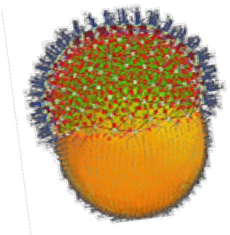
SEMINAIRE DE MASTER Digital Knowledge 2015

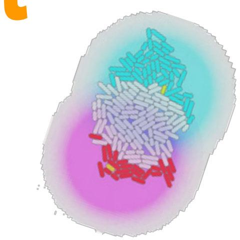
LA CONNAISSANCE COMPUTATIONNELLE

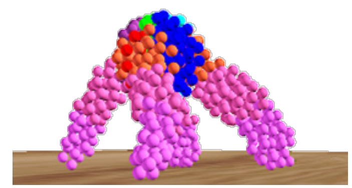
L'ARCHITECTURE NUMERIQUE : THEORIE ET CRITIQUE

Paris-Malaquais
jeudi 12 mars 2015
16h30, salle 102



From Multicellular Development to Morphogenetic Engineering to Synthetic Biology



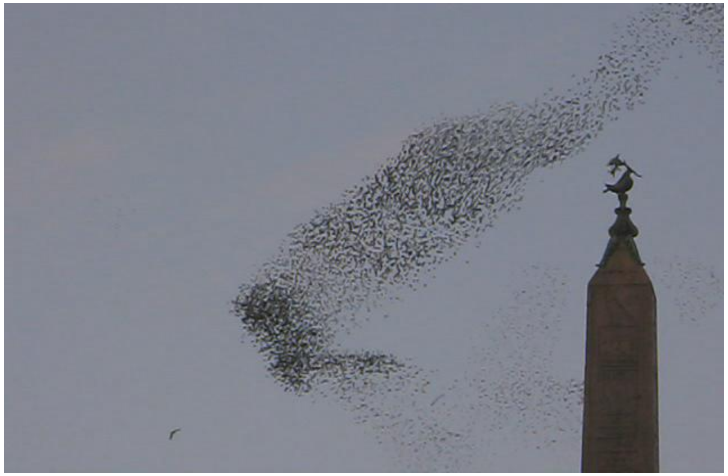


René Doursat

http://doursat.free.fr

cnrs dépasser les frontières · BioEmergences · Institut des Systèmes Complexes Paris Île-de-France · Education and Culture · Erasmus Mundus · l'École Polytechnique Université Paris-Saclay

Systems that are self-organized *and* architectured



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

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

Citroën Picasso

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

free self-organization

architecture, design

meta-design the agents

Citroën TV ad

decompose the system

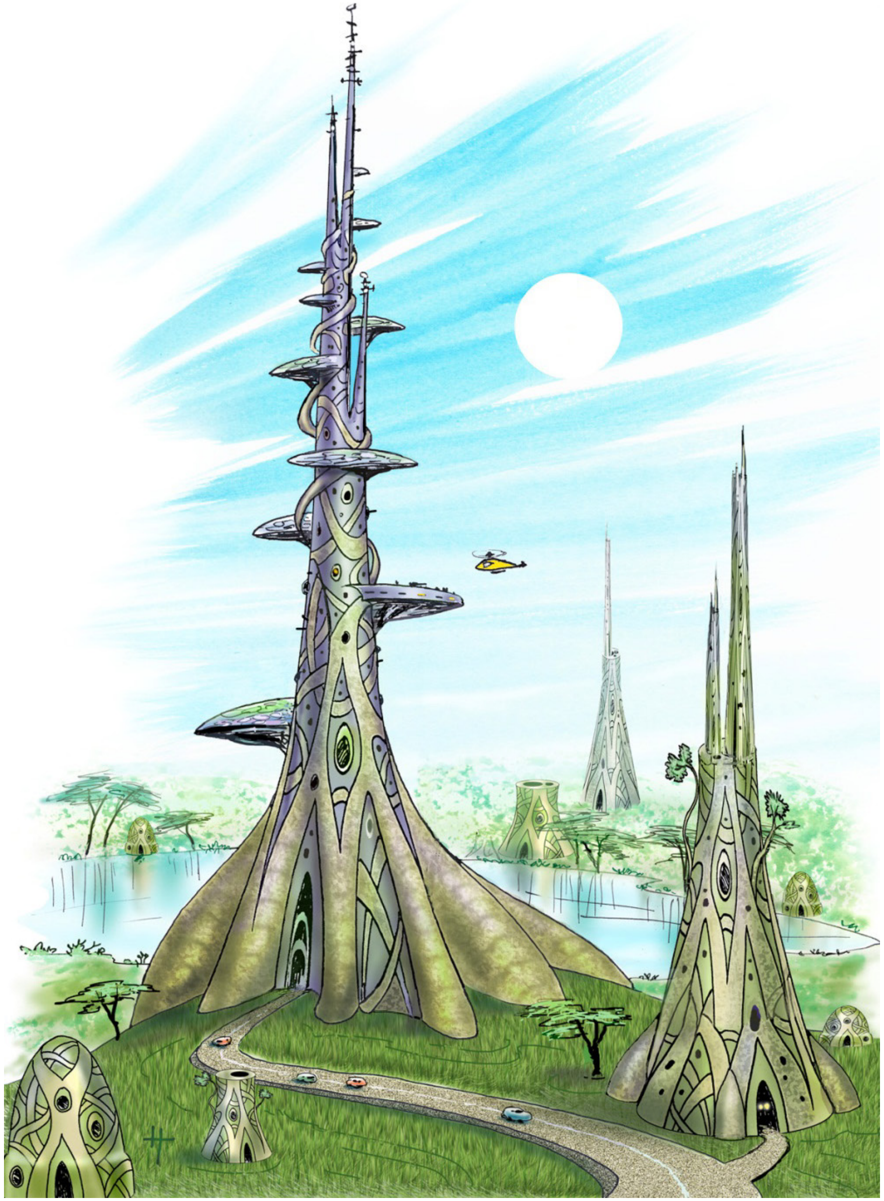
self-organized architecture / architectured self-organization

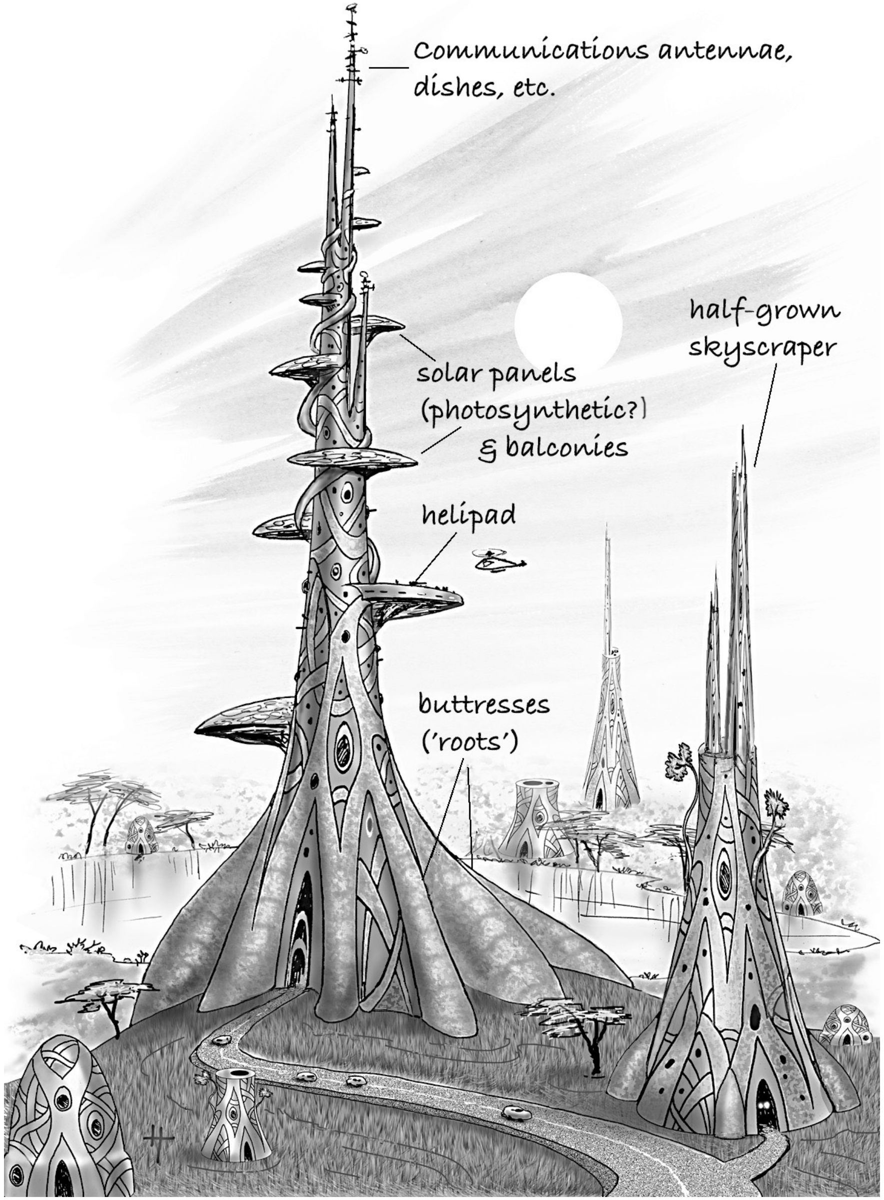
Ex1: SYMBRION: Symbiotic Evolutionary Robot Organisms

