is a main problem for segmentation

Methods :
- Subjective surface
- Watershed Segmentation
- 4D labeling based on multi-scale connectivity

Tracking

The tracking is based on greedy algorithm. After estimating cell movement with optical flow tech-nics, one try to find the closest cell in space. Further more we also use higher level information on cells to improve the tracking.

Interphase

Prophase

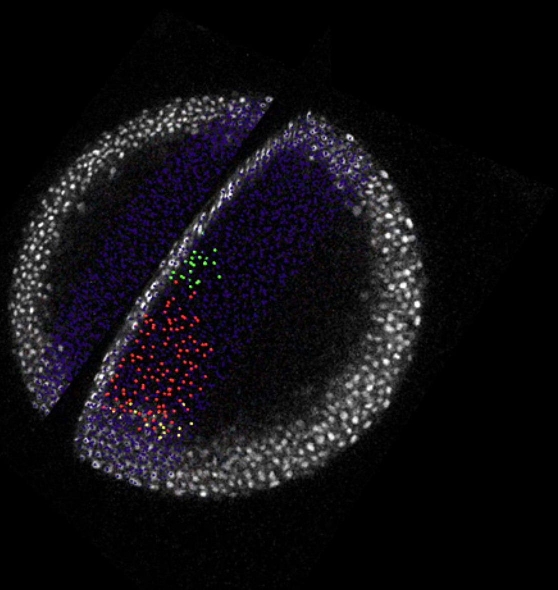
Prometaphase

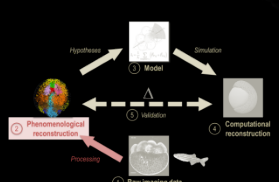
Metaphase

Telophase

Cytokinesis

Automatic Mitosis Detection with paremeters:
- volume
- convexity
- ellipse caracteristic
- intensity





<u>image processing and reconstruction workflow</u>: Emmanuel Faure, Benoit Lombardot, Thierry Savy, Rene Doursat, Paul Bourgine (Polytechnique/CNRS), Matteo Campana, Barbara Rizzi, Camilo Melani, Cecilia Zanella, Alex Sarti (Bologna), Olga Drblíkova, Zuzana Kriva, Karol Mikula (Bratislava), Miguel Luengo-Oroz (Madrid)

MECAGEN – *Mechano-Genetic Model of Embryogenesis*

Morphogenesis essentially couples mechanics and genetics

[A] Cell mechanics ("self-sculpting")

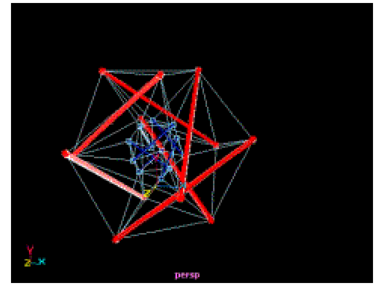
modification of cell size and shape

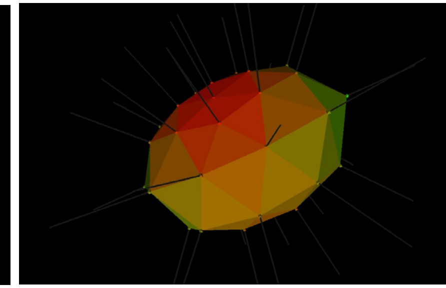
growth, division, apoptosis

motility, migration

differential adhesion

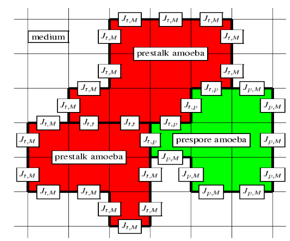
Tensional integrity
Donald Ingber, Harvard

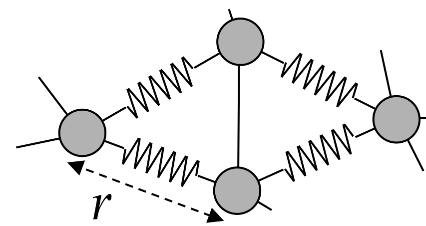




Deformable volume
Doursat, simul. by Delile

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





Spring-mass model
Doursat (2009) ALIFE XI

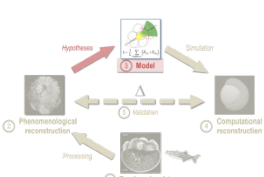
[B] Gene regulation ("self-painting")

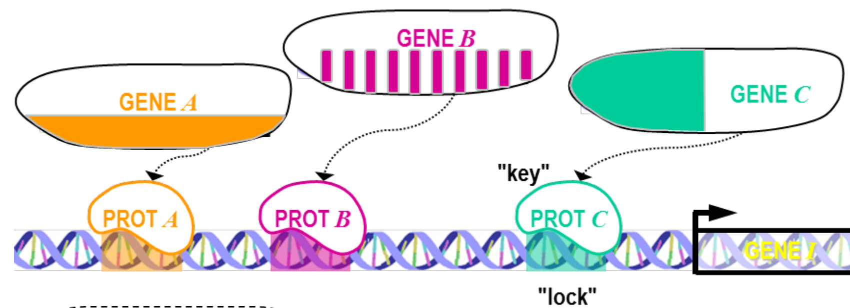
gene regulation

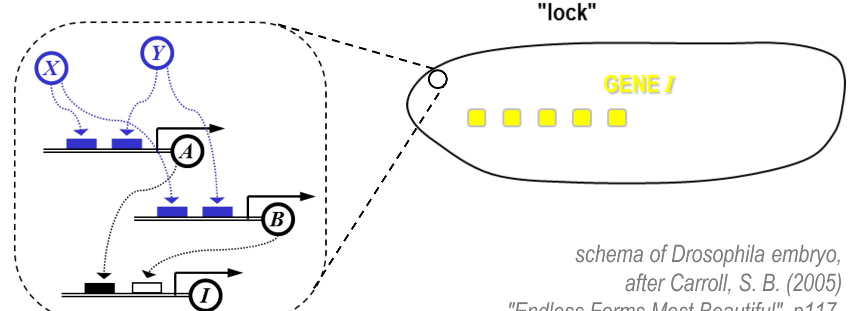
changes in cell-to-cell contacts

diffusion gradients ("morphogens")

changes in signals, chemical messengers





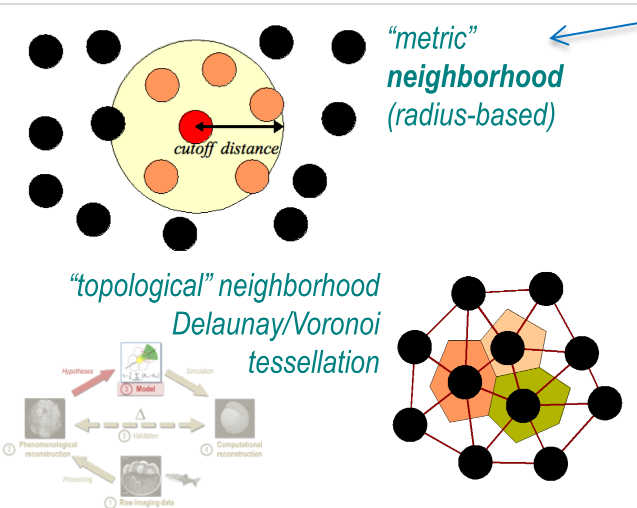


schema of Drosophila embryo, after Carroll, S. B. (2005) "Endless Forms Most Beautiful", p117

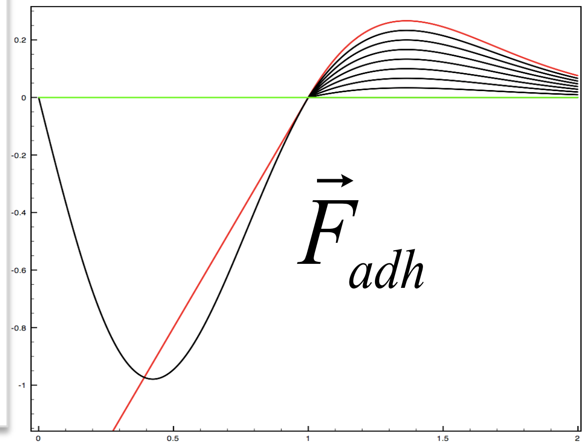
MECAGEN – *Mechano-Genetic Model of Embryogenesis*

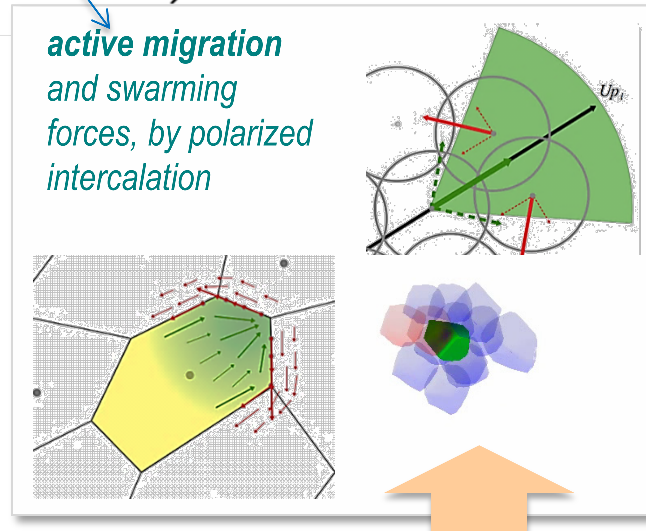
[A] Cell behavior: equations of motion

$$\cancel{m\vec{a}_i} + \lambda \vec{v}_i = \sum_{\boxed{j\in\mathcal{N}_i}} \left(\boxed{\vec{F}^{P}_{ij}} + \boxed{\vec{F}^{A,\mathrm{int}}_{ij} + \vec{F}^{A,\mathrm{ext}}_{ij}} \right)$$

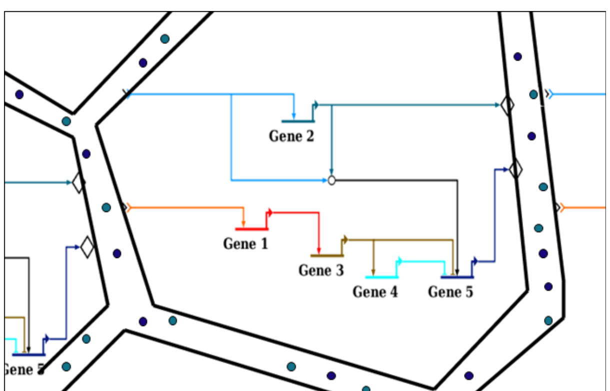


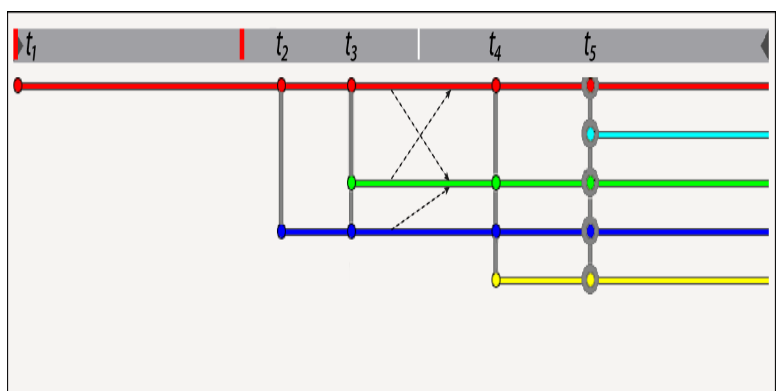
passive **relaxation forces**

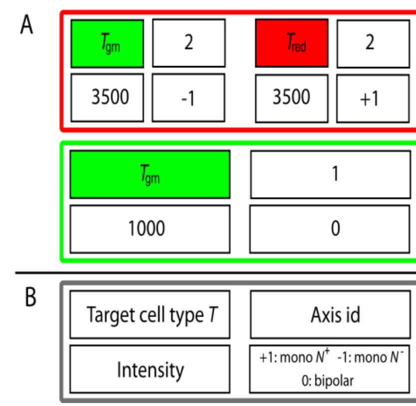




[B] Cell types: GRN or "Waddingtonian" timeline





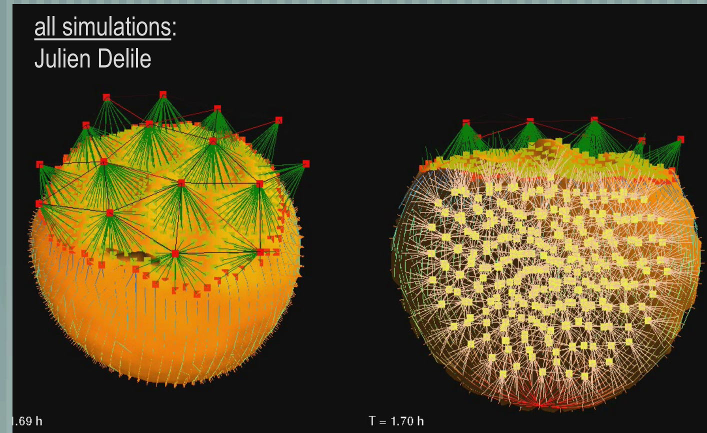


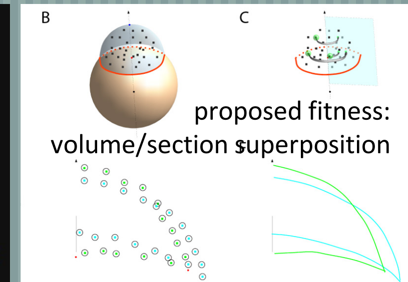
[C] coupling

MECAGEN → Case Studies in the Zebrafish

3. How is the Zebrafish blastula shaped?

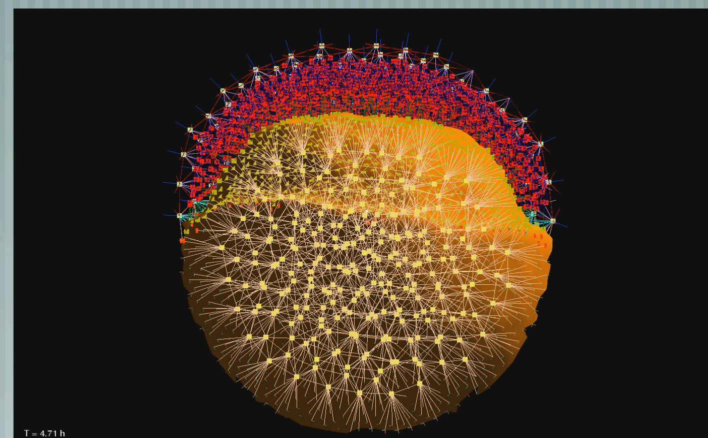
→ *How does blastula shape emerge from cell-cell interactions?*

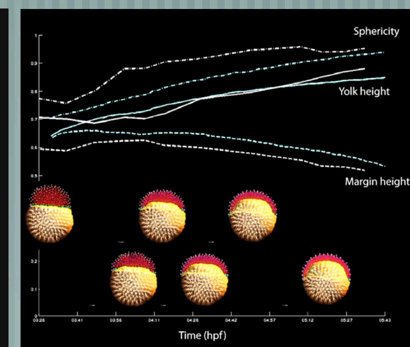




5. Intercalation patterns

→ *Are protrusions sufficient to drive epiboly ?*

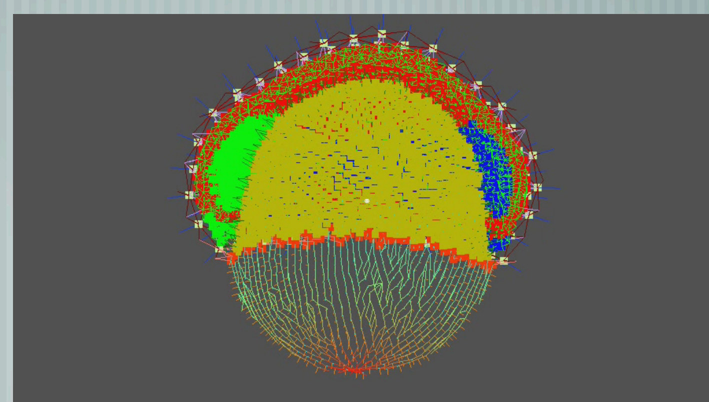




Macroscopic landmarks characterizing epiboly

6. Cell behaviors during gastrulation

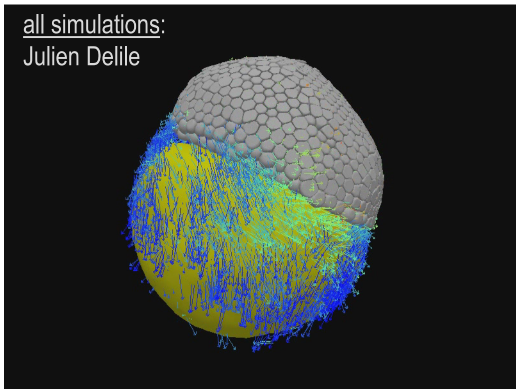
→ *How is cell division orientation and the polarization field during convergence-extension?*

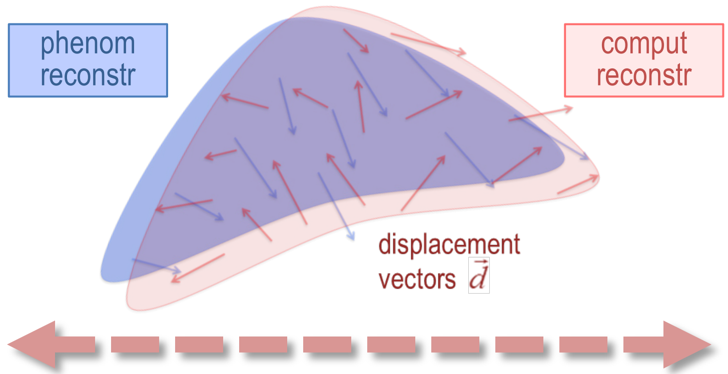


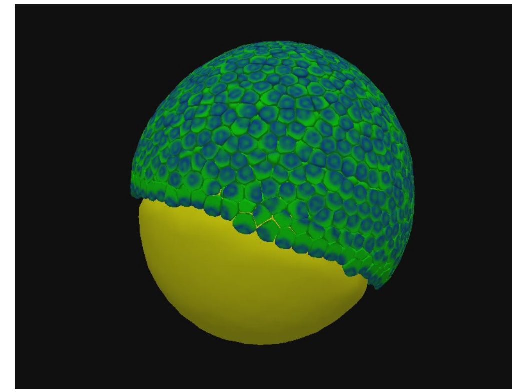
MECAGEN – *Mechano-Genetic Model of Embryogenesis*

➢ Validation and optimization: fitness and parameter search

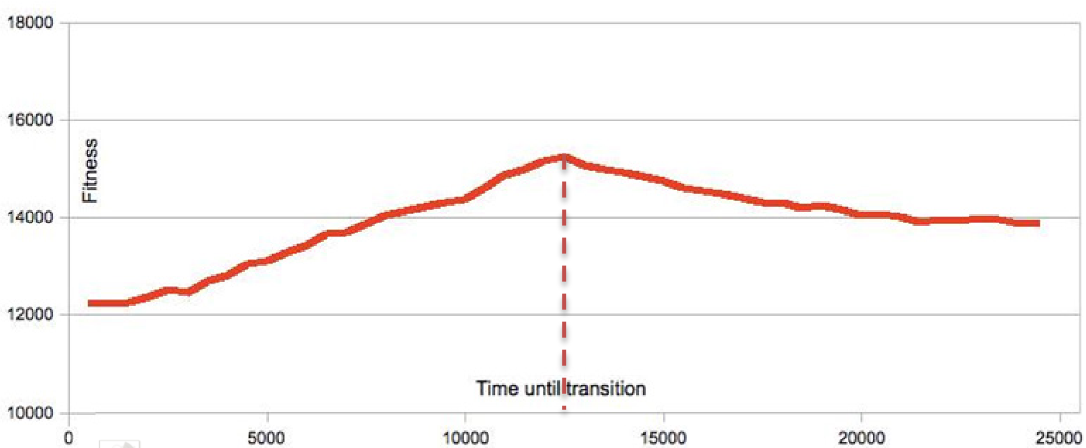
- find the most "realist" simulation, i.e. closest to the phenomenal reconstruction

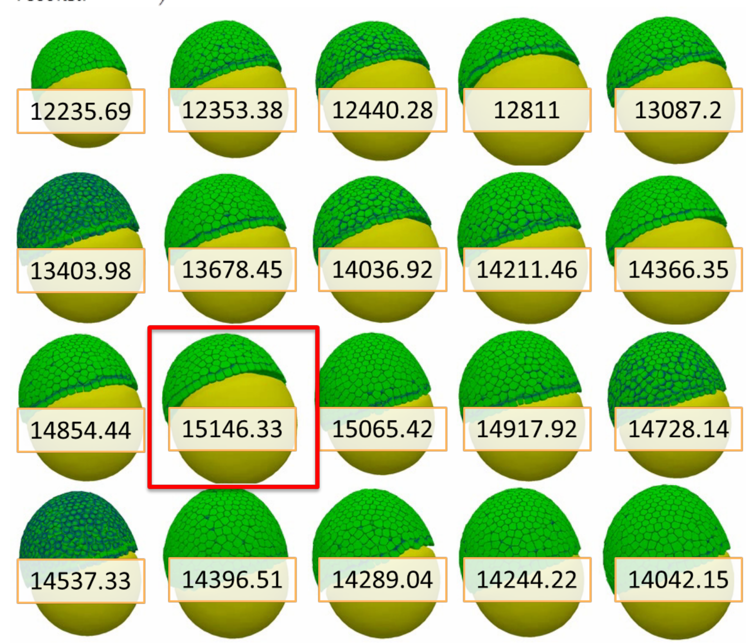


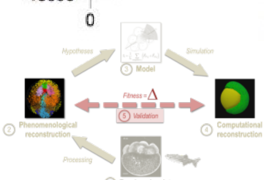




$$Fitness = \sum_{time\,t} \sum_{cells\,i} \max\left(0, \vec{d}_{simul}(i,t) \cdot \vec{d}_{reconstr}(i,t)\right)$$

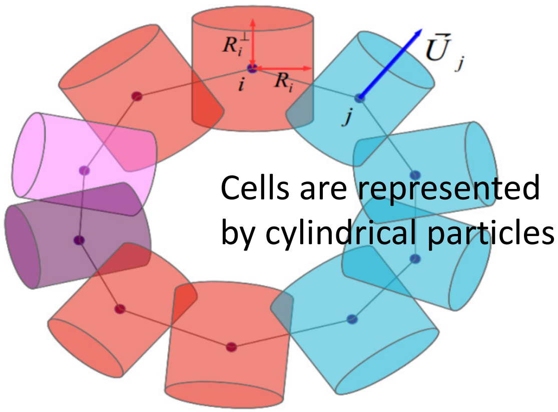


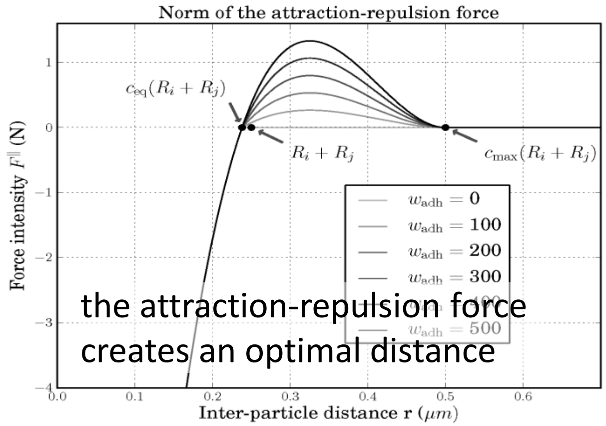


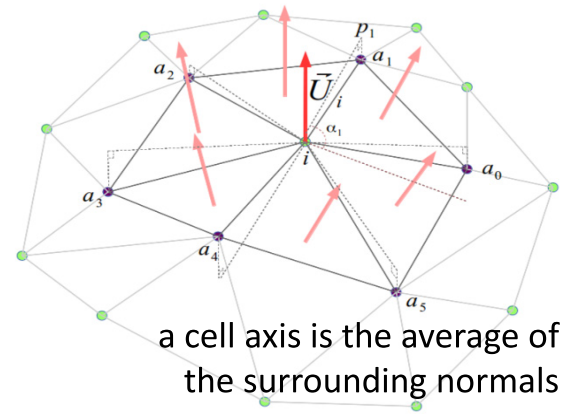


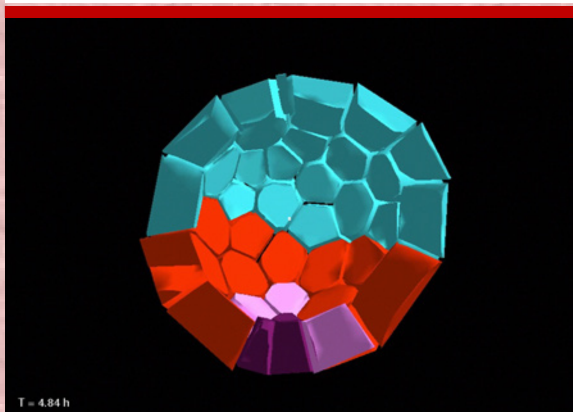
ex. of parameter: time_until_transition_to_epiboly

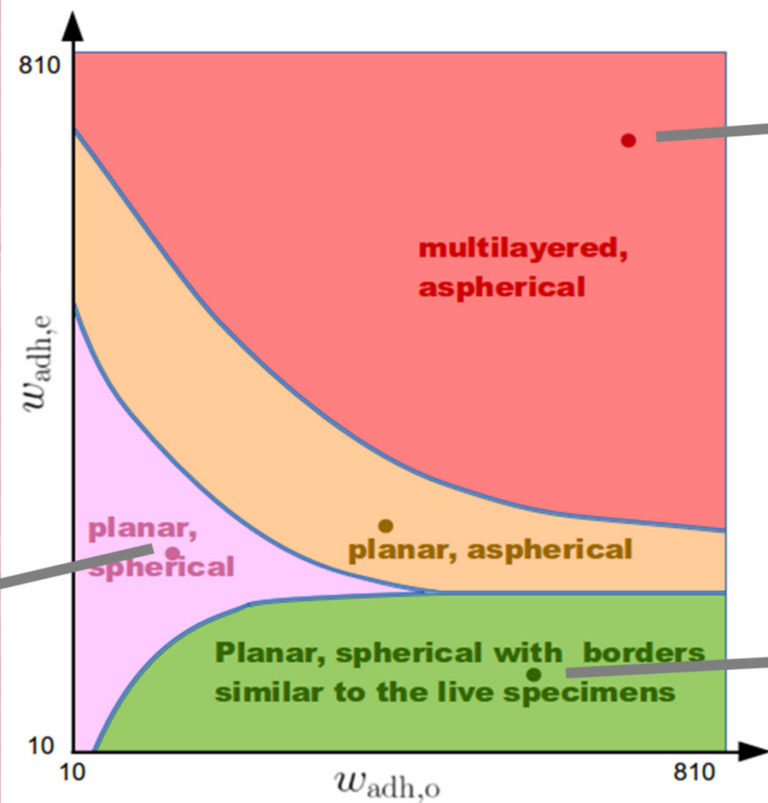
MECAGEN → Case Study in the Sea Urchin

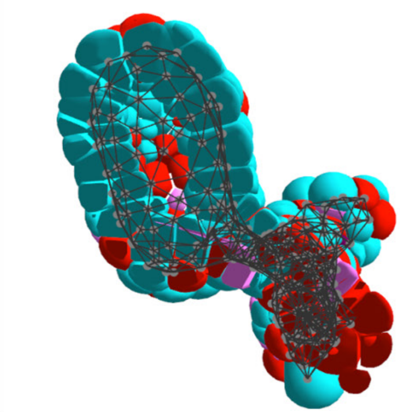


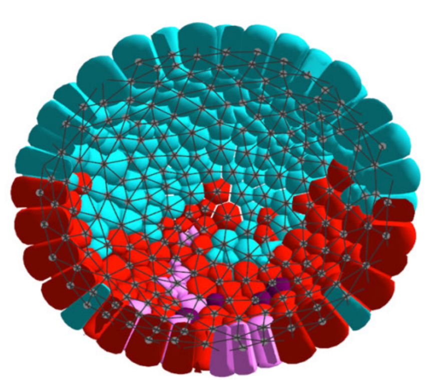


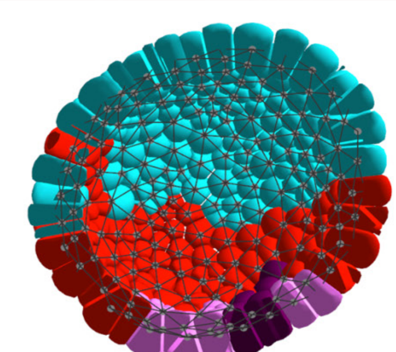




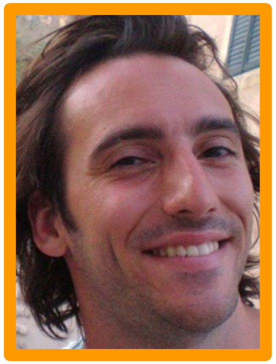








MecaGen Acknowledgments



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MECAGEN

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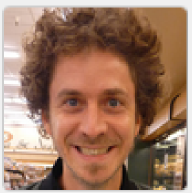
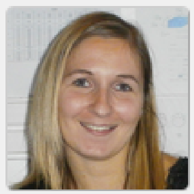
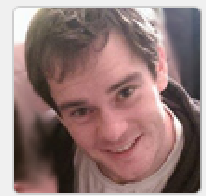
BioEmergences



Emmanuel Faure
Research Engineer
Arrived in 2005



Adeline Boyreau
Engineer/Ingénieure d'Étude
Arrived in 2012



Mathieu Bouyrie
PhD Student/Doctorant
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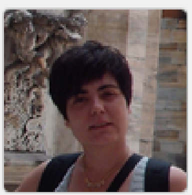
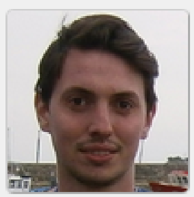
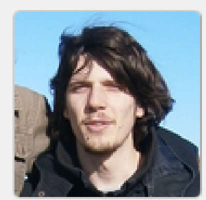


Barbara Rizzi
CNRS TEFOR
Arrived in 2010



Julien Dumont
Engineer/Ingénieur d'Étude
Arrived in 2013



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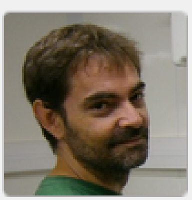


Thierry Savy
Research Engineer
Arrived in 2006

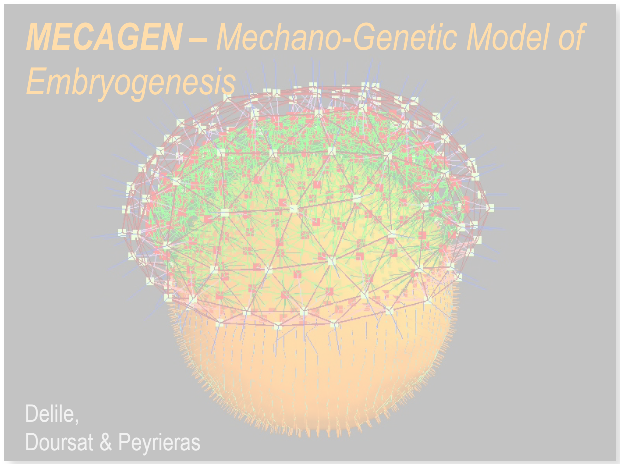
Paul Villoutreix
PhD Student/Doctorant
Arrived in 2011

Adeline Rausch
PhD Student/Doctorante
Arrived in April 2013

Systems that are self-organized *and* architectured

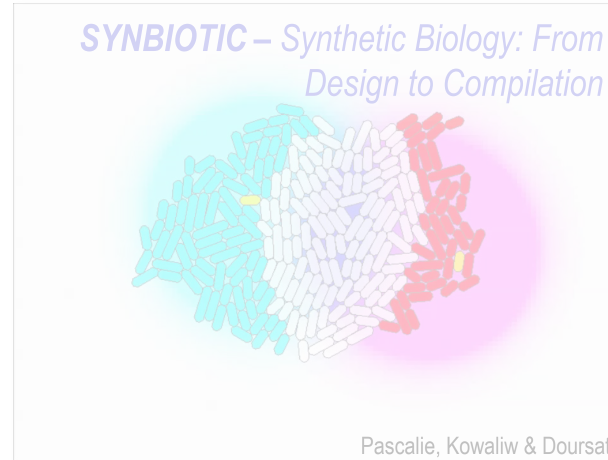
➢ Embryogenesis to **Simulated Development** to Synthetic Biology

illustration of Morphogenetic Engineering ideas

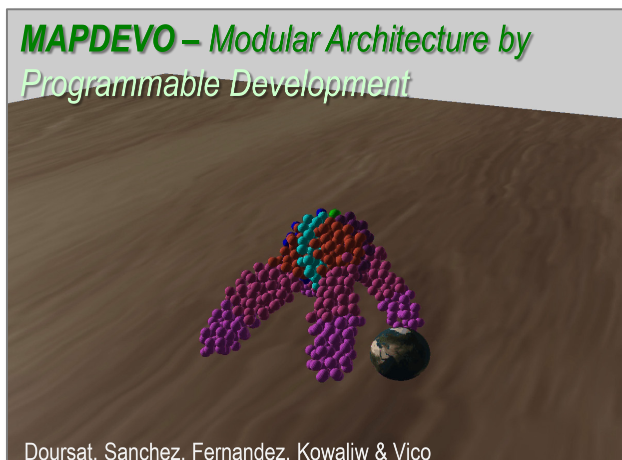


BIOMODELING
(LIFE)

mutually beneficial transfers between biology & CS



BIO-INSPIRED
ENGINEERING (ALIFE)