(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

Gardening Cyber-Physical Systems

Susan Stepney, Ada Diaconescu, René Doursat,
Jean-Louis Giavitto, Taras Kowaliw, Ottoline Leyser,
Bruce MacLennan, Olivier Michel, Julian F. Miller,
Igor Nikolic, Antoine Spicher, Christof Teuscher,
Gunnar Tufte, Francisco J. Vico, Lidia Yamamoto

Introduction

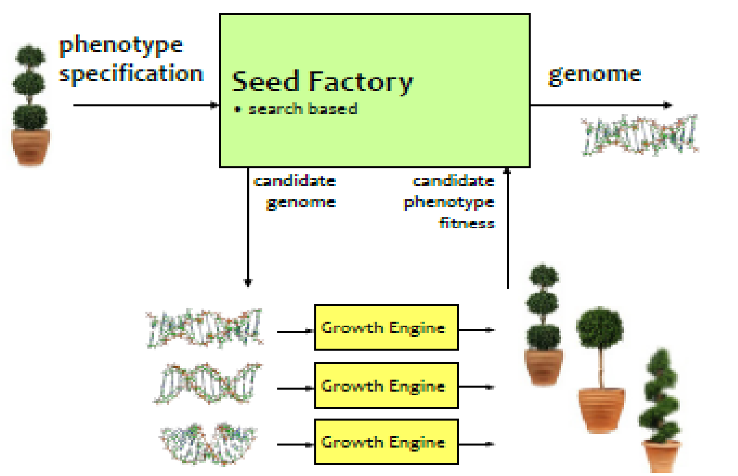
Our vision is of *construction by directed growth*, through gardening macroscopic cyber-physical artefacts formed from a growing, integrated combination of material and virtual subsystems.

Our GRO-CYPHY architecture comprises three major components:

1. a *Seed Factory*, a process for designing specific computational seeds to meet cyber-physical system requirements;
2. a **Growth Engine**, providing the computational processes that grow physical seeds in simulation, and grow virtual seeds into software;
3. a **Computational Garden**, where multiple seeds can be planted and grown in concert, where virtual seeds can be interfaced with embodied growth processes, and where a high-level gardener can shape the whole into complex cyber-physical systems.

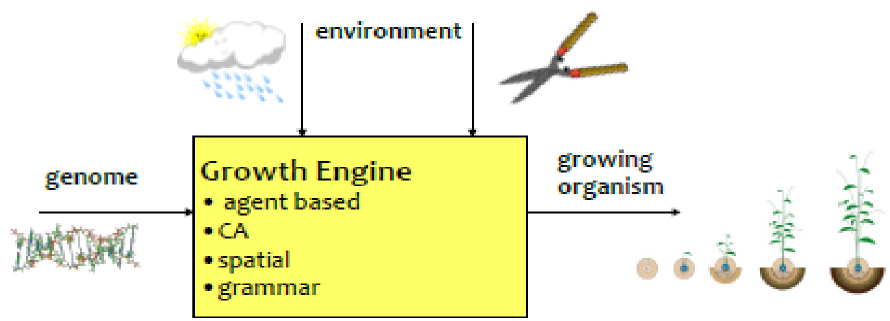
1 Seed Factory

High-level phenotype (grown) specifications are input; the search process develops the relevant seeds (subsystem genomes); it uses the Growth Engine to grow candidate seeds into phenotypes, which it evaluates against the specification, and feeds the information back into its search process.



2 Growth Engine

A Growth Engine provides the computational mechanisms to grow a seed. This might be required to grow in simulation a seed intended for a physical device, or to grow the seed of a virtual component such as a software control system.



Gardening Cyber-Physical Systems

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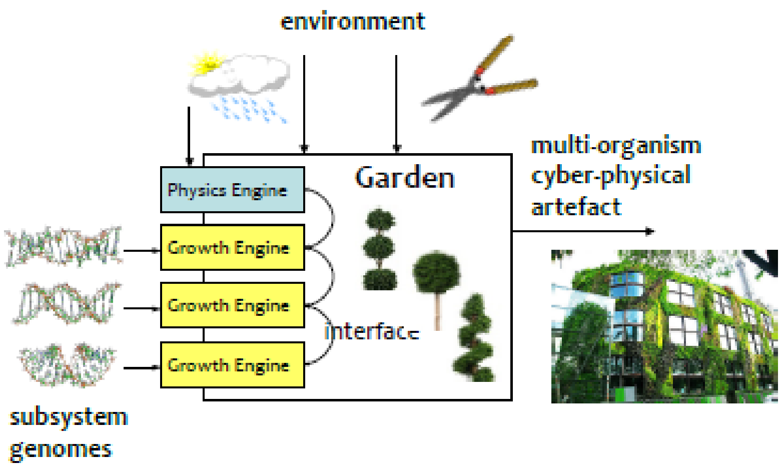
3

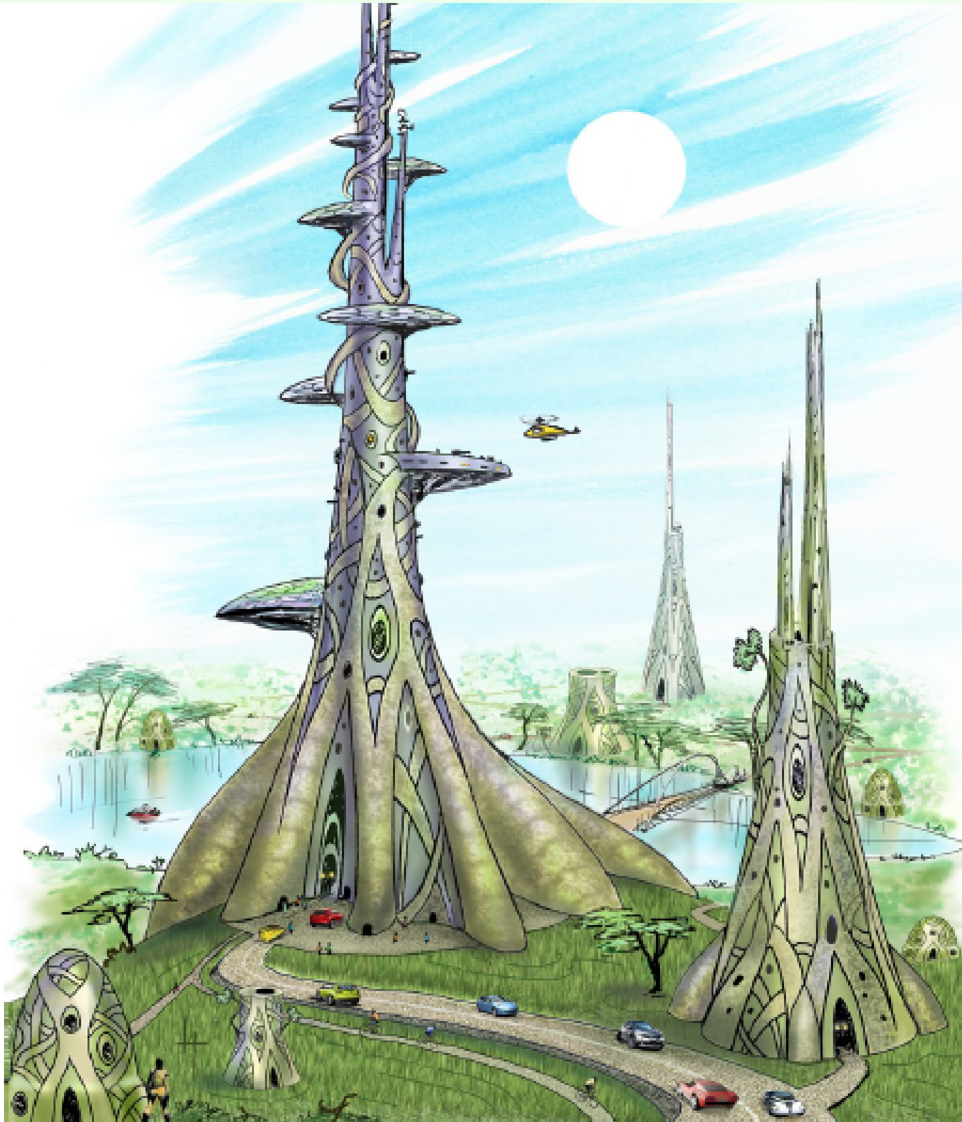
Computational Garden

The computational garden is where the various seeds are planted and grow together, responding to their environment, into the resultant artefact. The garden provides a high-level metaphor: high-level guiding of a robust complex growing system, rather than low-level engineering of the precise placement of every cell or particle.