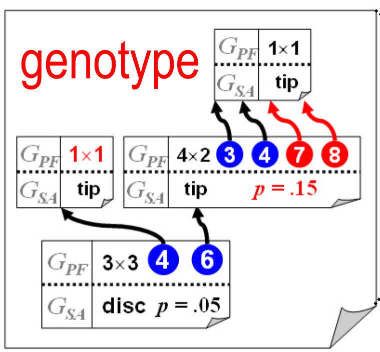


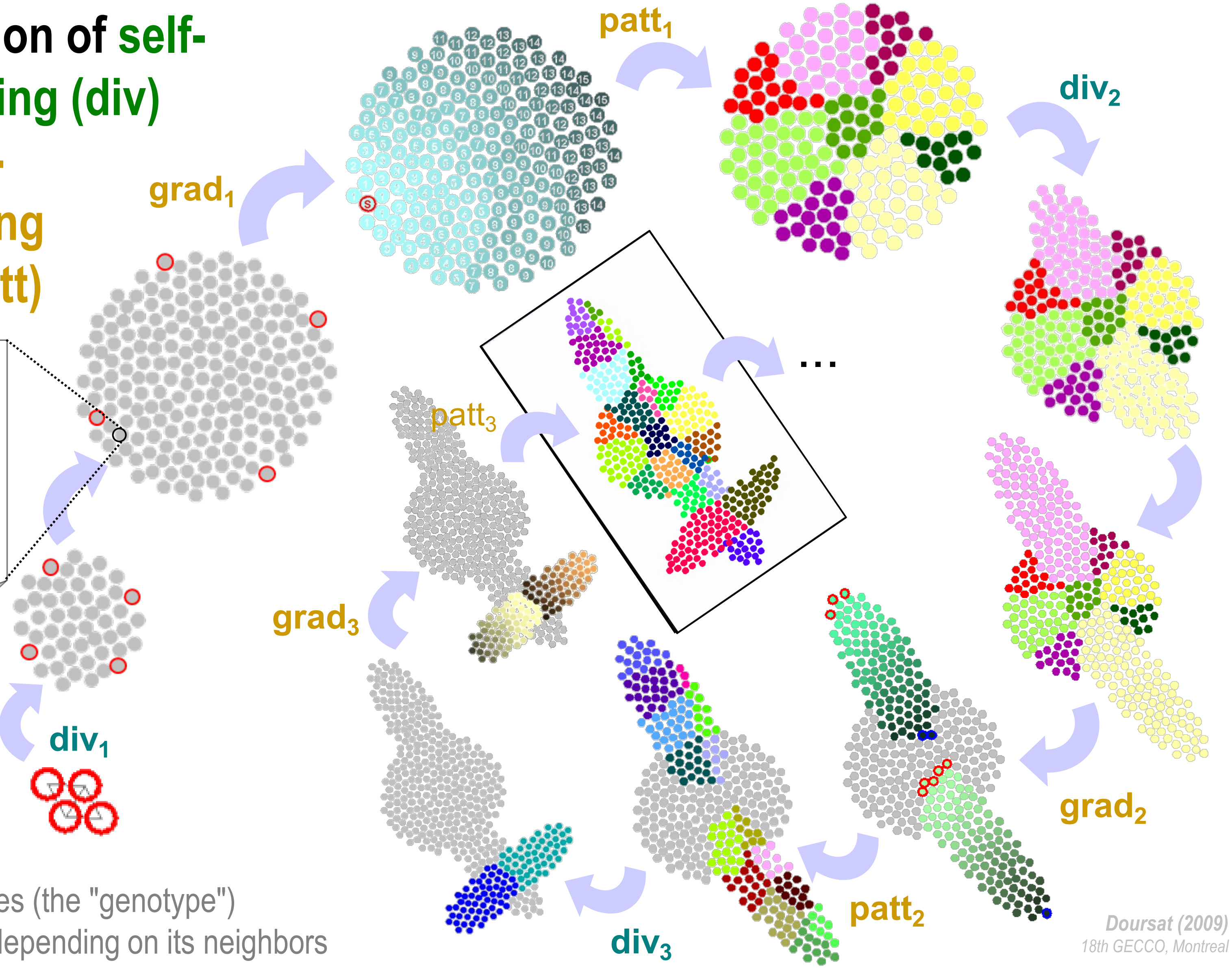
BIOENGINEERING
(HYBRID LIFE)

MAPDEVO – Modular Architecture by Programmable Development

Capturing the essence of morphogenesis in an Artificial Life agent model

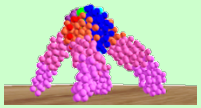
- **Alternation of self-positioning (div) and self-identifying (grad/patt)**





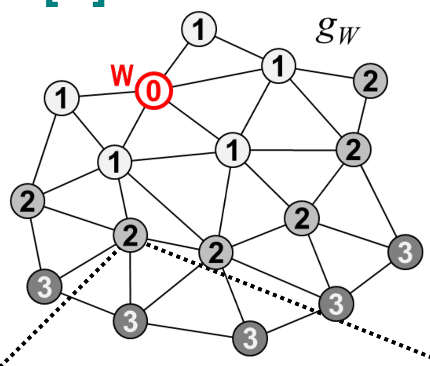
each agent
follows the same set
of self-architecting rules (the "genotype")
but reacts differently depending on its neighbors

Doursat (2009)
18th GECCO, Montreal



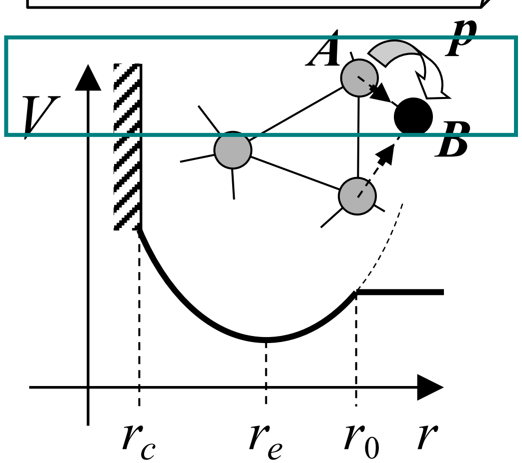
MAPDEVO – Modular Architecture by Programmable Development

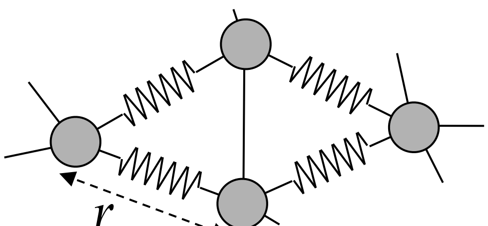
[A] "mechanics"



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

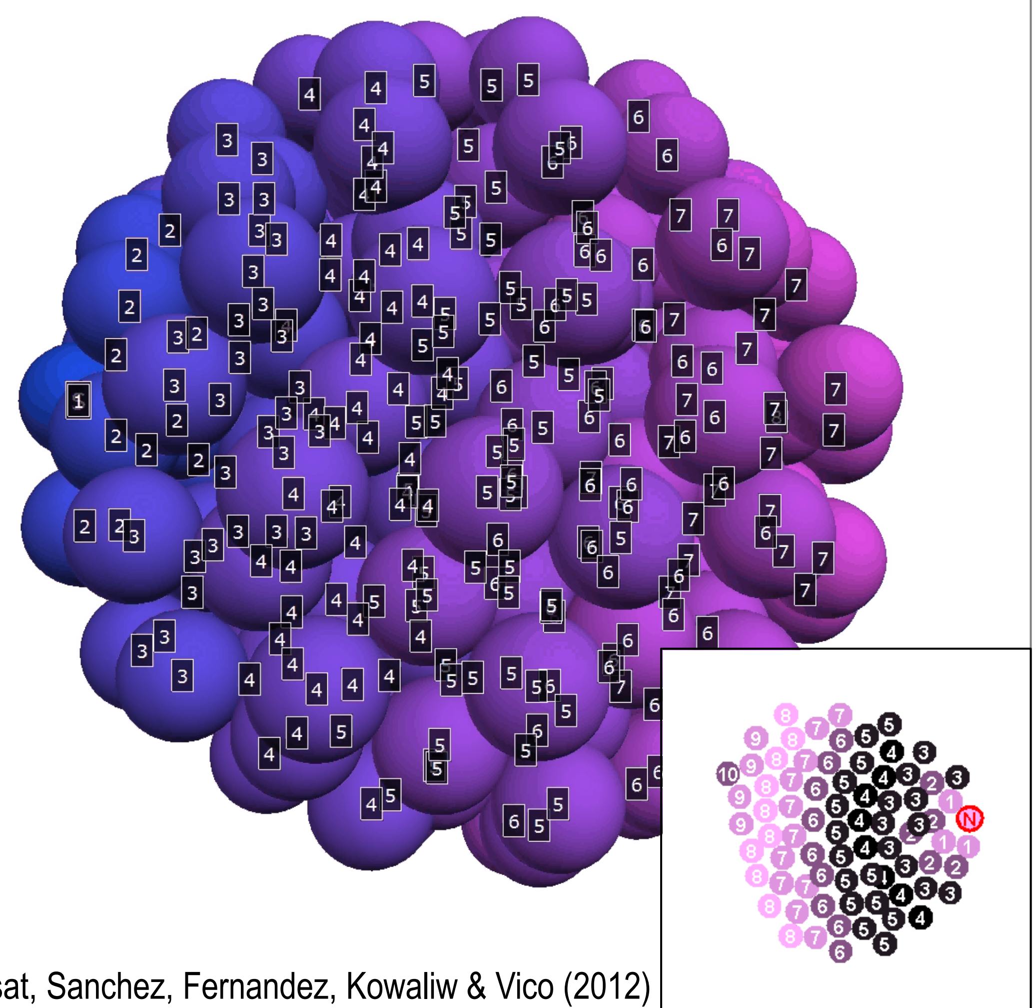
$p = 0.05$



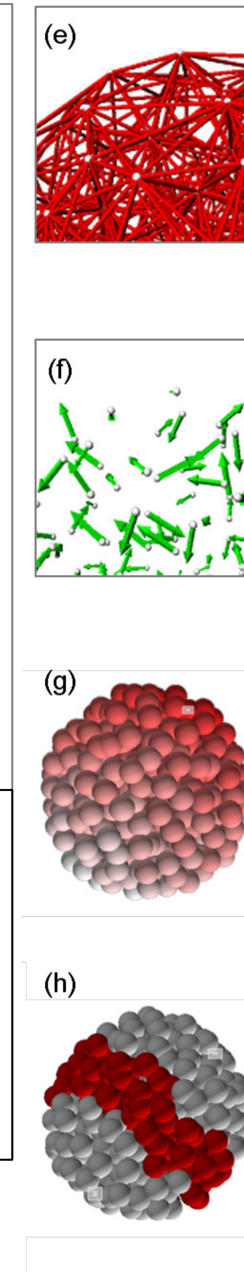


all 3D+t simulations:

Carlos Sanchez (tool: ODE)

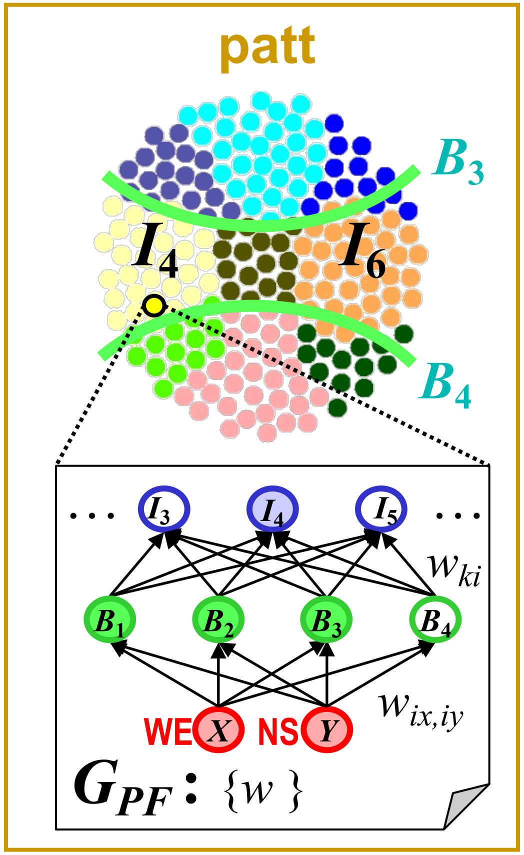


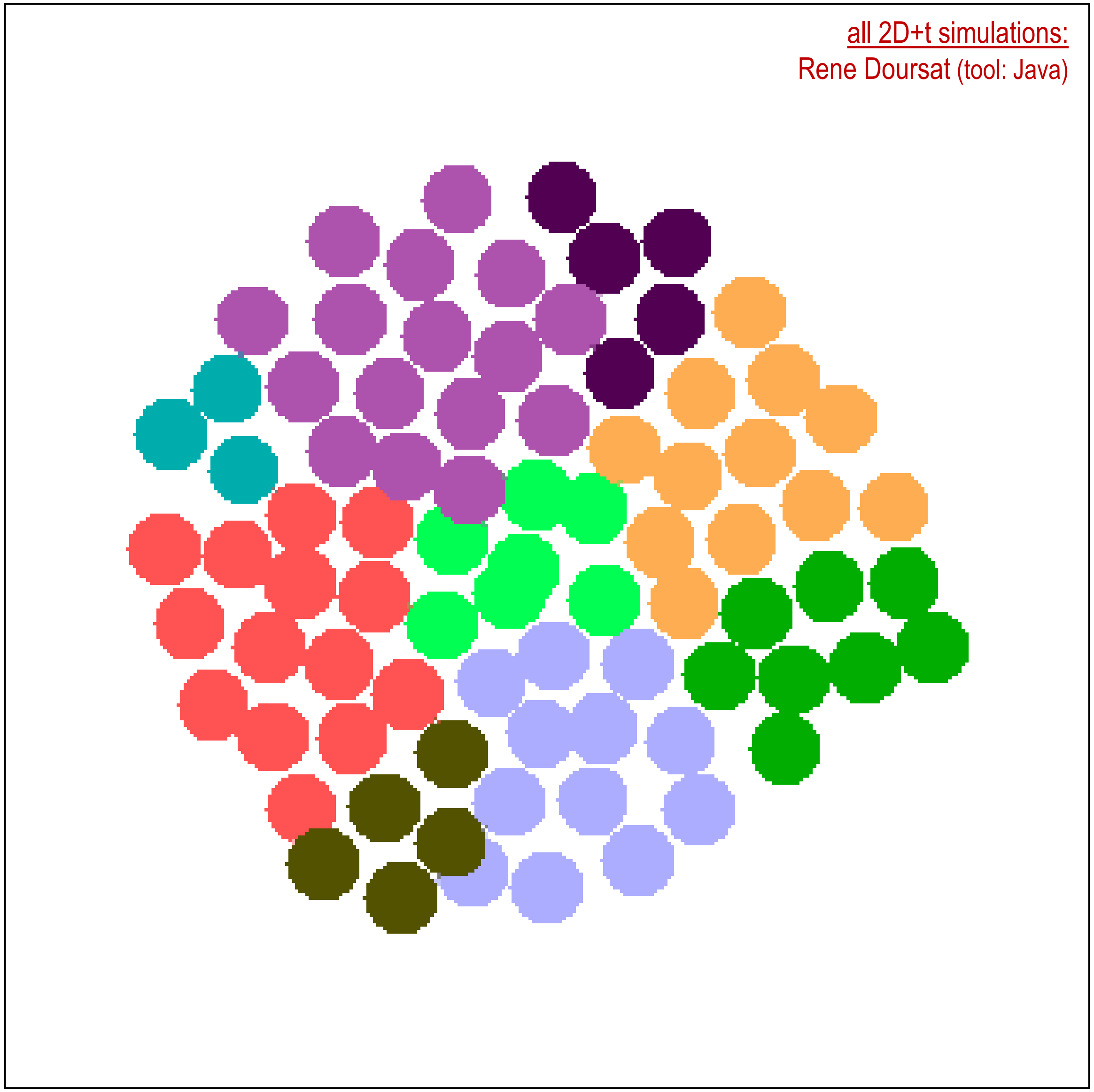
Doursat, Sanchez, Fernandez, Kowaliw & Vico (2012)



$$m\frac{d^2\vec{r}}{dt^2} = -\frac{dV}{dr}\vec{u} - \lambda\frac{d\vec{r}}{dt}, \quad \Rightarrow \quad \Delta\vec{r} = -k'\Delta t\,(r - r_e)\,\vec{u}$$

MAPDEVO – Modular Architecture by Programmable Development





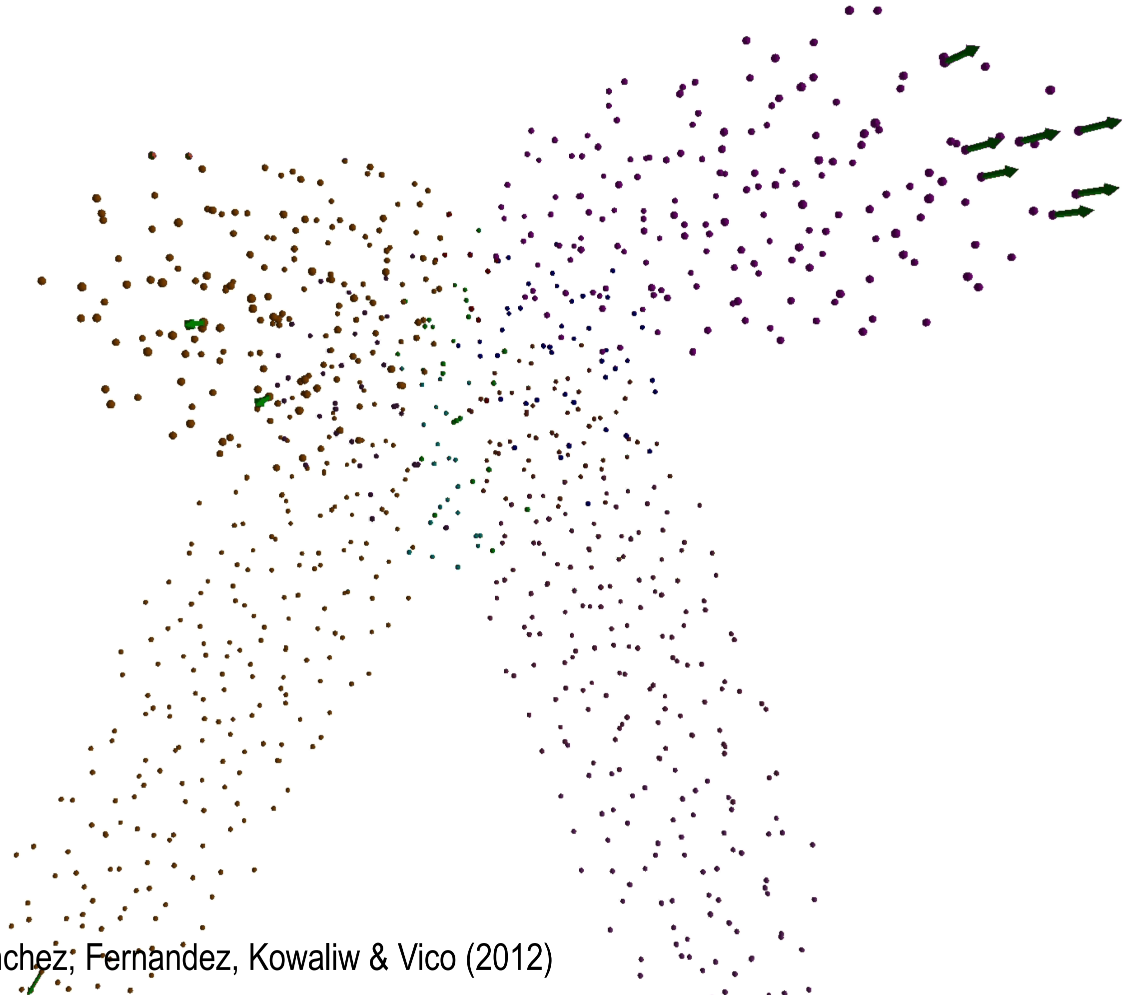
$$B_i = \sigma(L_i(X, Y)) = \sigma(w_{ix}\, X + w_{iy}\, Y - \theta_i)$$

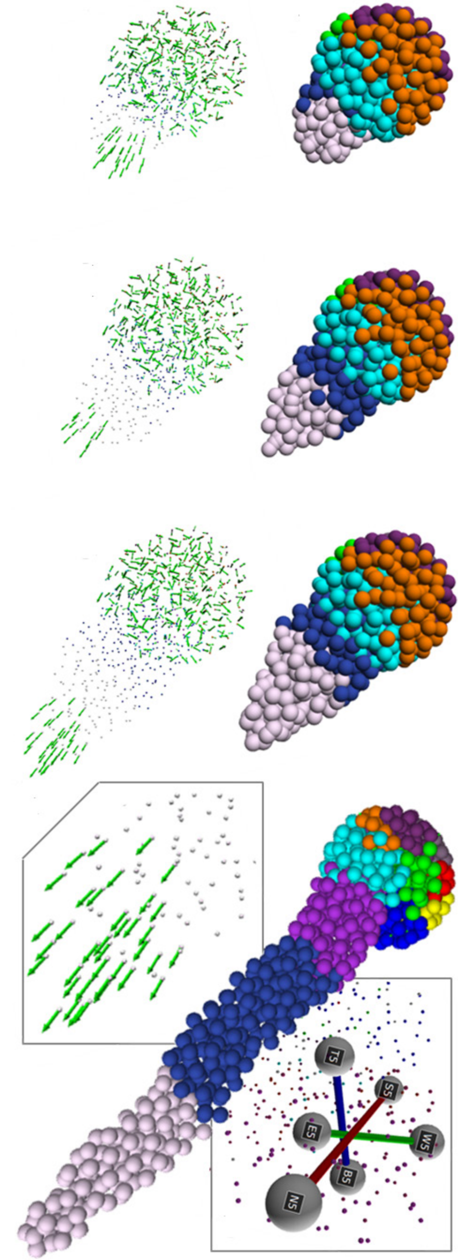
$$I_k = \prod_i |w'_{ki}|(w'_{ki} B_i + (1 - w'_{ki})/2)$$

MAPDEVO – Modular Architecture by Programmable Development

➢ Limbs' development

all 3D+t simulations:
Carlos Sanchez (tool: ODE)

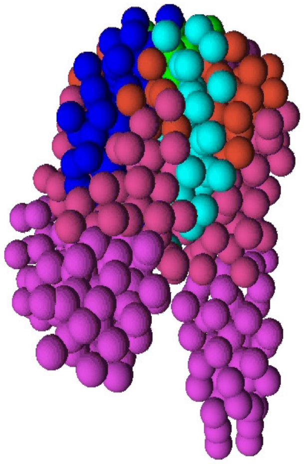


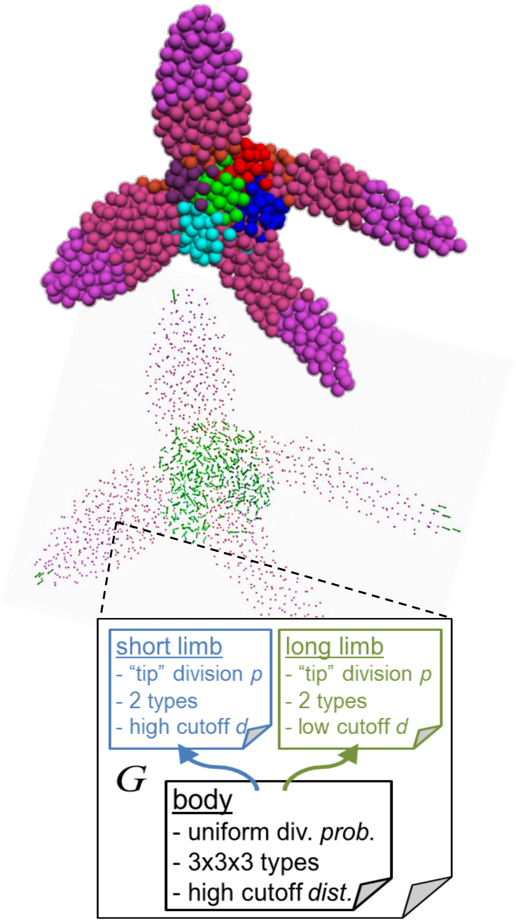


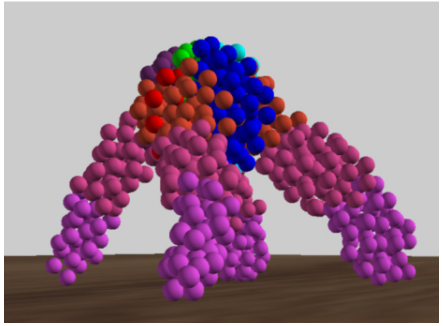
Doursat, Sanchez, Fernandez, Kowaliw & Vico (2012)

➢ 3D Development

all 3D+t simulations:
Carlos Sanchez (tool: ODE)



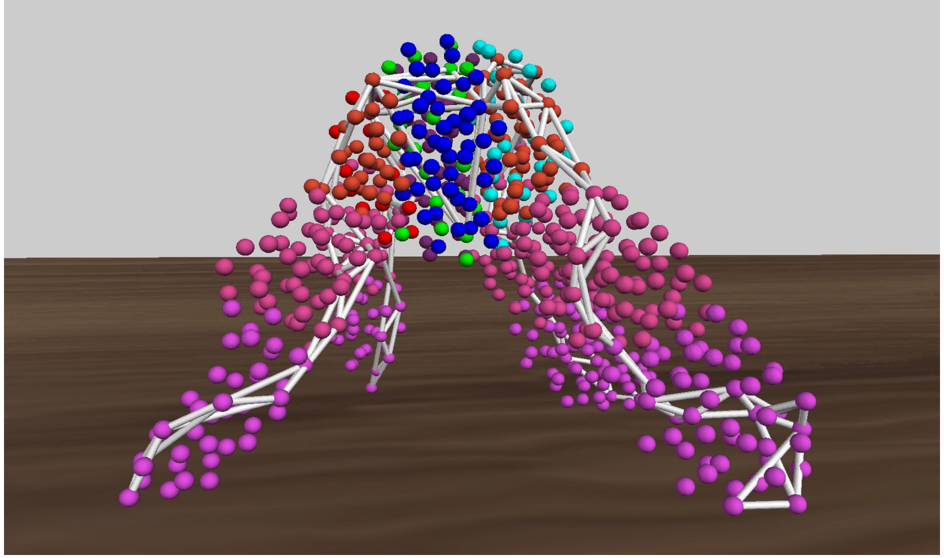


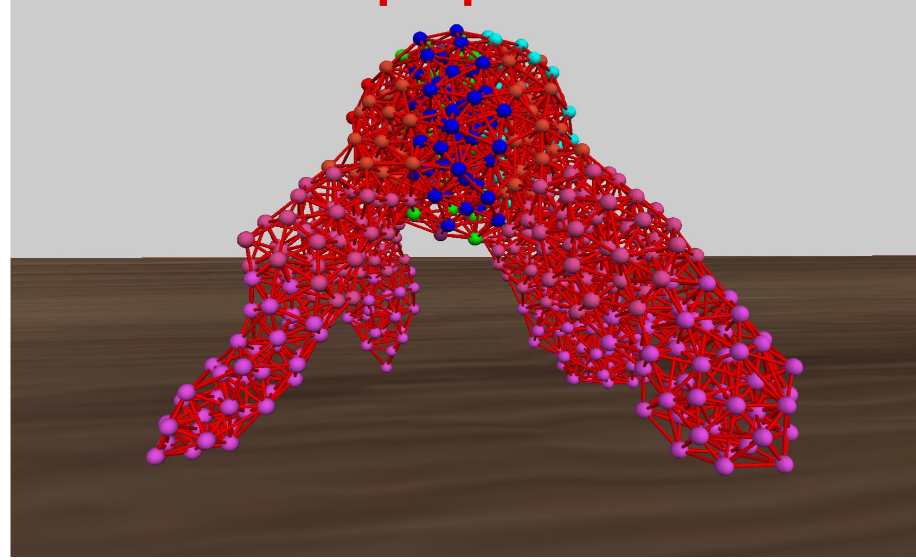


Doursat, Sanchez, Fernandez, Kowaliw & Vico (2012)

MAPDEVO – *Modular Architecture by Programmable Development*

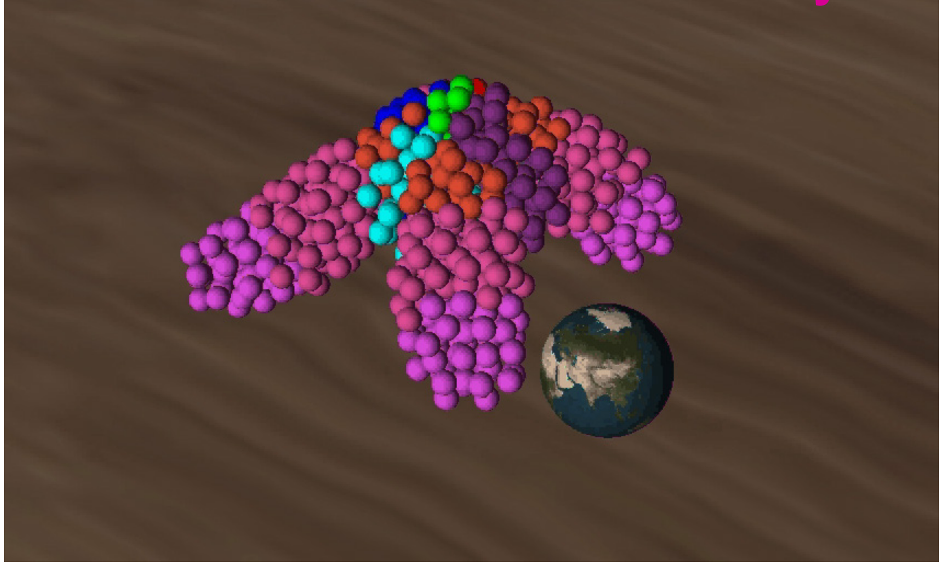
➢ Bones & muscles: structural differentiation and properties

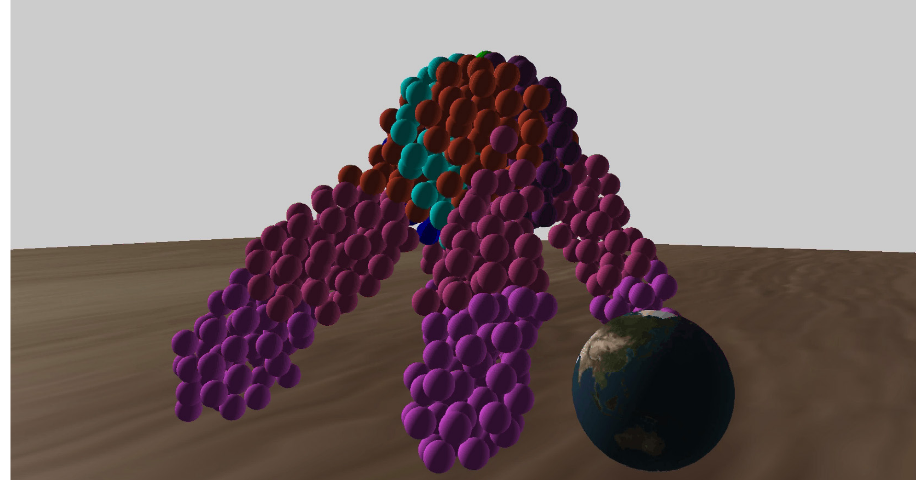




➢ Locomotion and behavior by muscle contraction

all 3D+t simulations:
Carlos Sanchez (tool: ODE)

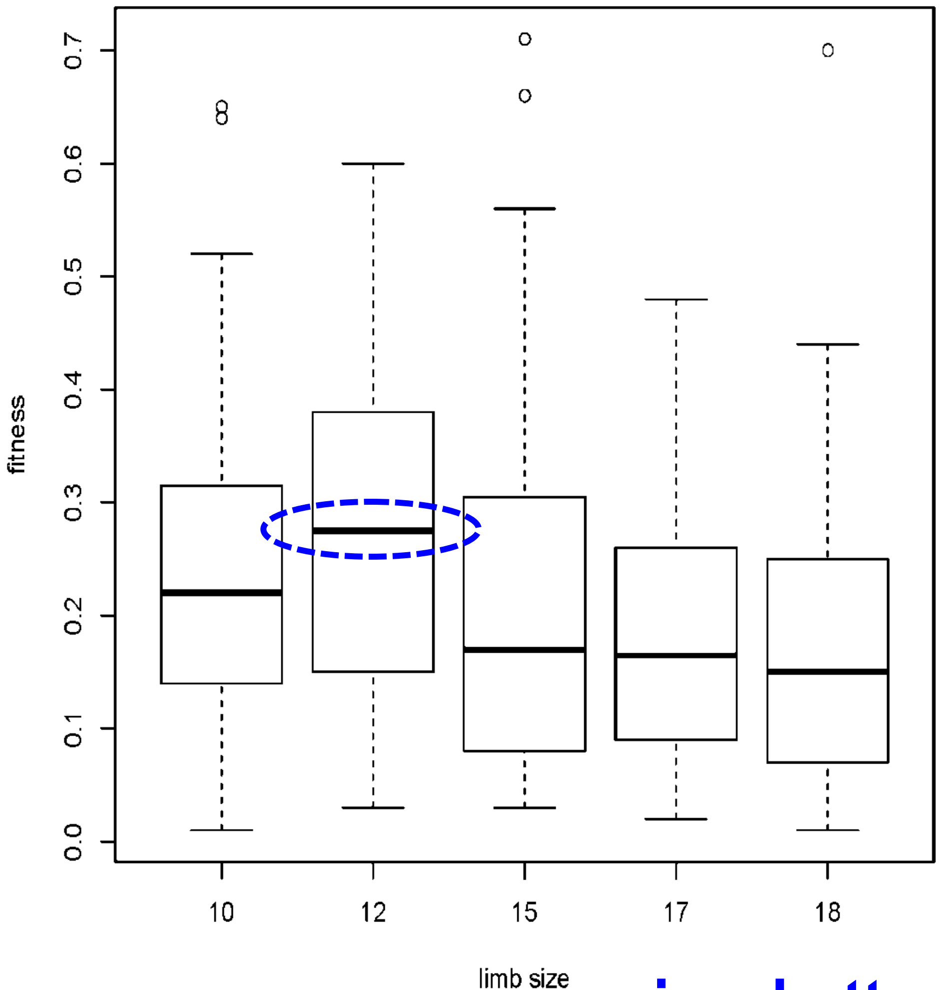


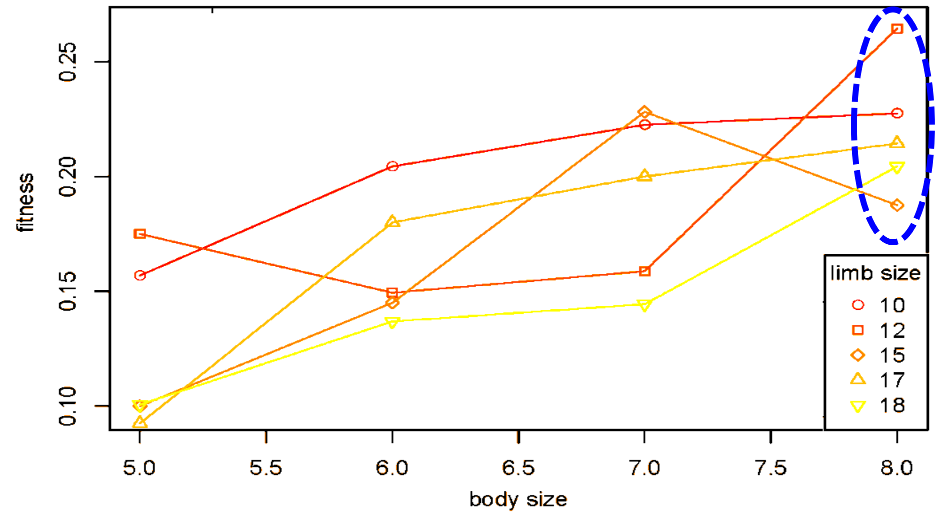


Doursat, Sanchez, Fernandez, Kowaliw & Vico (2012)