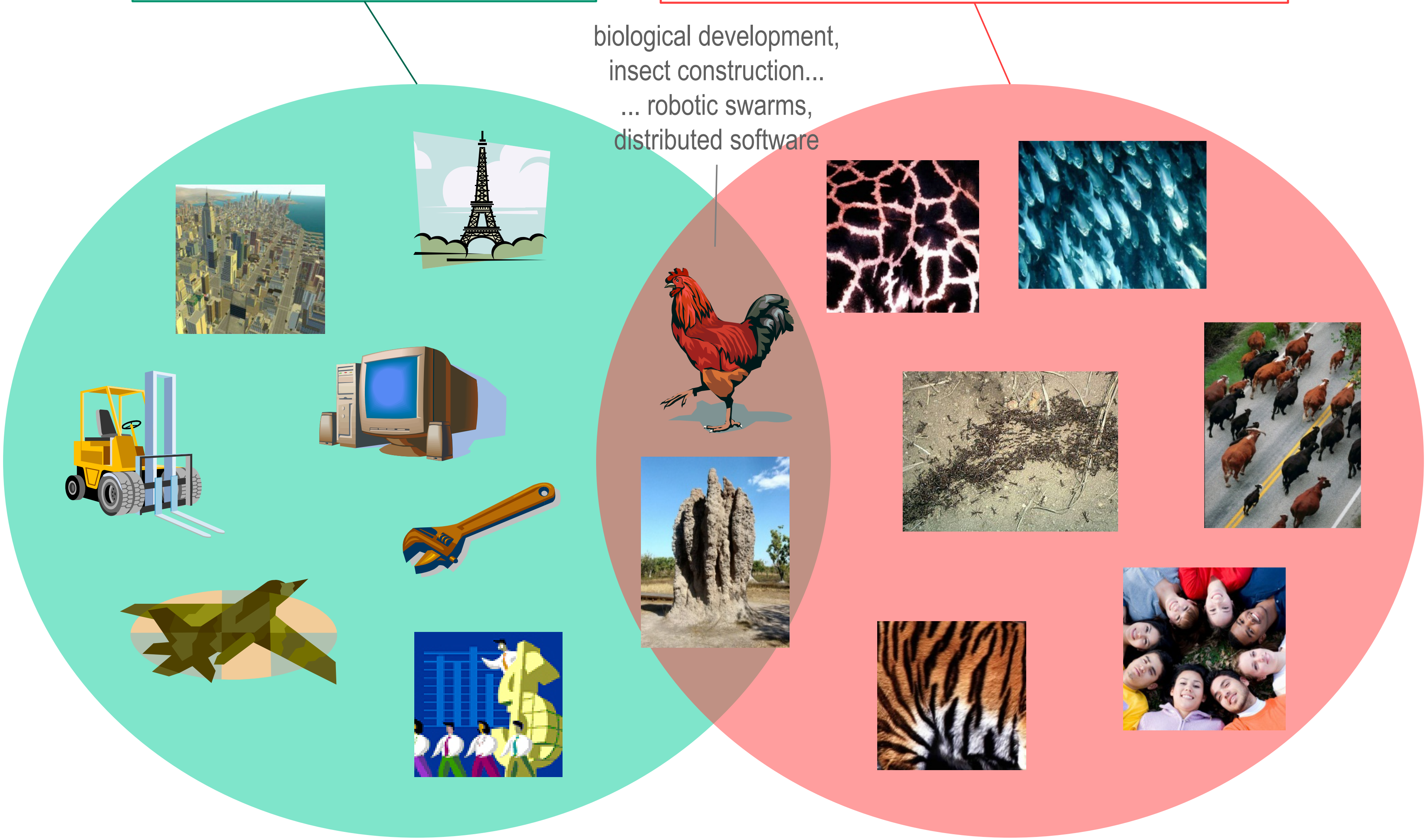
Depts of Computer Science and Electronics, U. York, UK; LTCI CNRS, Télécom-ParisTech, France;
GEB, Universidad de Málaga, Spain; ISC-PIF, CNRS, Paris, France; UMR STMS 9912, IRCAM – CNRS, France;
Sainsbury Laboratory, U. Cambridge, UK; EECS, Univ. Tennessee, Knoxville, USA; LACL – U-PEC, France;
TPM, TU Delft, NL; ECE, Portland State U, USA; NTNU, Norway; University of Strasbourg, France

contact : susan.stepney@york.ac.uk



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

ARCHITECTURE & SELF-ORGANIZATION



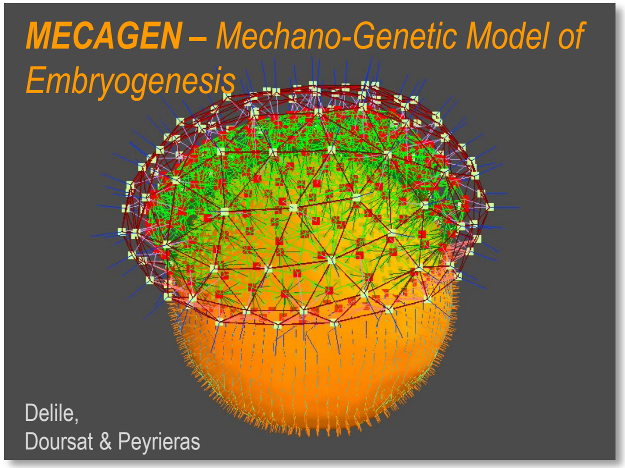
planned actitivities: civil engineering, mechanical engineering, electrical engineering, computer engineering, companies, (building) architecture, enterprise architecture, urbanism

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

Systems that are self-organized *and* architectured

➢ Embryogenesis to Simulated Development to Synthetic Biology

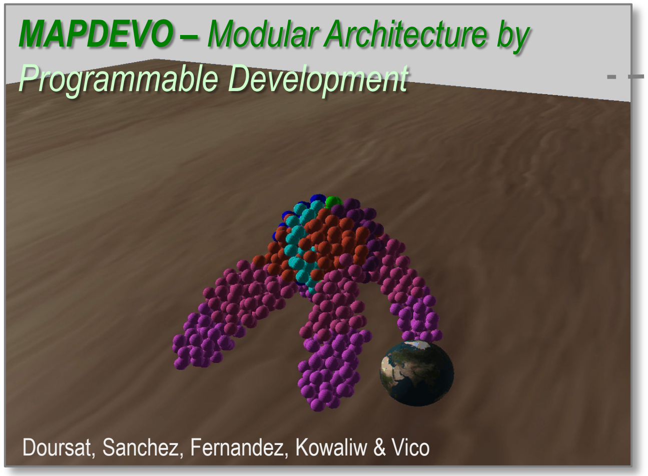
*illustration of **Morphogenetic Engineering** ideas*

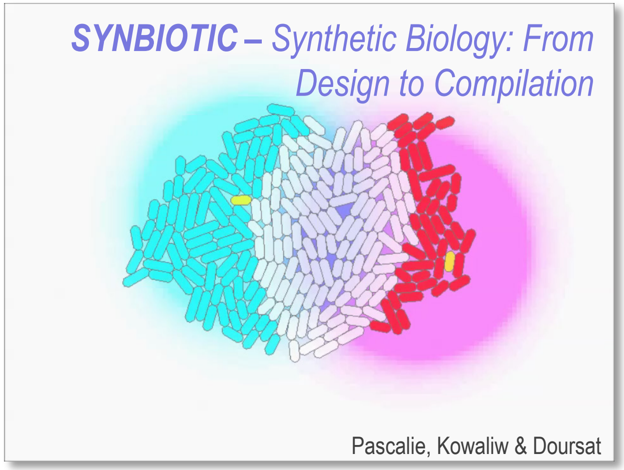


BIOMODELING
(LIFE)

mutually beneficial transfers between biology & CS

BIO-INSPIRED
ENGINEERING (ALIFE)



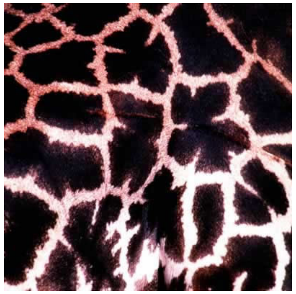


BIOENGINEERING
(HYBRID LIFE)

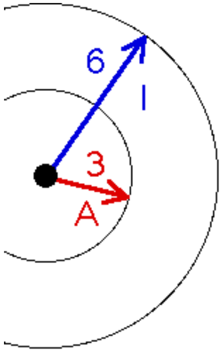
Natural Complex Systems

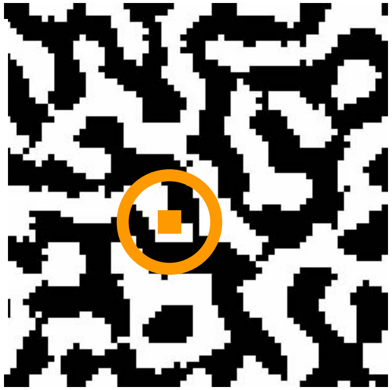
Ex: Pattern formation – Animal colors

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

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





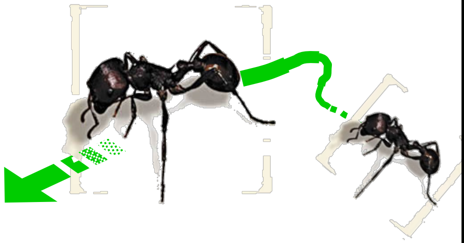
NetLogo Fur simulation

Ex: Swarm intelligence – Insect colonies

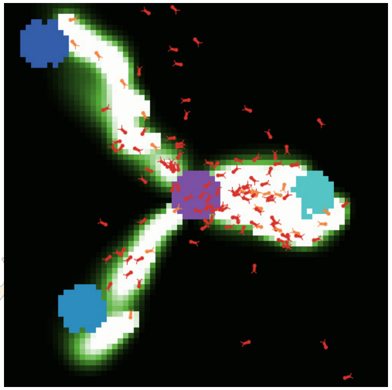
- ✓ trails form by ants that follow and reinforce each other's pheromone path

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

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



Harvester ants
(Deborah Gordon, Stanford University)

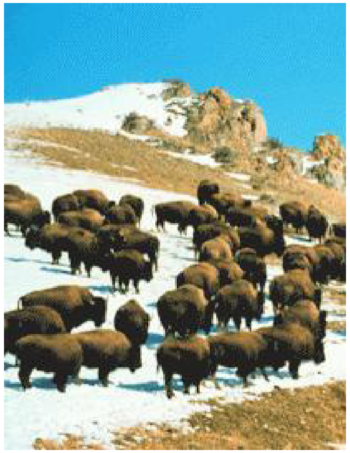


NetLogo Ants simulation

Natural Complex Systems

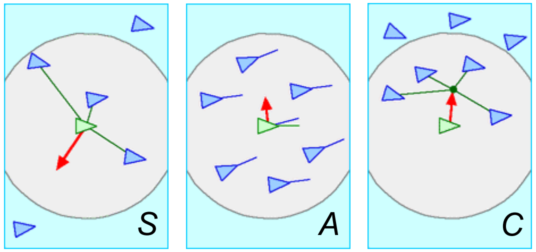
➢ Ex: Collective motion – Flocking, schooling, herding

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

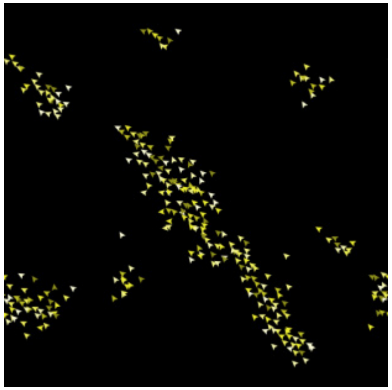


Bison herd
(Montana State University, Bozeman)

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



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

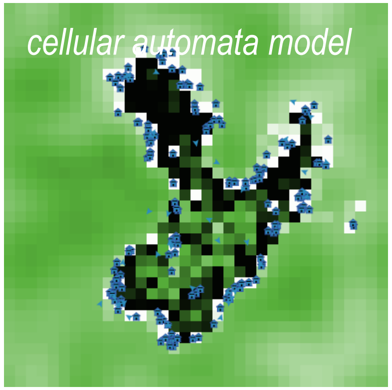


NetLogo Flocking simulation

➢ Ex: Diffusion and networks – Cities and social links

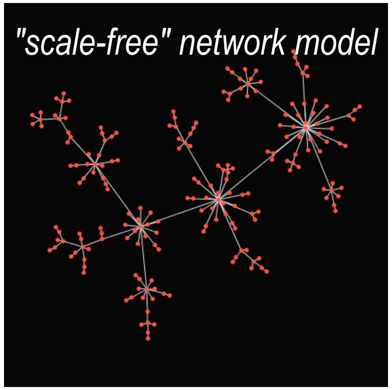
✓clusters and cliques of homes/people that aggregate in geographical or social space