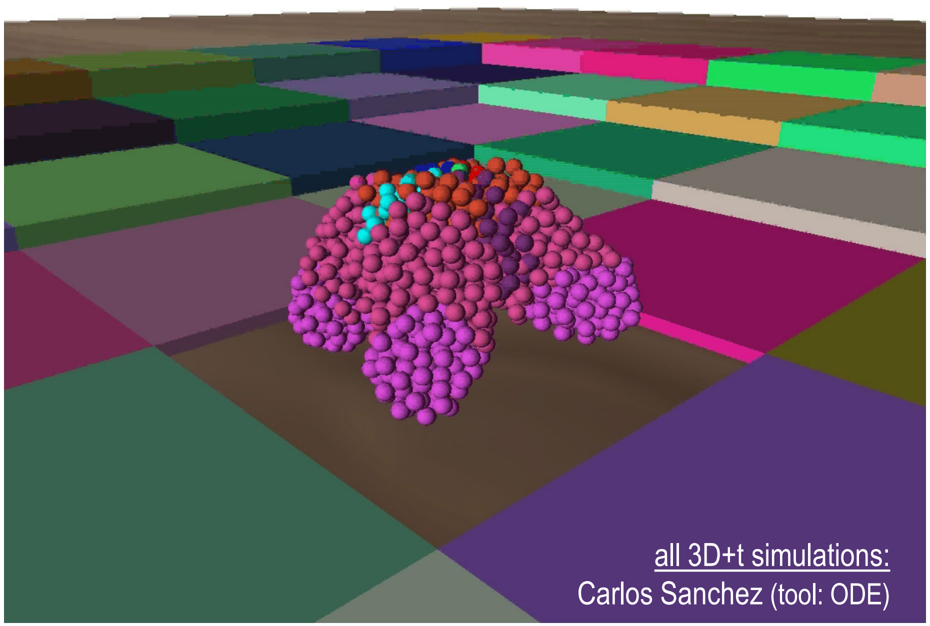
MAPDEVO – Modular Architecture by Programmable Development

➢ Stair climbing challenge: ∃ better body and limb sizes...





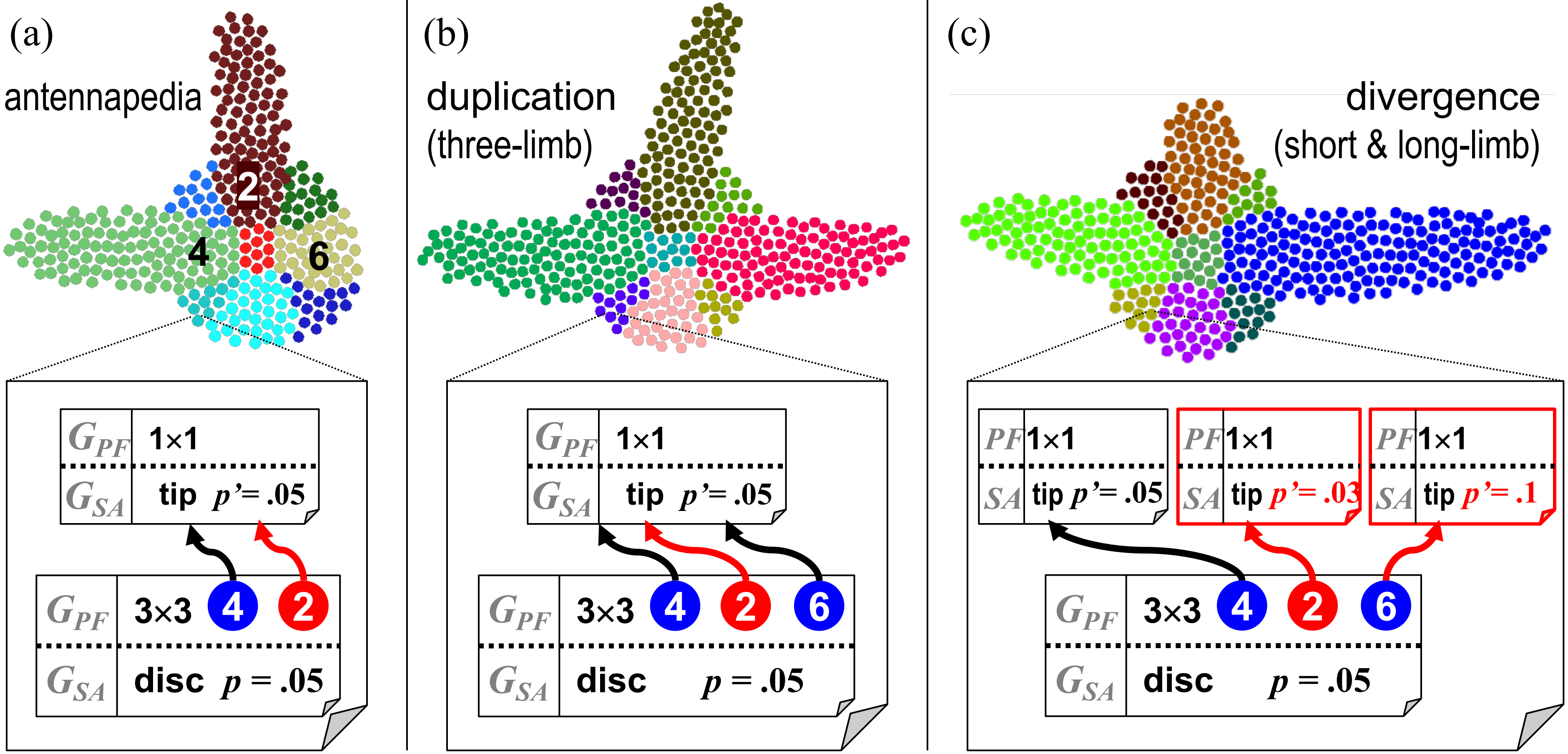
... i.e., better developmental genomes!



MAPDEVO – Modular Architecture by Programmable Development

➢ To be explored: qualitative mutations in limb structure

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

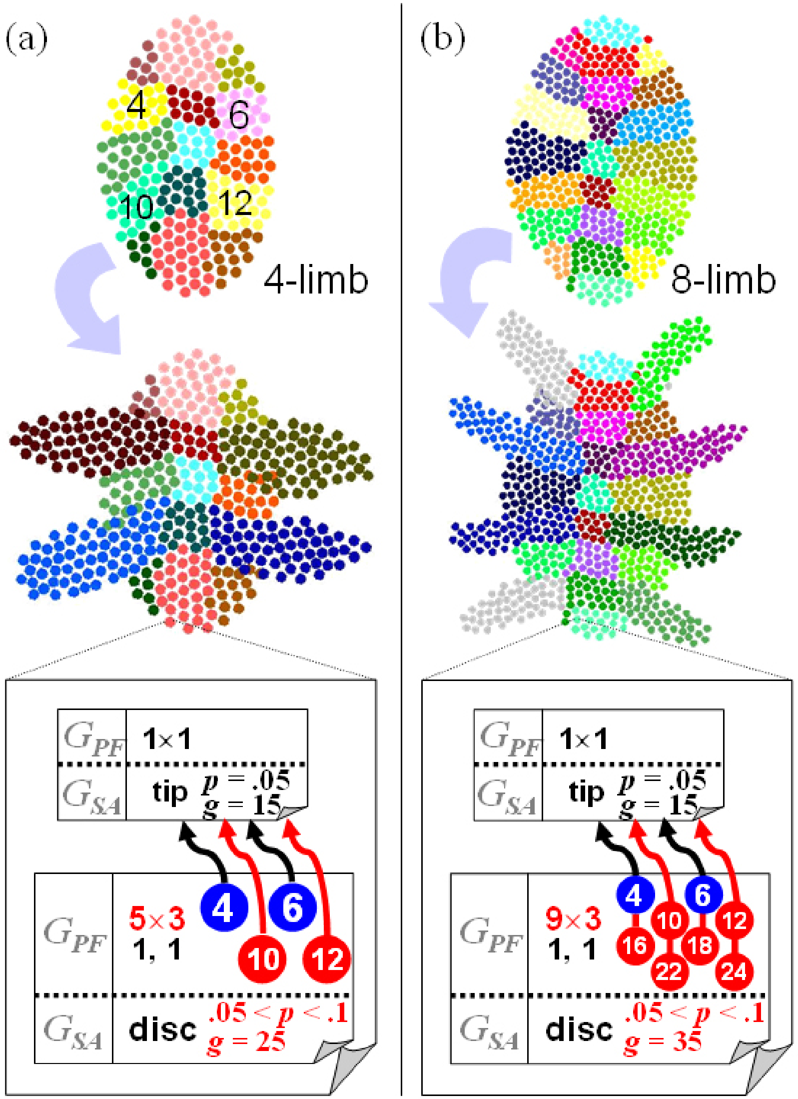


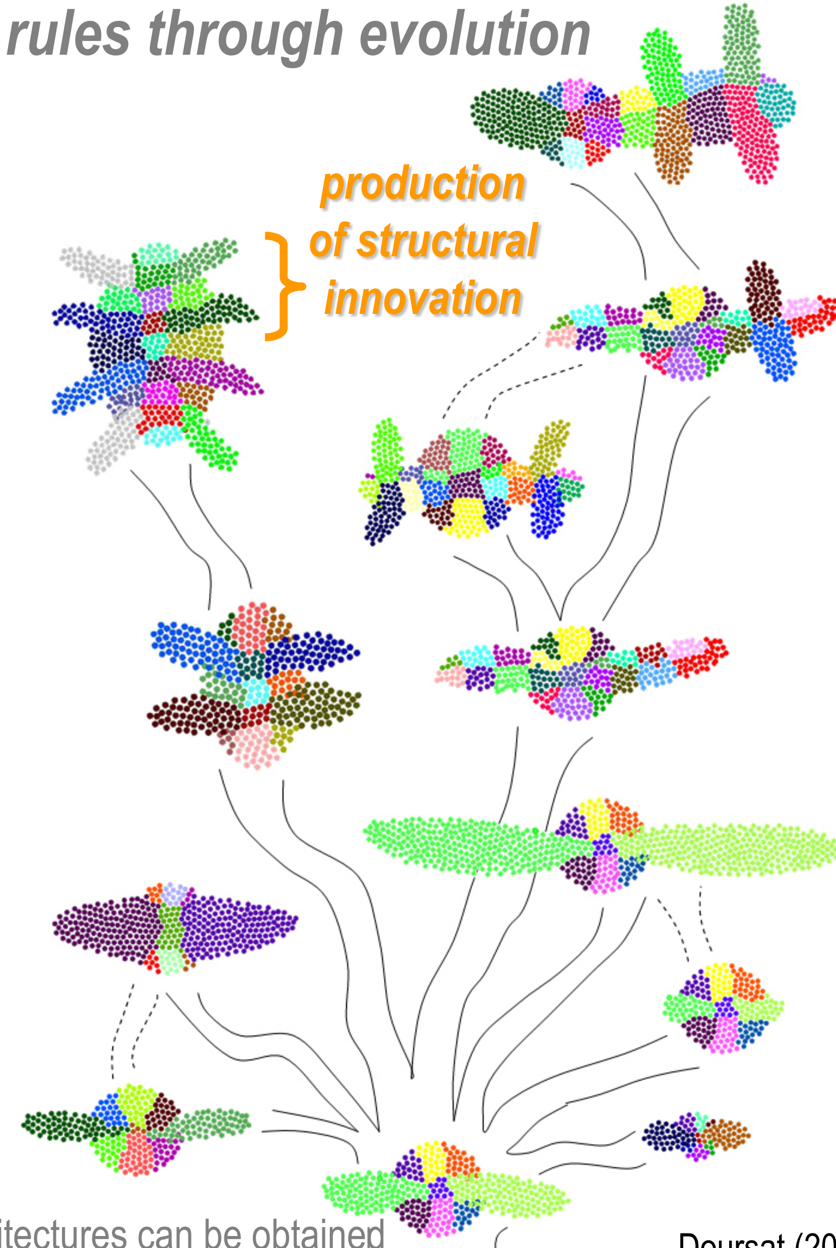
all 2D+t simulations:
Rene Doursat (tool: Java)

Doursat (2009)

MAPDEVO – Modular Architecture by Programmable Development

Changing the agents' self-architecting rules through evolution





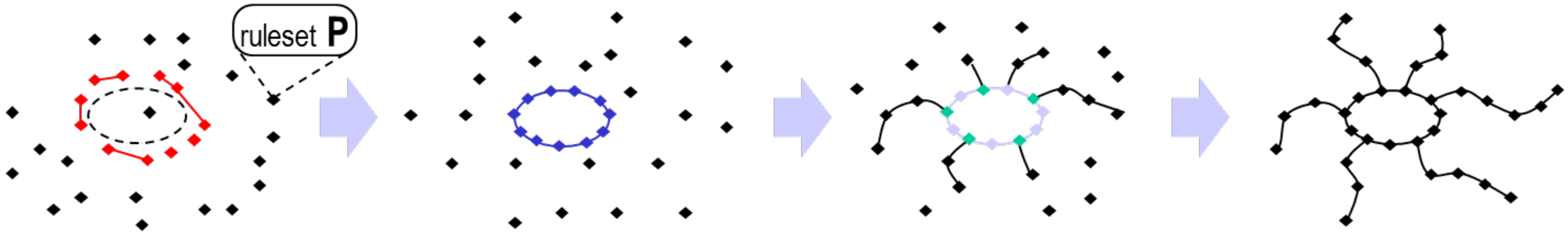
all 2D+t simulations:
Rene Doursat (tool: Java)

by tinkering with the genotype, new architectures can be obtained

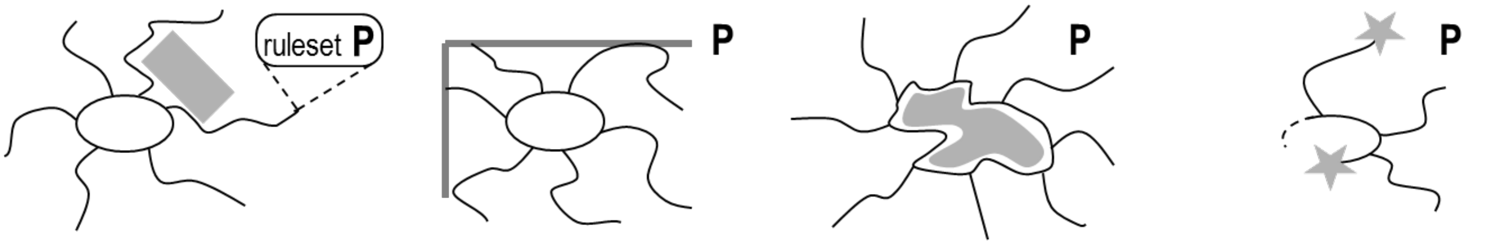
Doursat (2009)