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



NetLogo urban sprawl simulation

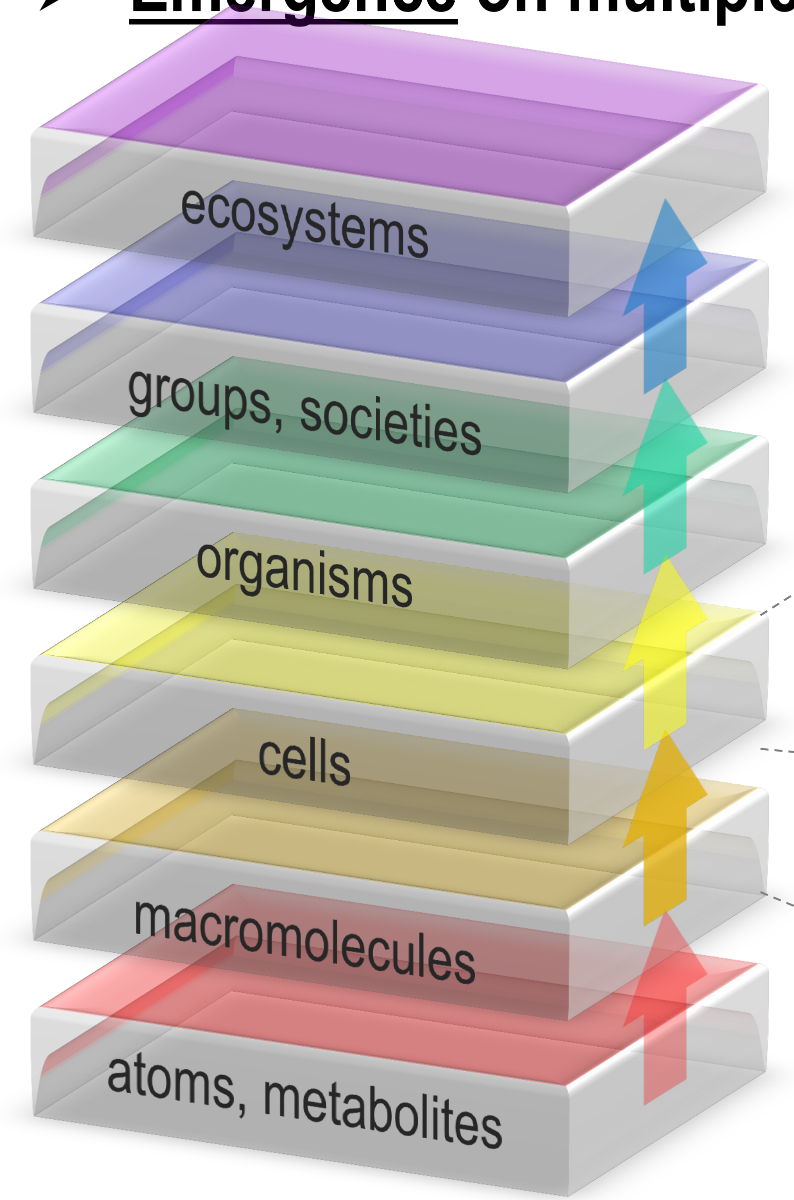
MS PowerPoint clip



NetLogo preferential attachment

Canonical Complex Systems

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

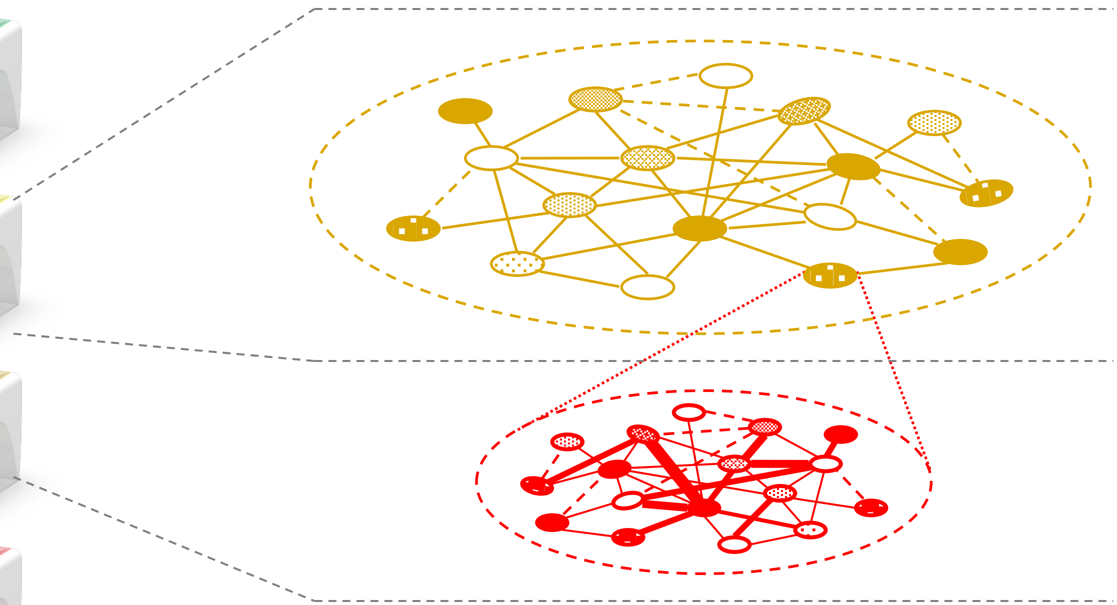


"complex systems" =

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



Canonical Complex Systems

- **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)*

The Archipelago of Complex Systems

➢ 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

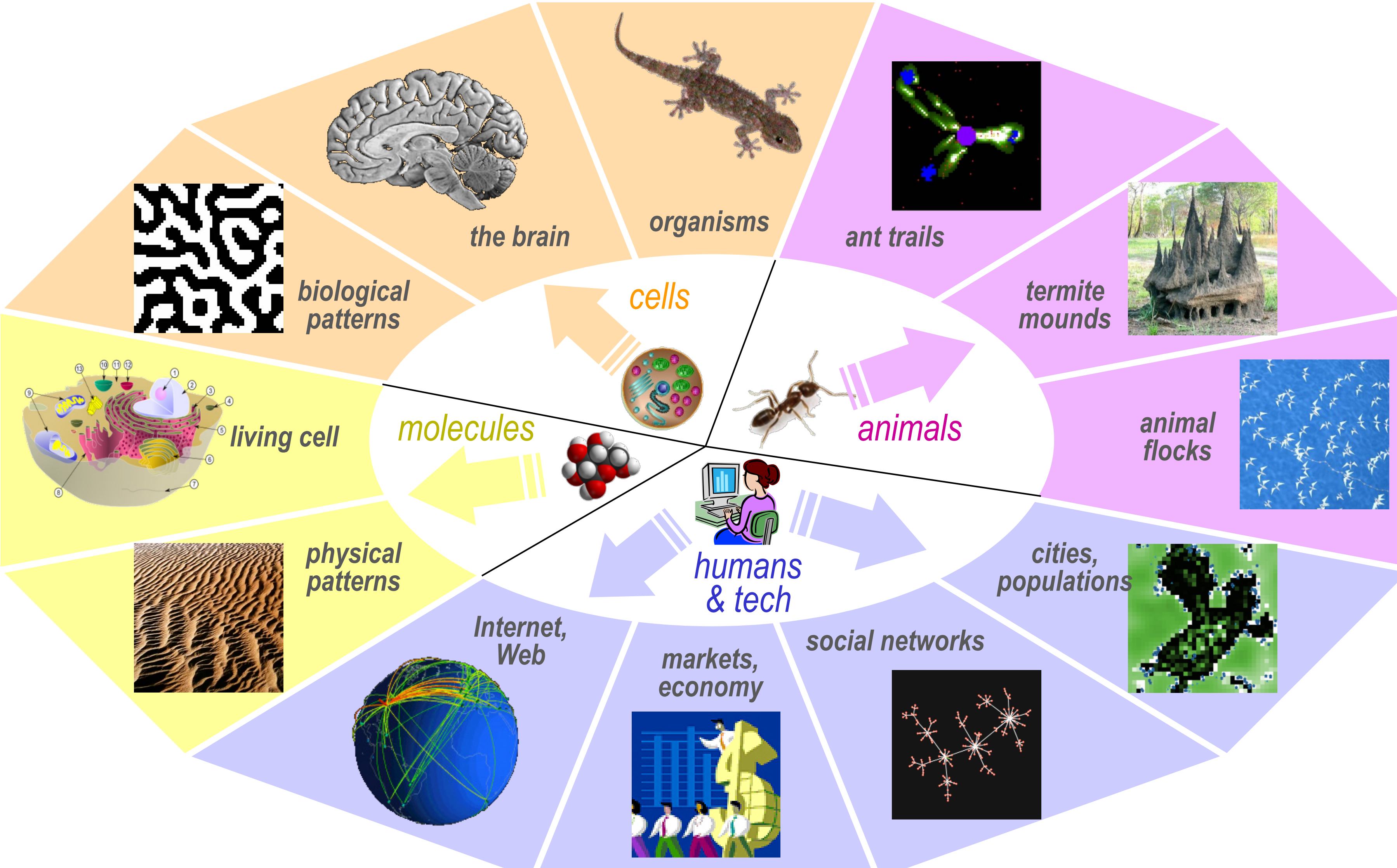
- nonlinear dynamics & chaos
- stochastic processes
- systems dynamics (macro variables)

multitude, statistics: large-scale properties of systems

- graph theory & networks
- statistical physics
- agent-based modeling
- distributed AI systems

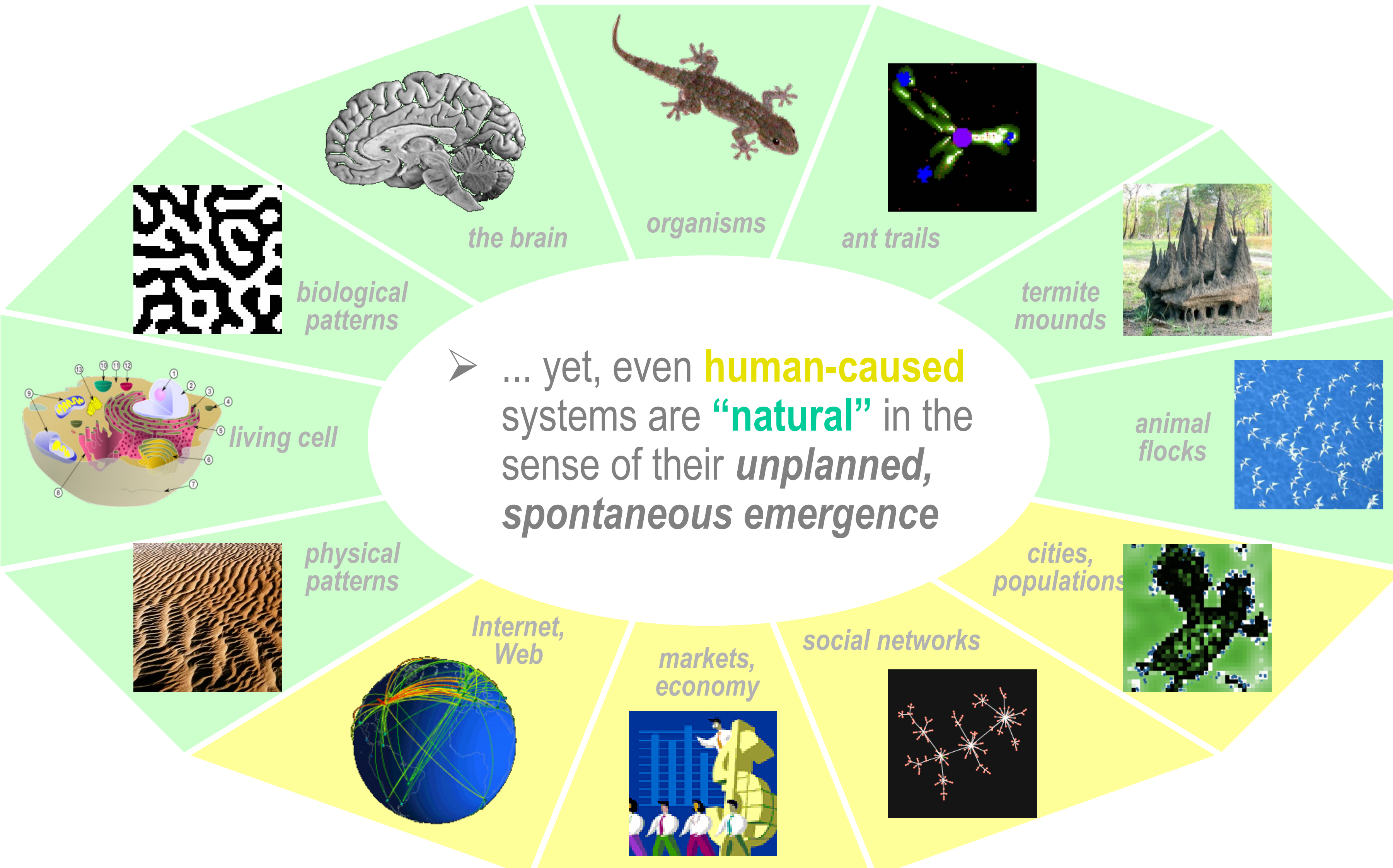
Canonical Complex Systems

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



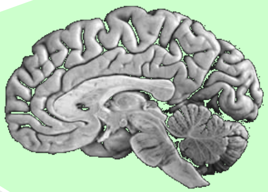
“Natural” vs. “Human-Caused” Complex Systems