MAPDEVO – Modular Architecture by Programmable Development

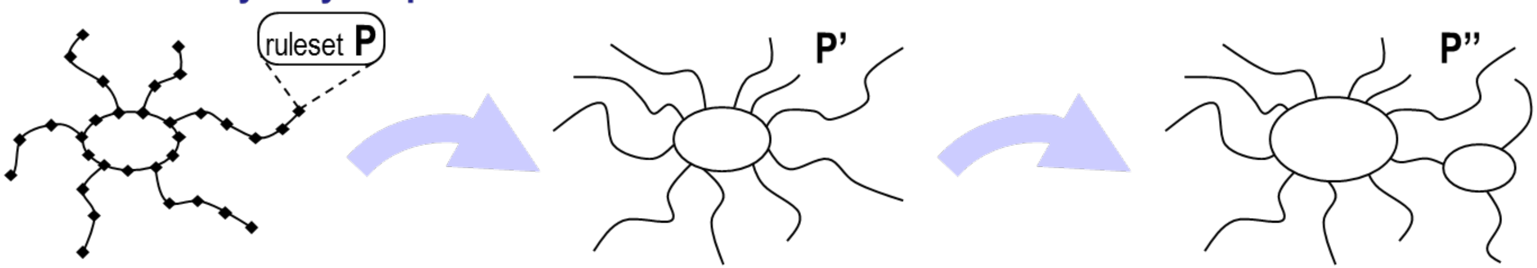
Stereotyped Development



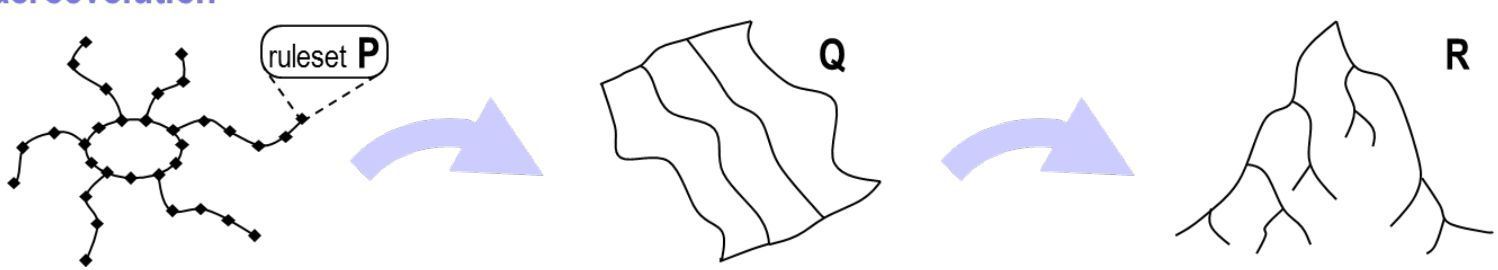
Environment-Induced Polyphenism

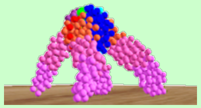


Microevolutionary Polymorphism

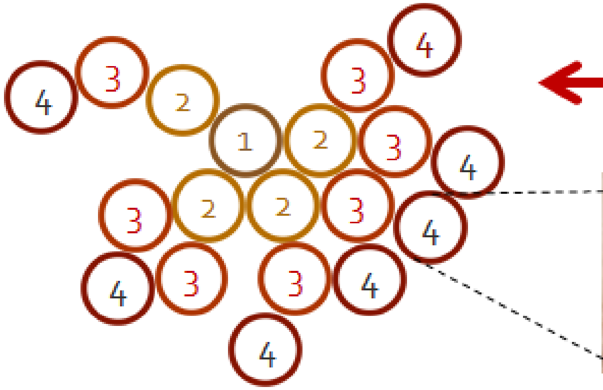


Macroevolution

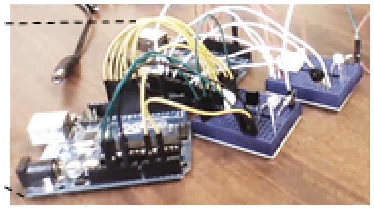


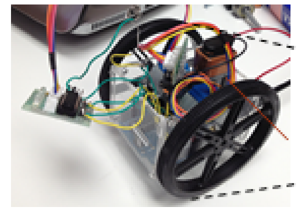


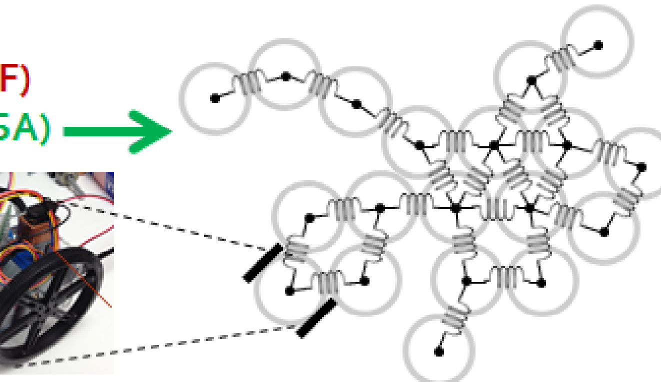
Morphogenetic Engineering Work-bot (MEWbot)



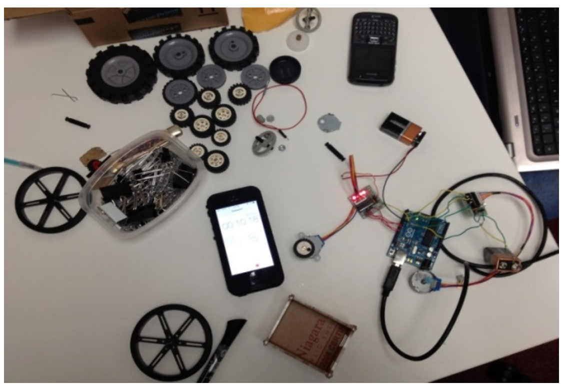
Morphogenesis combines
chemical pattern formation (PF)
and mechanical self-assembly (SA)

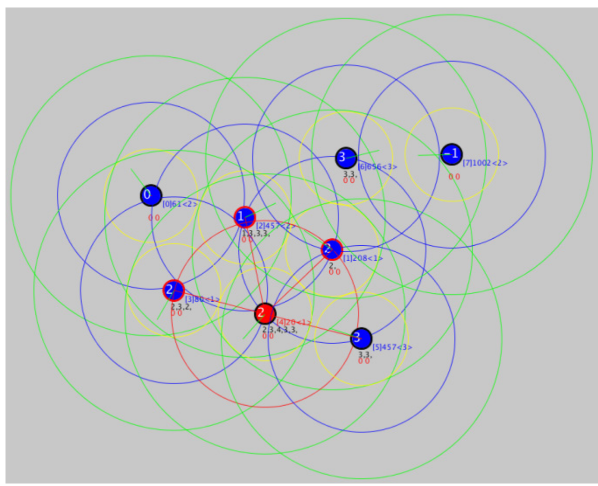


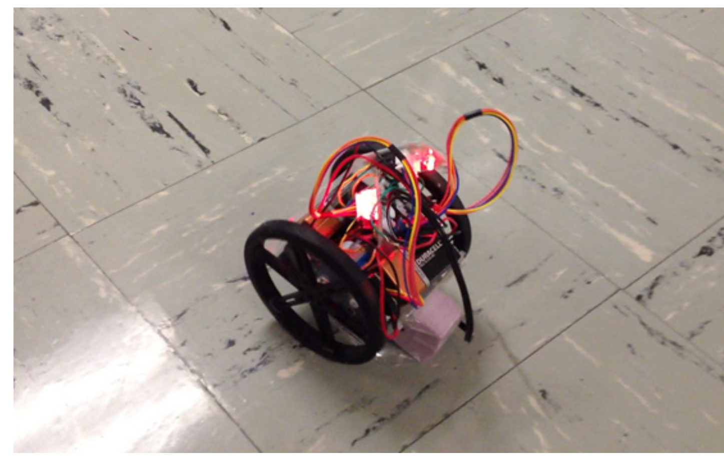




PF: Gradient formation & differentiation + *SA: Virtual multi-spring-mass system*

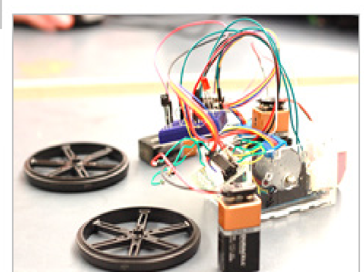


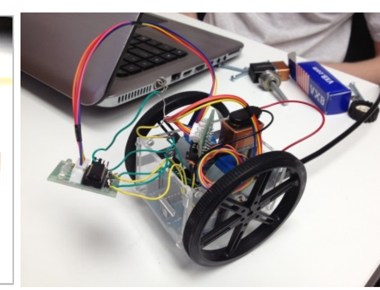




Material used

- *Arduino* microcontrollers
- Infrared LEDs for communication
- C/C++ programming
- Inexpensive parts: step motors, etc. (≈ $30/bot)



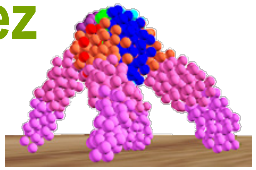


MapDevo / MEWbot Acknowledgments

Hiroki Sayama
Associate Professor

Binghamton University
SUNY

Carlos Sánchez
PhD Student



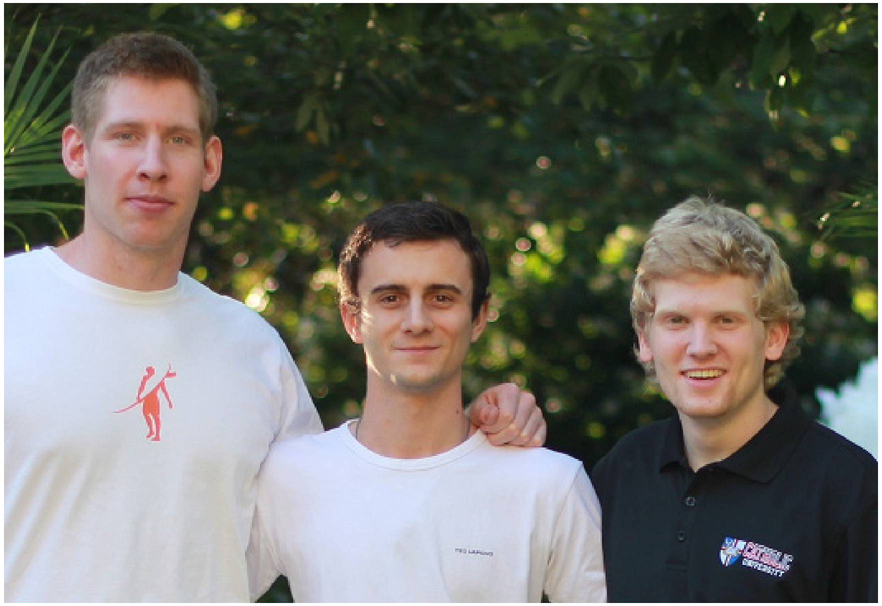
Universidad de Málaga, Spain

grupo de estudios en biomimética

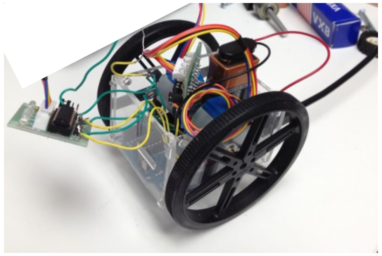
Taras Kowaliw, PhD
Research Scientist

Ecole Polytechnique, Paris, France

INSTITUT DES SYSTEMES COMPLEXES



Peter Schramm	Lucas Cousi	Michael Gribbin
Senior Student	Senior Student	Senior Student
CUA, Washington	ESEIA, Paris	CUA, Washington

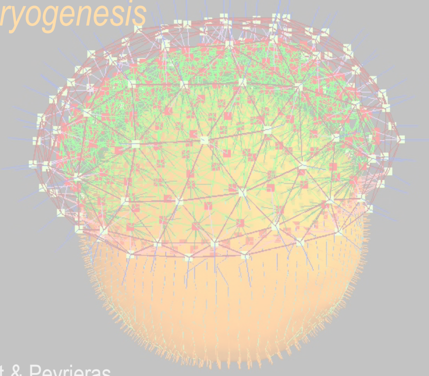


Systems that are self-organized *and* architectured

➢ Embryogenesis to Simulated Development to Synthetic Biology

*illustration of **Morphogenetic Engineering** ideas*

MECAGEN *– Mechano-Genetic Model of Embryogenesis*



Delile, Doursat & Peyrieras

BIOMODELING (LIFE)

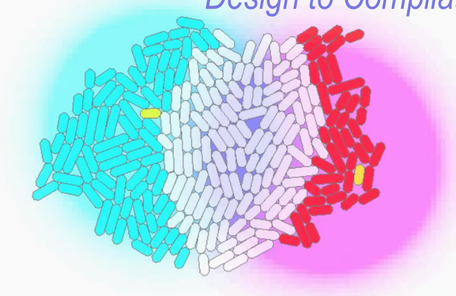
mutually beneficial transfers between biology & CS

BIO-INSPIRED ENGINEERING (ALIFE)

MAPDEVO *– Modular Architecture by Programmable Development*

Doursat, Sanchez, Fernandez, Kowaliw & Vico

SYNBIOTIC *– Synthetic Biology: From Design to Compilation*

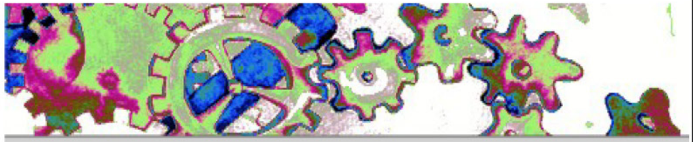


Pascalie, Kowaliw & Doursat

BIOENGINEERING (HYBRID LIFE)

Synthetic biology's ambitions

- ✓ construct new biological functions and systems not found in nature
- ✓ (re-)build cells to make them
  - transform chemicals
  - create new materials
  - produce energy and food
  - improve human health and environment
  - process information, compute
  - create spatial structures (organs, buildings)
- ✓ introduce the engineering principles of abstraction & standardization into biology
- ✓ design and manufacture reusable biological components

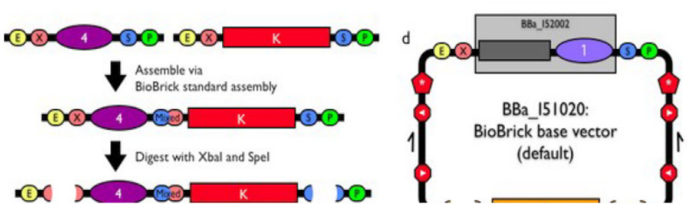


Registry of Standard Biological Parts

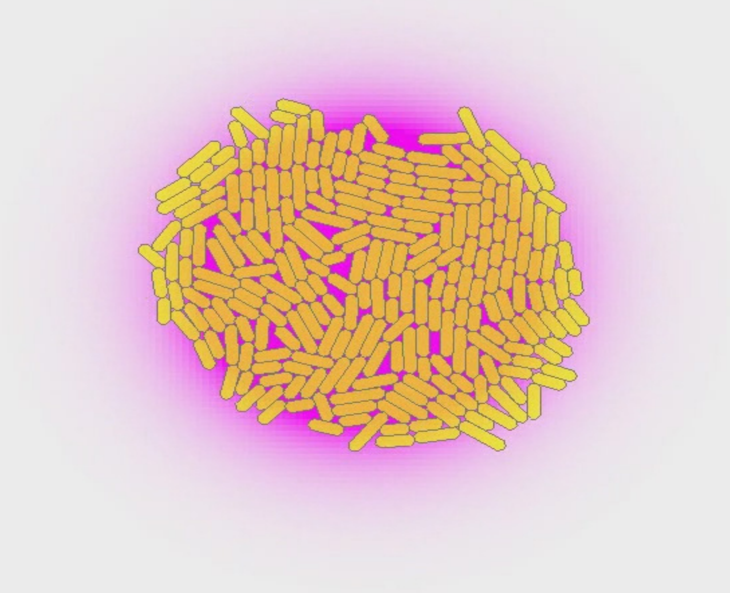
BioBricks FOUNDATION

- DNA sequences of defined structure and function
- sharing a common interface
- composed together and incorporated into living cells (plasmids)

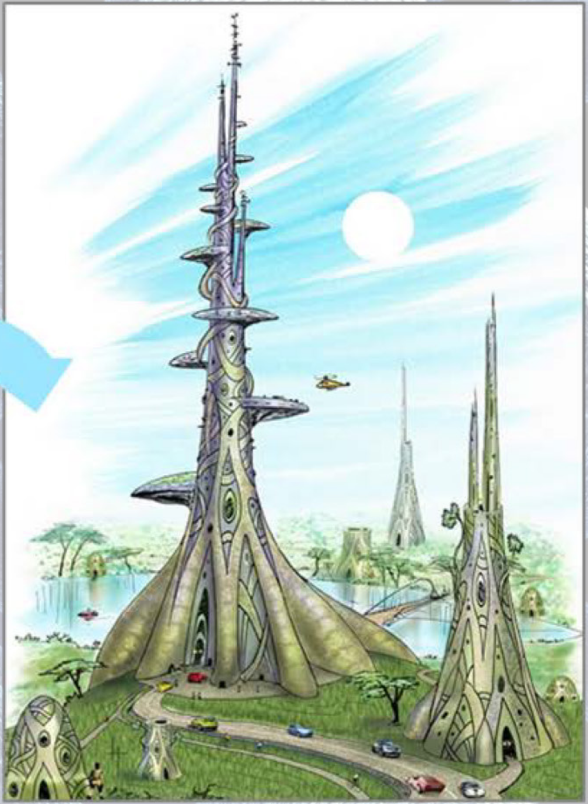
Part Number	Function	Notation
BBa_G00000	BioBrick cloning site prefix	E X
BBa_G00001	BioBrick cloning site suffix	S P
BBa_P1016	ccdB positive selection marker	
BBa_I50022	minimal pUC-derived high copy replication origin	1
BBa_B0042	translational stop sequence	
BBa_B0053 & BBa_B0054	forward transcriptional terminator	
BBa_B0055 & BBa_B0062	reverse transcriptional terminator	
BBa_G00100	forward sequencing primer annealing site (VF2)	
BBa_G00102	reverse sequencing primer annealing site (VR)	
BBa_B0045	NheI restriction site	N
BBa_P1006	ampicillin resistance marker (reverse orientation)	A
BBa_P1002	ampicillin resistance marker	A
BBa_P1003	kanamycin resistance marker	K
BBa_P1004	chloramphenicol resistance marker	C
BBa_P1005	tetracycline resistance marker	T
BBa_I50042	pSC101 replication origin	4
BBa_I50032	p15A replication origin	3



Simulation (based on the *Gro* Language):
Jonathan Pascalie



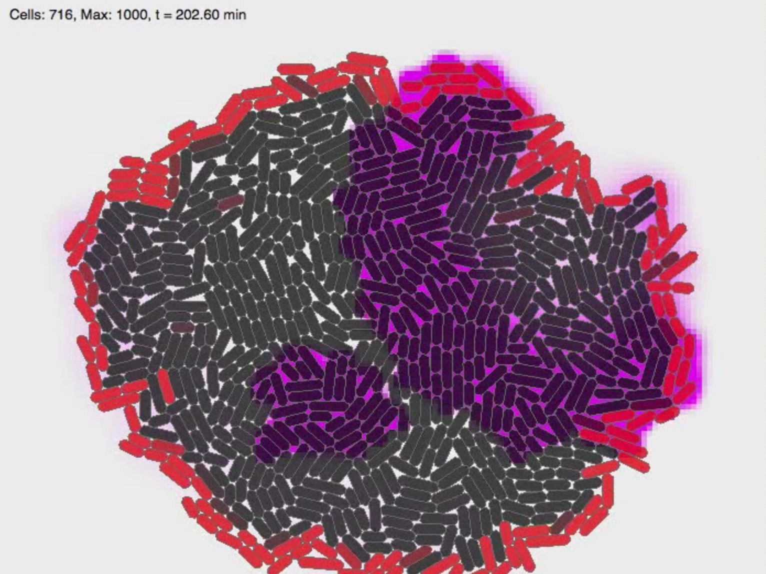
Jang, Oishi, Egbert, Klavins, "Specification and simulation of multicelled behaviours", ACS Synthetic Biology, 2012.