Natural and human-caused categories of complex systems



Architecture without Architects

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



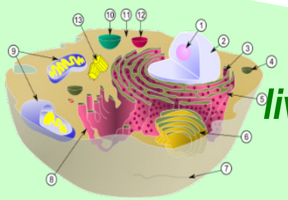
the brain

organisms

ant trails

biological patterns

termite mounds



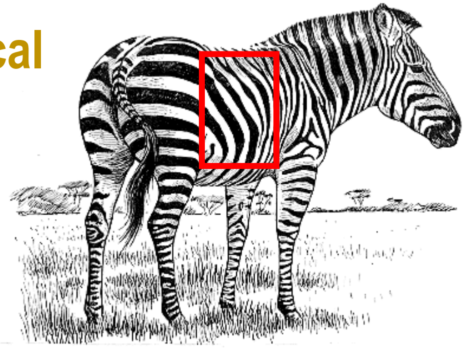
living cell

animal flocks

physical patterns

➢ biology strikingly demonstrates the possibility of **combining pure self-organization and an elaborate architecture**

➢ there is a whole class of **morphological (self-dissimilar) systems**, in which morphogenesis ≥ pattern formation



"The stripes are easy, it's the horse part that troubles me"
—attributed to A. Turing, after his 1952 paper on morphogenesis

"Supra-Human" Complex Systems

Human superstructures are "natural" CS

by their unplanned, spontaneous emergence and adaptivity...

... arising from a multitude of traditionally designed artifacts

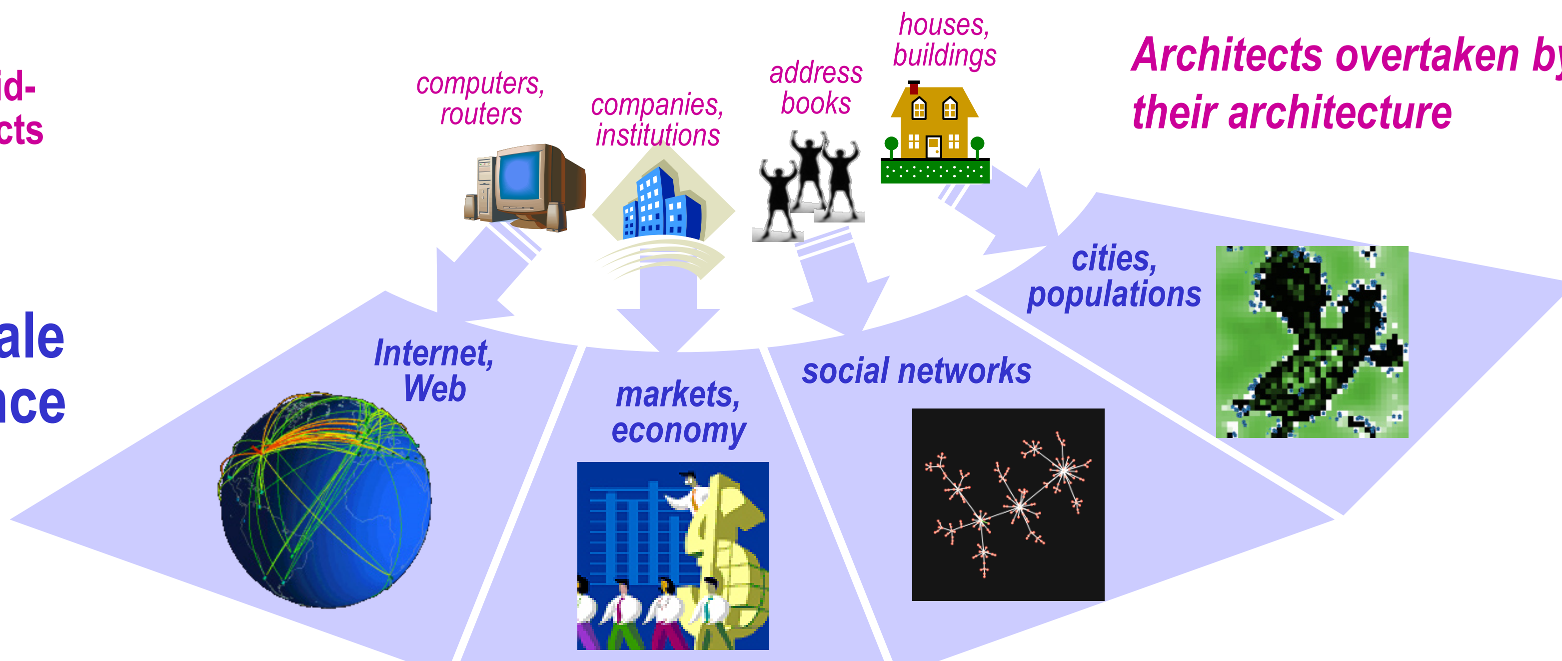
geography: cities, populations	⇐	houses, buildings
people: social networks	⇐	address books
wealth: markets, economy	⇐	companies, institutions
technology: Internet, Web	⇐	computers, routers

small to mid-scale artifacts

⇓

large-scale emergence

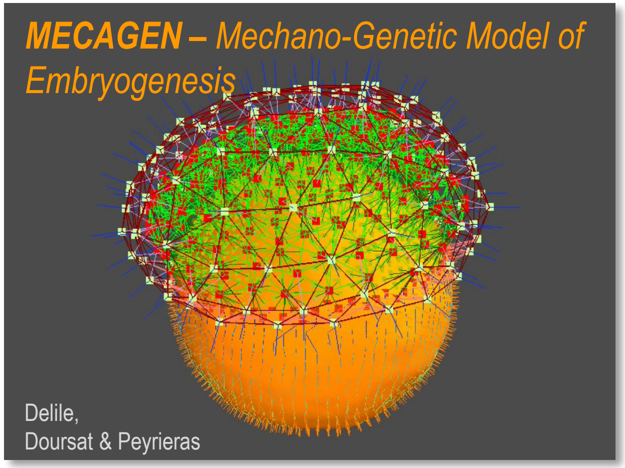
Architects overtaken by their architecture



Systems that are self-organized *and* architectured

➢ Embryogenesis to Simulated Development to Synthetic Biology

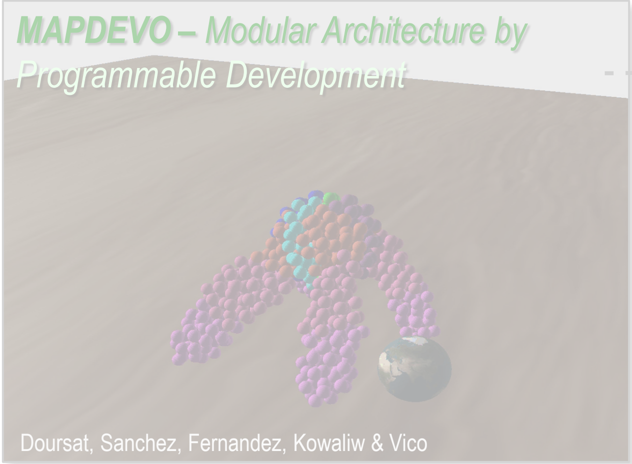
illustration of **Morphogenetic Engineering** ideas

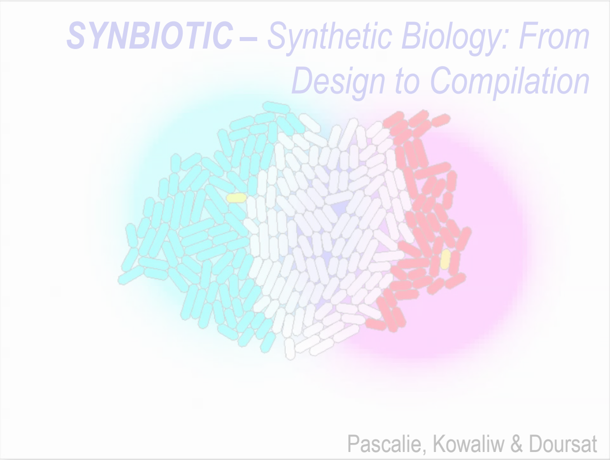


BIOMODELING
(LIFE)

mutually beneficial transfers between biology & CS

BIO-INSPIRED
ENGINEERING (ALIFE)



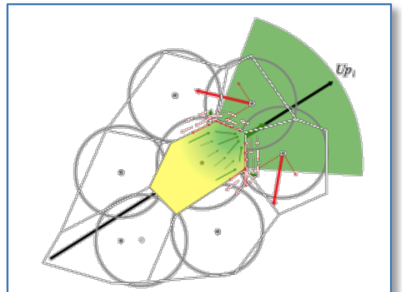


BIOENGINEERING
(HYBRID LIFE)

MECAGEN – *Mechano-Genetic Model of Embryogenesis*

➢ Methodology and workflow

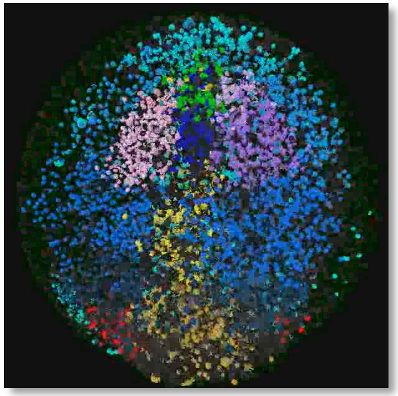
Hypotheses



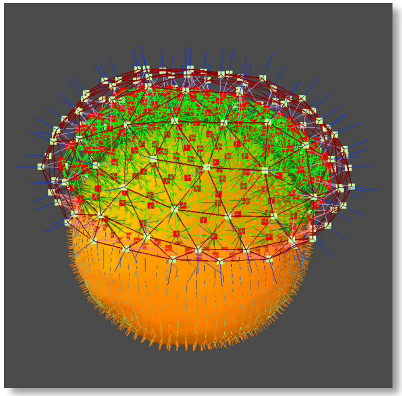
$$\vec{v}_i = \frac{1}{\lambda_i} \sum_{neighbors\ j} \left(\vec{F}_{P\,i,j} + \vec{F}_{A\,i,j} \right)$$

3 Agent-based Model

Simulation



2 Phenomenological reconstruction

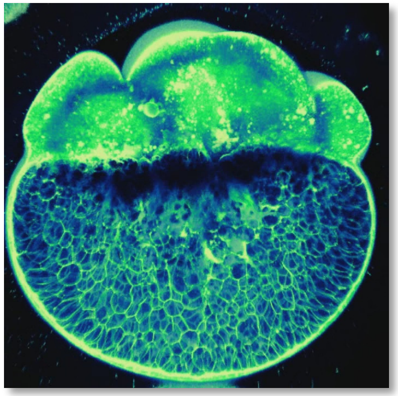


4 Computational reconstruction

Δ

5 *Validation*

Processing



1 Raw imaging data

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

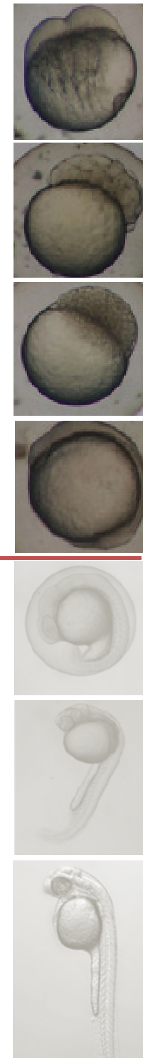
MECAGEN – *Mechano-Genetic Model of Embryogenesis*

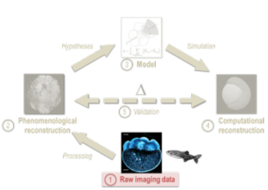
➢ Zebrafish development

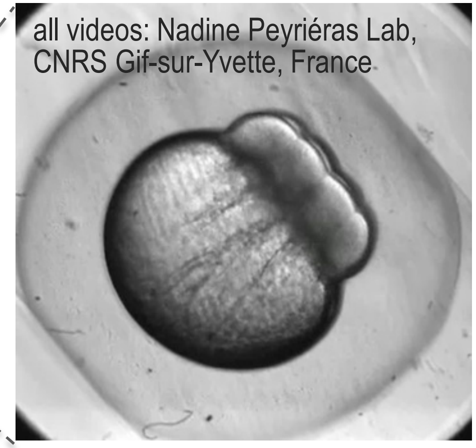
- 00.00 – 00.75 hrs **Zygote Period**
- 00.75 – 02.25 hrs **Cleavage Period**
- 02.25 – 05.25 hrs **Blastula Period**
- 05.25 – 10.33 hrs **Gastrula Period**
- 10.33 – 24 hrs **Segmentation Pd**
- 24 hrs – 48 hrs **Pharyngula Period**
- 48 hrs – 72 hrs **Hatching Period**

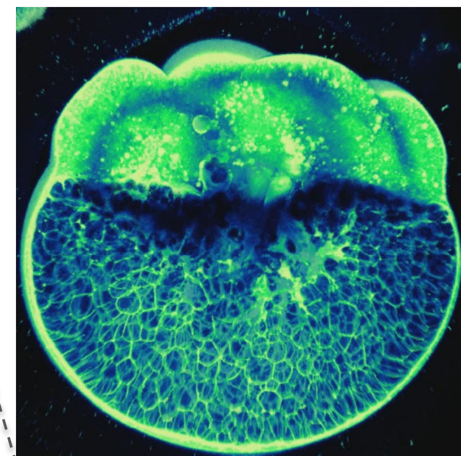
Larval Period

Adult



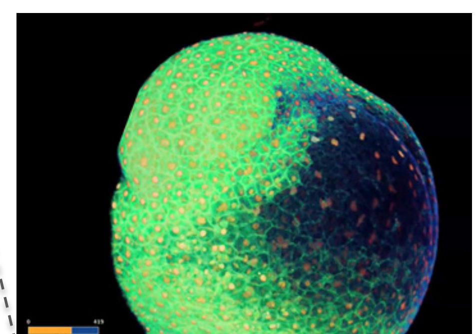






- nonlinear optics imaging method (without dyes): based on natural "Second and Third Harmonic Generation" (SHG, THG) of photons by live tissue from a laser excitation

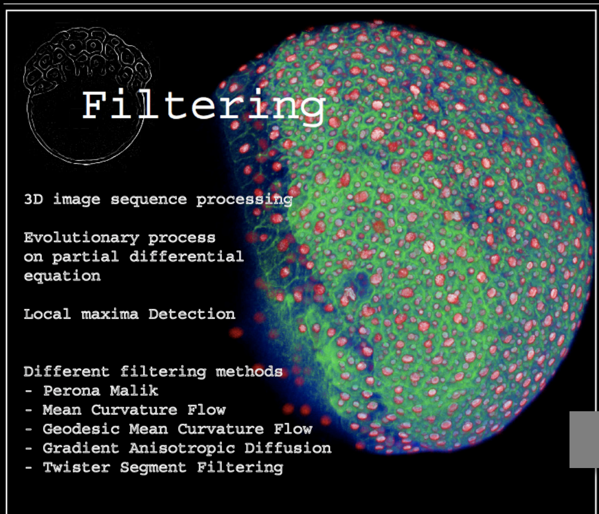
Emmanuel Beaurepaire's Optics & Bioscience Lab at Ecole Polytechnique Paris