Susan Stepney et al. (2012) GroCyPhy Project: Gardening cyber-physical systems.

Gro Programming Language

- The **Gro** language (E. Klavins) includes pre-programmed capabilities such as bacterial physics, cell behaviors, and diffusive chemical signals
- Capable of simulating experiments involving the growth and self-organization of *E. Coli* colonies on agar dishes

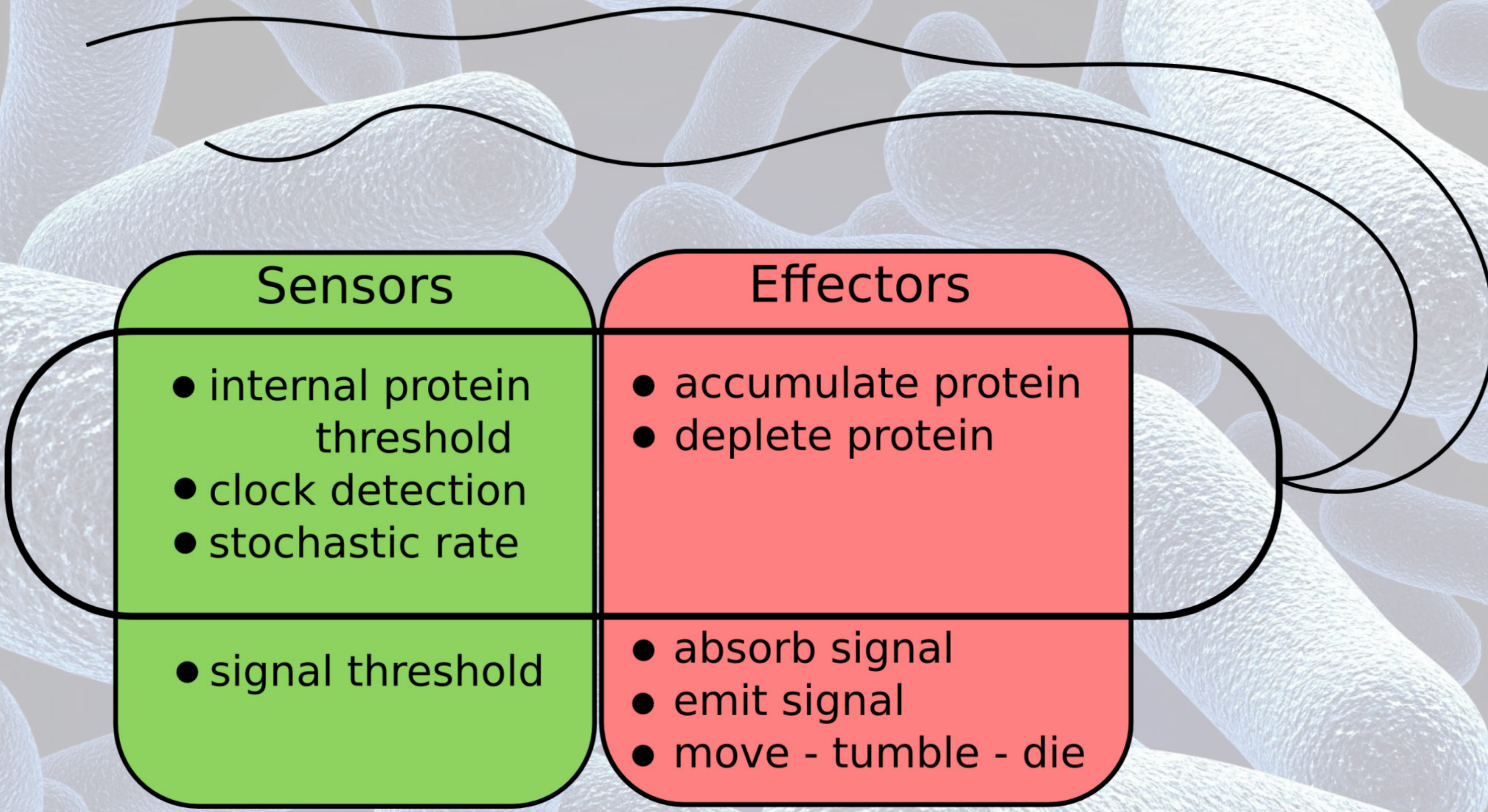


Simulation (based on *Gro*): Jonathan Pascalie

```
...
p.type = EMITER & get_signal(A) > .5 :
{
    emit_signal(B,6) ;
}

p.type = DEPLETER & get_signal(B) > 6.5 :
{
    absorb_signal(B,17) ;
}
...
```

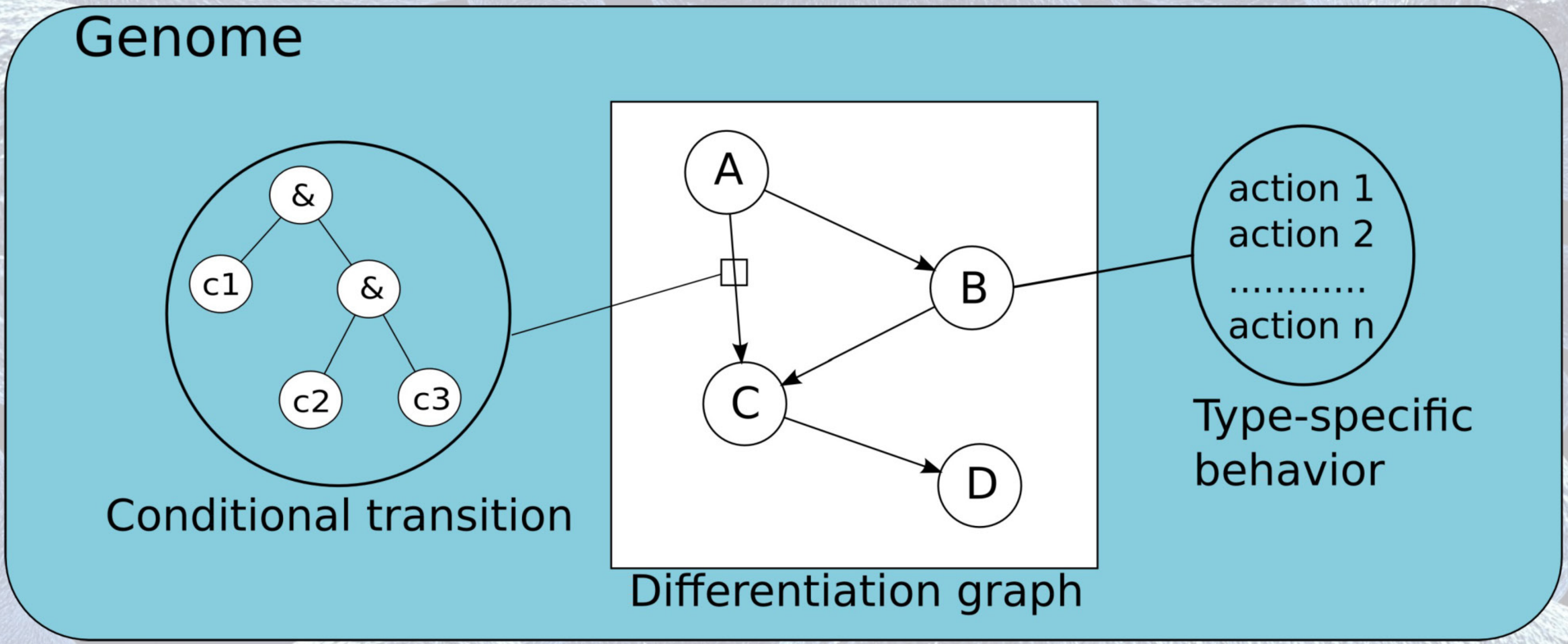
Our Model – Virtual *E. coli*

- Our model of *E. coli* includes a set of sensors/effectors



Our Model – Genome

- Bacterial dynamics is encapsulated in a finite state machine:
  - ✔ Nodes (states) are the types into which bacteria differentiate
    - Each state corresponds to a set of actions executed by the bacteria
  - ✔ Edges (transitions) describe the conditions of differentiation
    - Conditions pertain to protein concentrations and time



Genomic Representation – SBGP

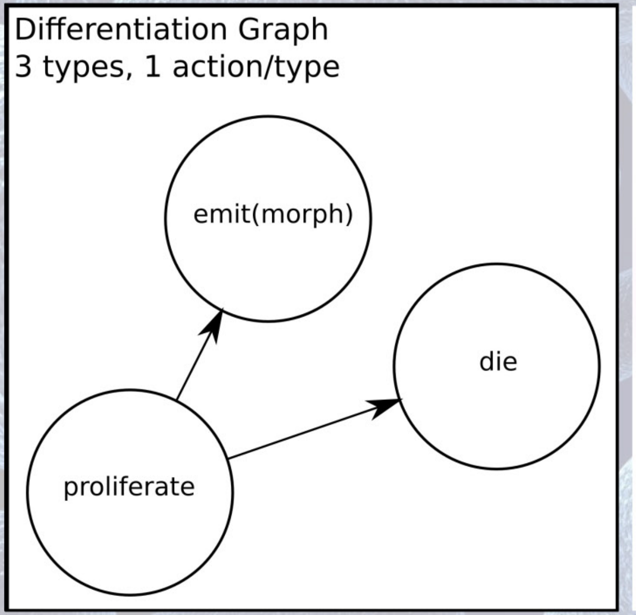
- The **Synthetic Biology Genetic Programming** (SBGP) declarative language describes bacterial dynamics and environmental chemistry

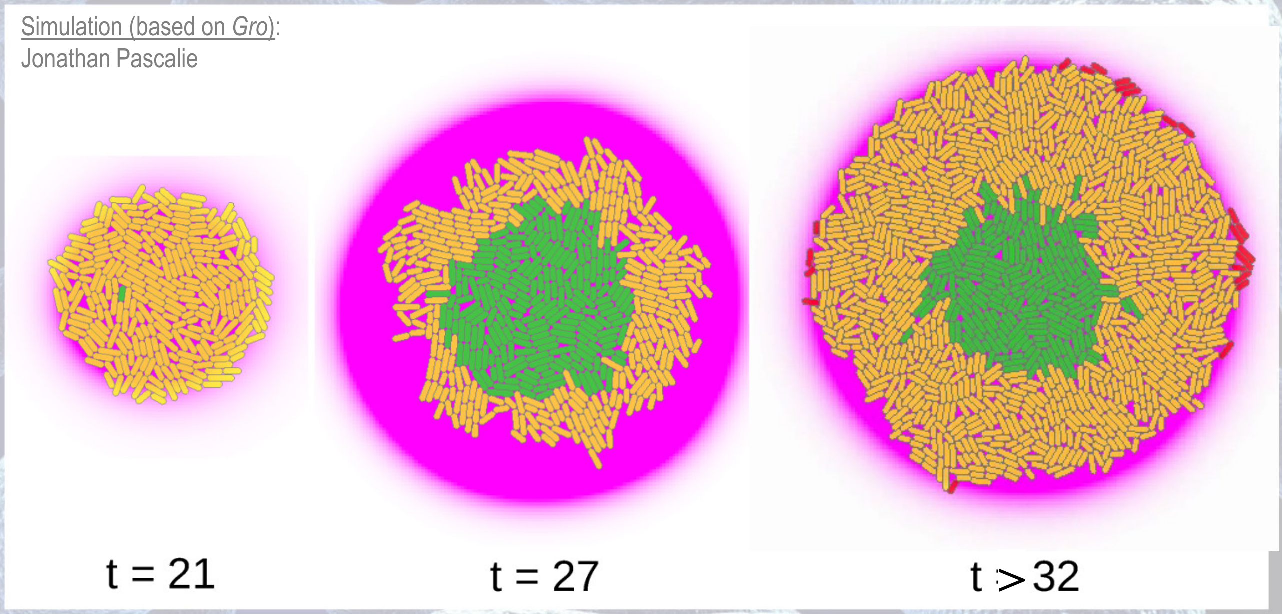
```
"signals" : [
  ["A", 3, 0.4],
  ["B", 5, 0.01],
  ["C", 6, 0.5],
  ["D", 6, 0.5],
  ["E", 6, 0.5],
  ["F", 6, 0.5],
  ["G", 6, 0.5]
],

"reactions" : [
  [["A", "B"], ["C"], 0.5],
  [["D", "E"], ["F"], 0.5]
],

"type" : [
  "INIT",
  "INTER",
  "CENTRAL",
  "EMIT",
  "DEAD"
],

"parameters" : {
  "P1" : 250,
  "P2" : 35
},
```

```
"behavior" : {
  "INIT" : [{"EmitSignal" : ["A", "50"]}],
  "INTER" : [{"Ungrowth" : []}],
  "CENTRAL" : [{"Growth" : []}],
  "EMIT" : [{"EmitSignal" : ["A", "35"]}],
  "DEAD" : [{"EmitSignal" : ["B", "750"]},
            {"Die" : []}]
},

"transition" : [
  ["NA", "NA", "C1", "NA", "NA"],
  ["NA", "NA", "NA", "NA", "C2"],
  ["NA", "C3", "NA", "C4", "NA"],
  ["NA", "C5", "NA", "NA", "C2"],
  ["NA", "NA", "NA", "NA", "NA"]
],

"cond_transition" :  {
  "C1" : {"AfterCond" : ["0.01"]},
  "C2" : {"OR" : [
            {"LessThreshold" : ["A", "5"]},
            {"GreaterThreshold" : ["B", "0.2"]}
          ]}
  "C3" : {"GreaterThreshold" : ["B", "0.2"]},
  "C4" : {"GreaterThreshold" : ["A", "25"]},
  "C5" : {"LessThreshold" : ["A", "25"]},
}
```

Example: Homeostatic Growth

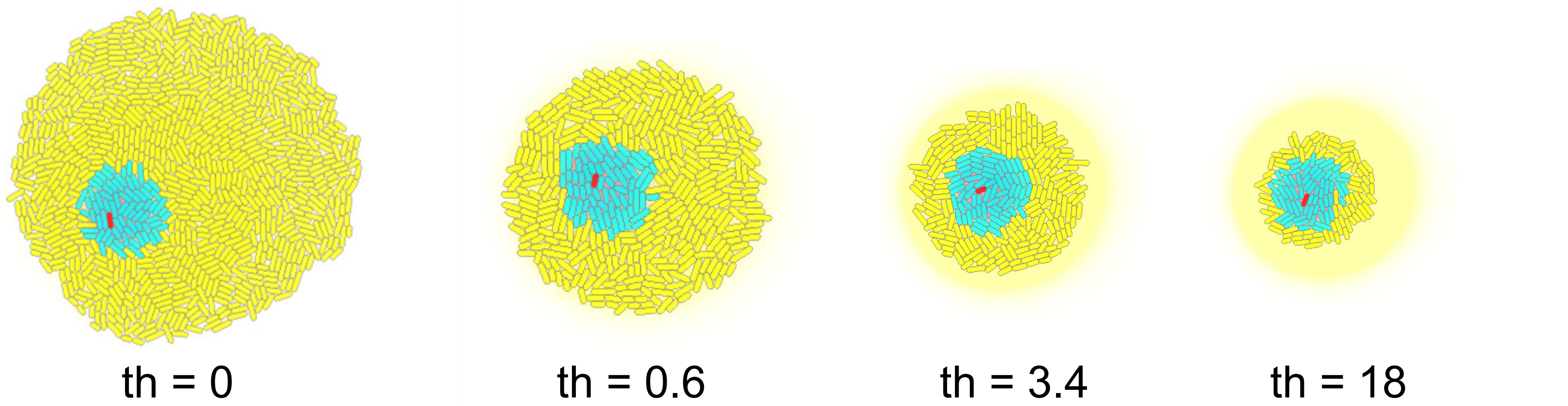
- A leader cell (green cell) emits a diffusive morphogen
- Followers cells (yellow) divide while above a certain threshold
- Death occurs if followers detect morphogens below the threshold

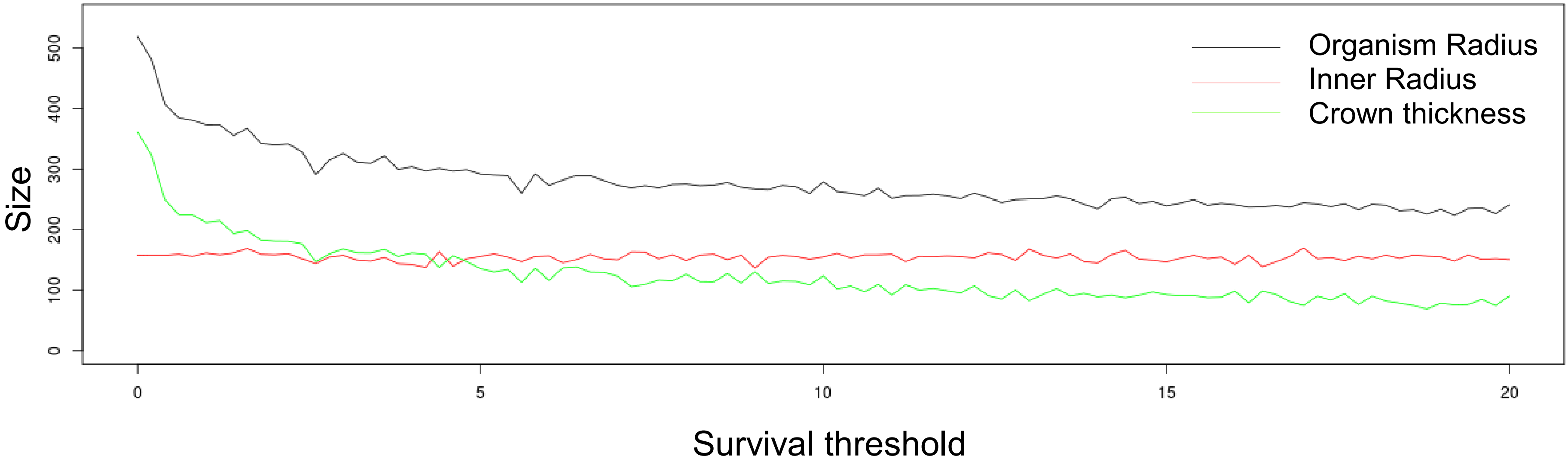




Quantitative variations

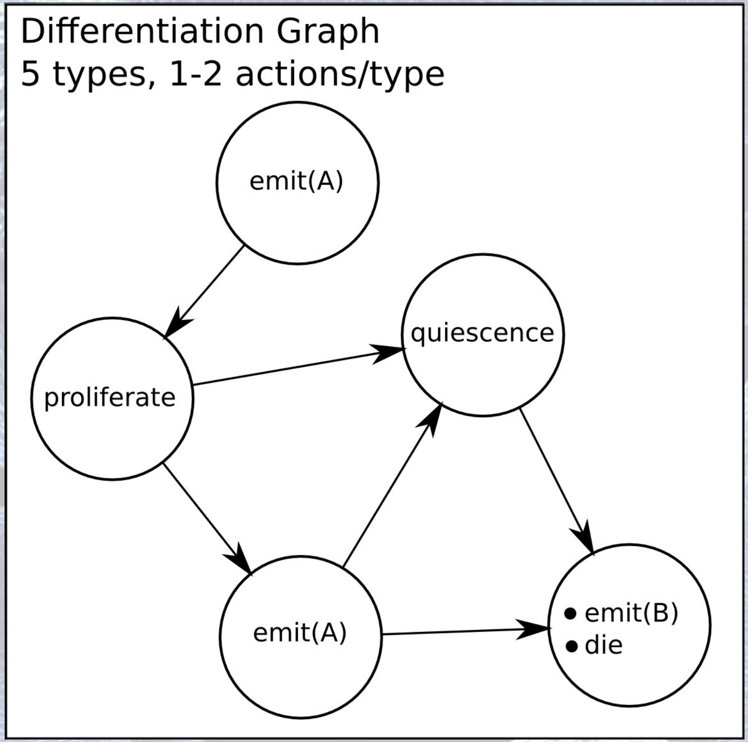
Variations in the "survival threshold" (th) impact group size and crown's thickness

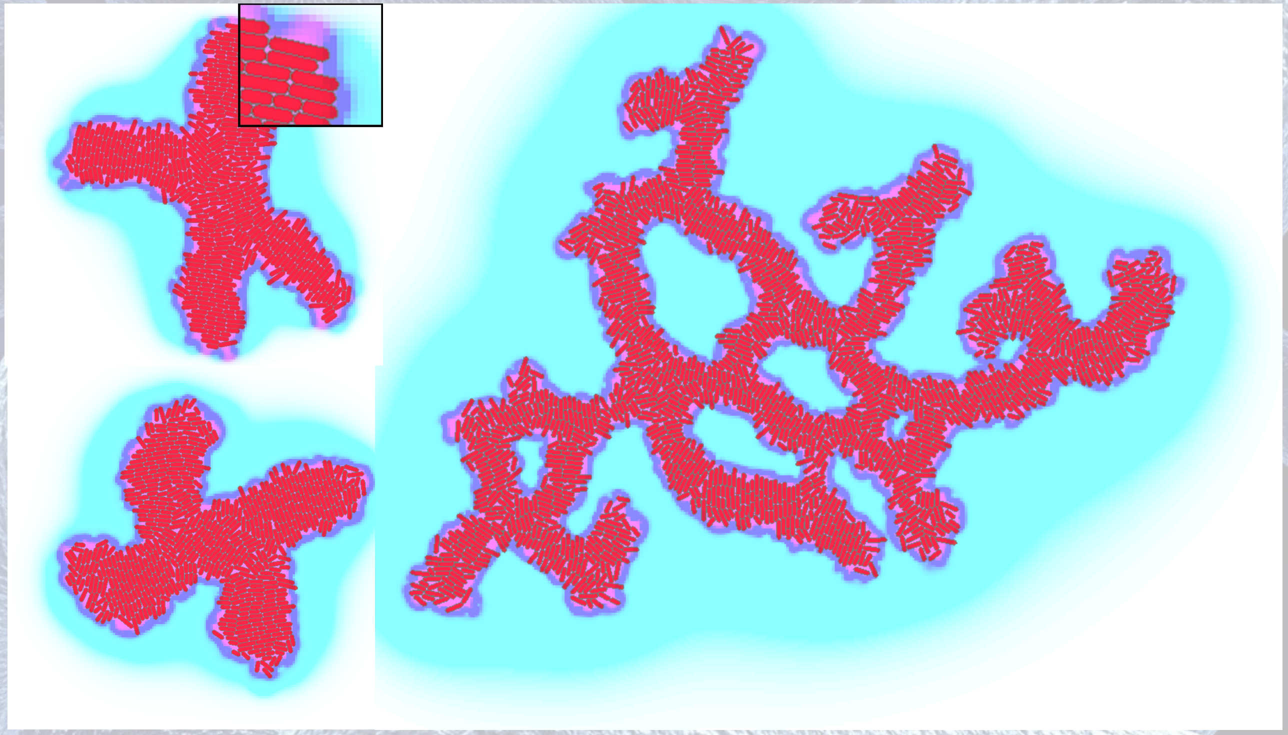




Example: Shape Formation

- Cells emit a slowly diffusive morphogen
- Cells die if morphogen concentration falls below a certain threshold
- Dying cells also send a faster diffusive signal that reacts with the morphogen and degrades it.
- This rate difference creates a mechanism of border reinforcement
- Mechanical forces induced by contacts between bacteria support *branching* structures

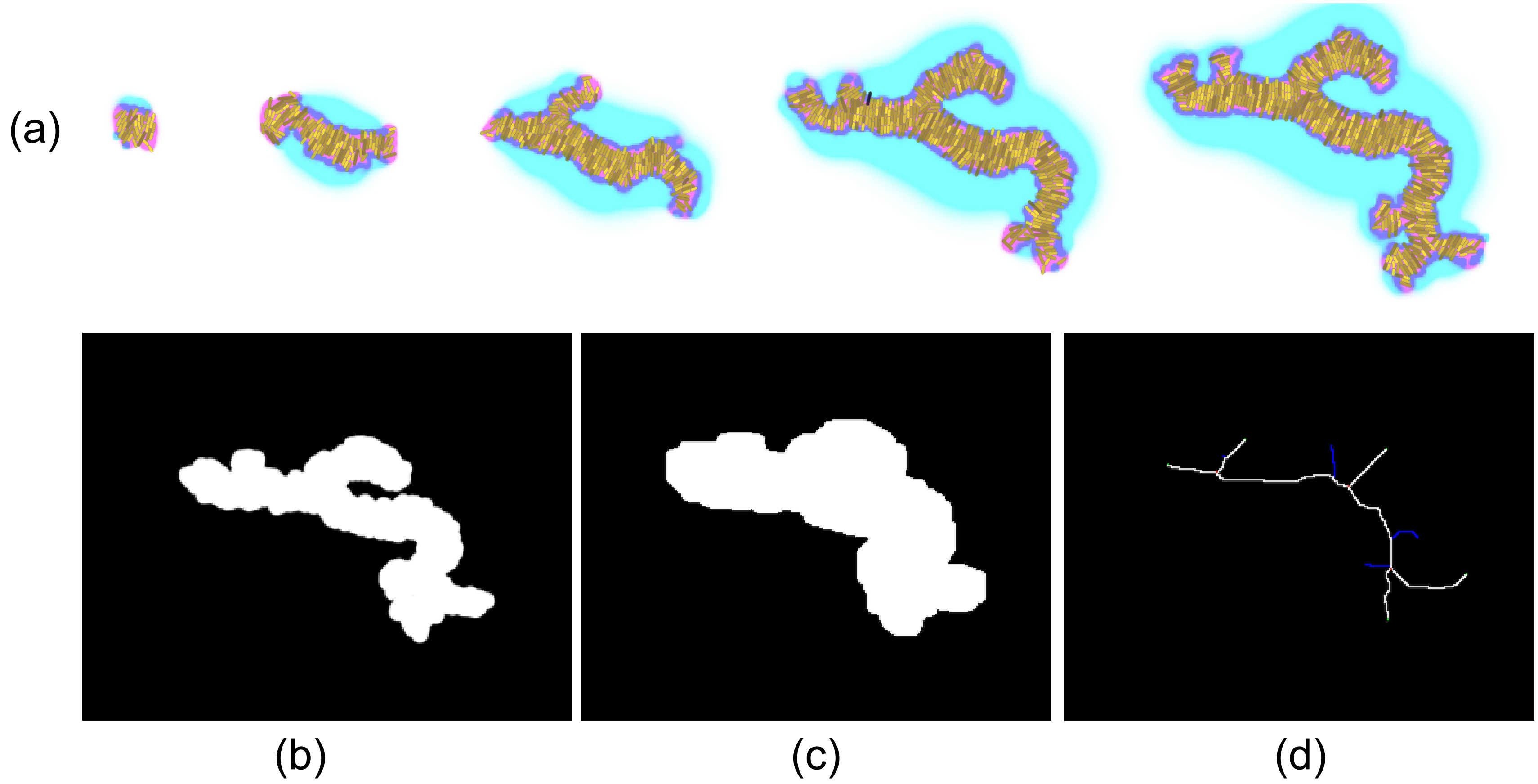




Morphological Analysis

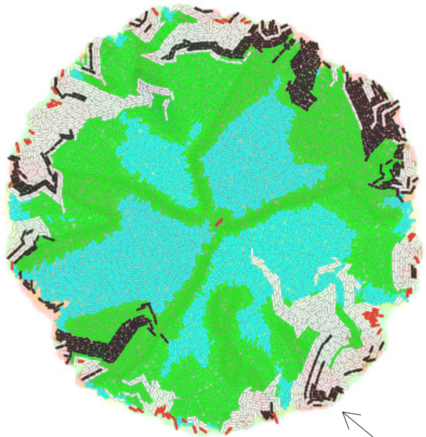
After growth (a), organism morphology can be characterized by image analysis:

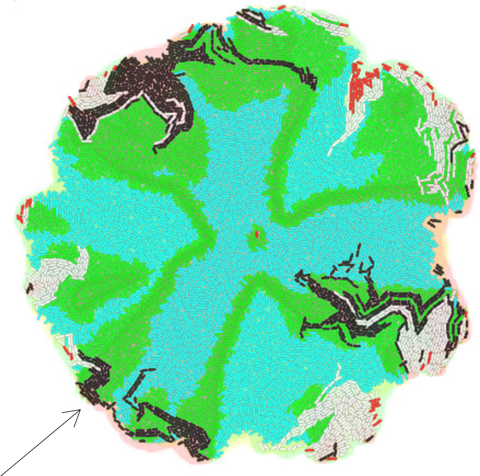
- (b) binary image and (c) Gaussian convolution to reduce contour irregularities
- (d) skeletonization, then pruning of short branches

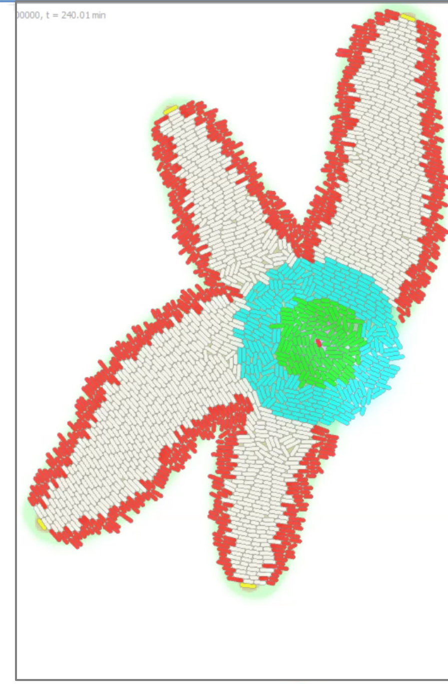


Toward Building Complex Shapes

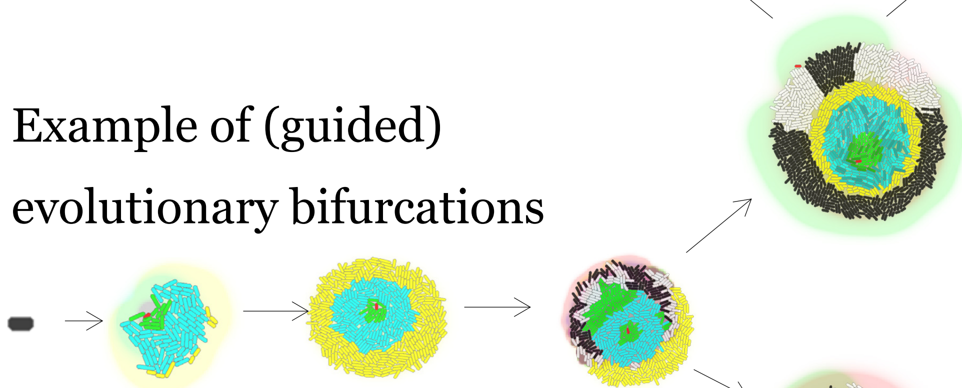
Chemical species emitted by **black** cells react with ones emitted by white cells to product **green** cells' survival signals



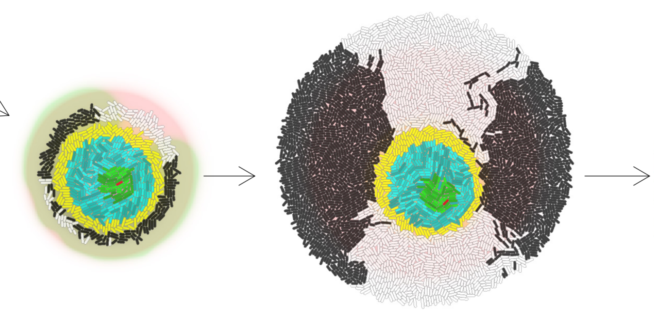


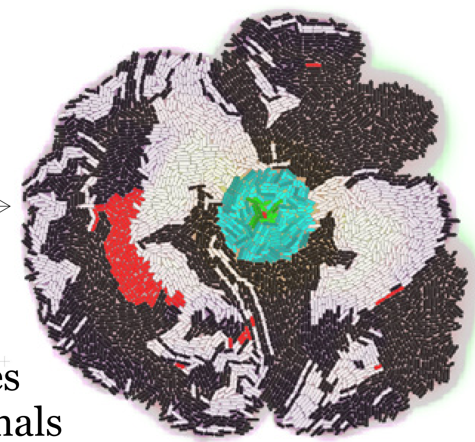


Example of (guided) evolutionary bifurcations



Random changes in spontaneous crown segmentation lead to differences in growth dynamics





Simulation (based on *Gro*): Jonathan Pascalie

Chemical species emitted by **black** cells react with the ones emitted by white cells to product **black** cells' survival signals

SynBioTIC Acknowledgements


Jonathan Pascalie
ISC-PIF

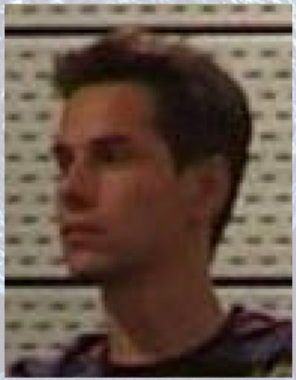

René Doursat
CNRS – École Polytechnique


Martin Potier
UPEC - LACL

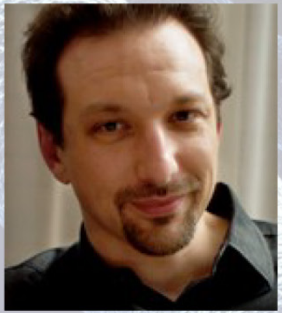

Antoine Spicher
UPEC - LACL

Institut des Systèmes Complexes Paris Île-de-France

UPEC
UNIVERSITÉ PARIS-EST CRÉTEIL


Olivier Michel
UPEC - LACL


Jean-Louis Giavitto
IRCAM


Taras Kowaliw
ISC-PIF