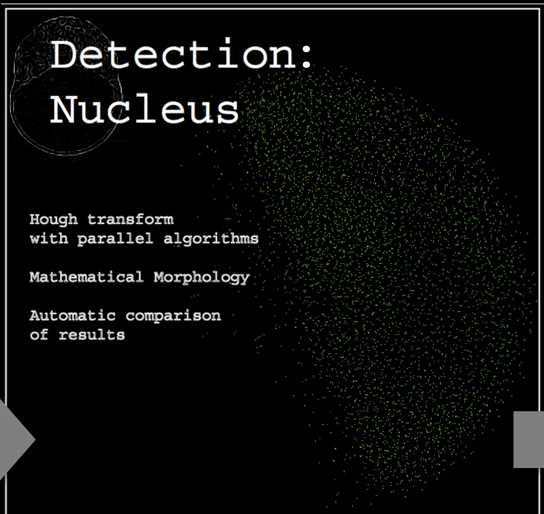


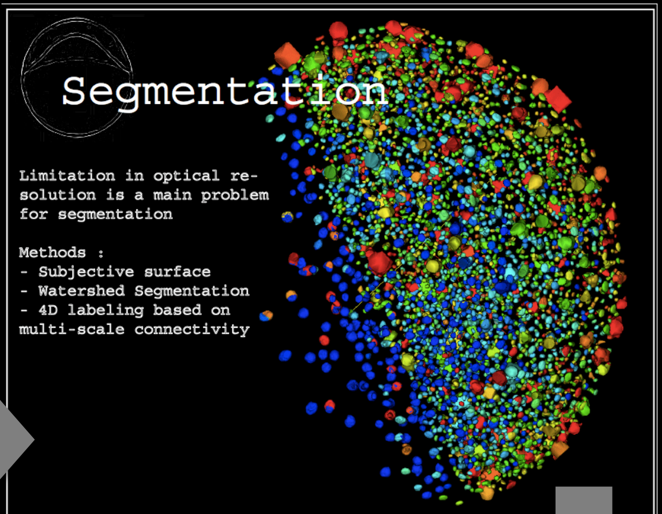
- biological marker imaging method: "Double Labelling" ubiquitous staining with two fluorescent proteins targeted at the cell nuclei and membranes

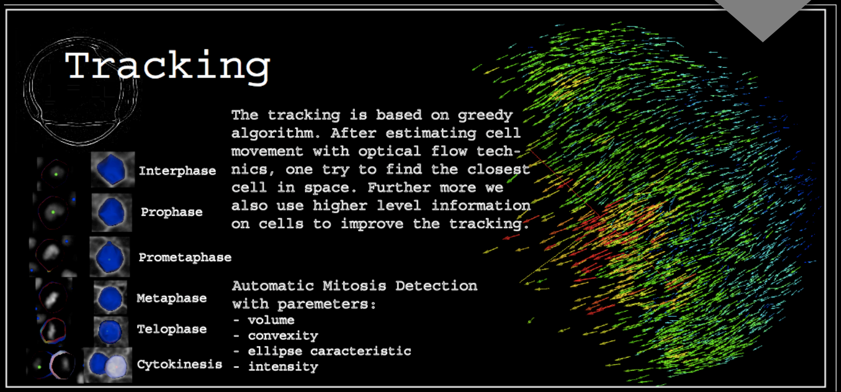
MECAGEN – *Mechano-Genetic Model of Embryogenesis*

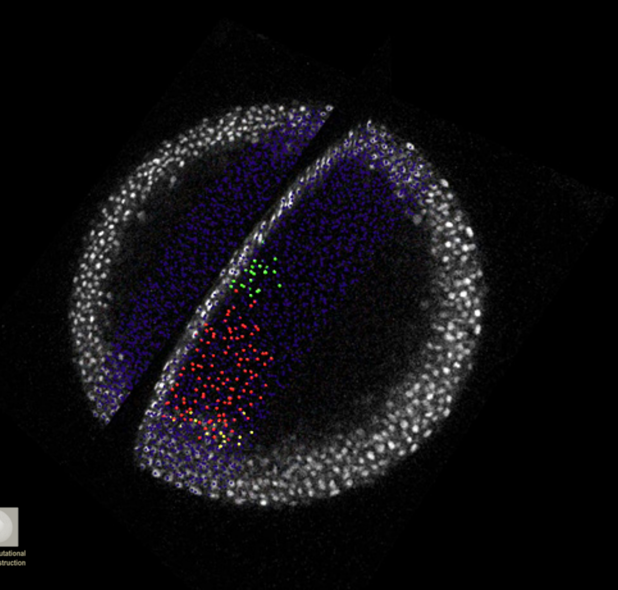
➢ Phenomenological reconstruction: *BioEmergences* workflow

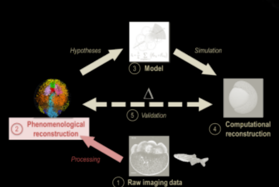












<u>image processing and reconstruction workflow</u>: Emmanuel Faure, Benoit Lombardot, Thierry Savy, Rene Doursat, Paul Bourgine (Polytechnique/CNRS), Matteo Campana, Barbara Rizzi, Camilo Melani, Cecilia Zanella, Alex Sarti (Bologna), Olga Drblíkova, Zuzana Kriva, Karol Mikula (Bratislava), Miguel Luengo-Oroz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

MECAGEN – *Mechano-Genetic Model of Embryogenesis*

Morphogenesis essentially couples mechanics and genetics

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

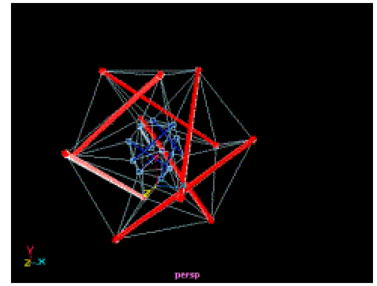
modification of cell size and shape

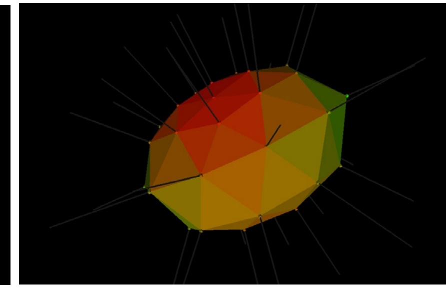
growth, division, apoptosis

differential adhesion

motility, migration

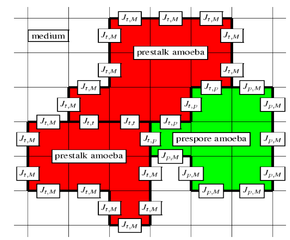
Tensional integrity
Donald Ingber, Harvard

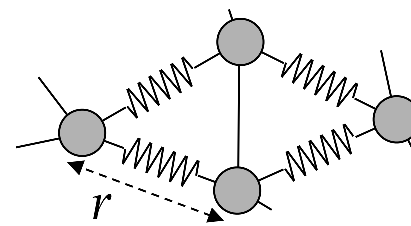




Deformable volume
Doursat, simul. by Delile

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





Spring-mass model
Doursat (2009) ALIFE XI

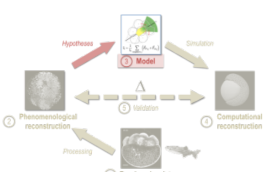
[B] Gene regulation ("self-painting")

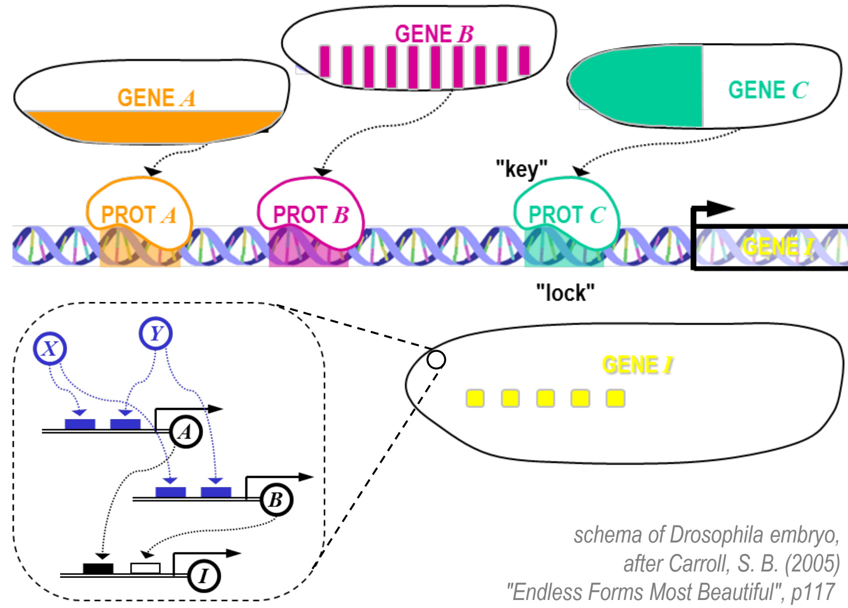
gene regulation

changes in cell-to-cell contacts

diffusion gradients ("morphogens")

changes in signals, chemical messengers



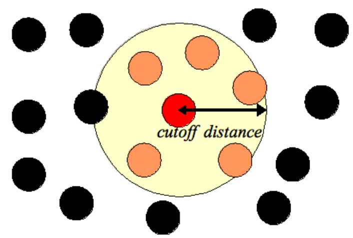


schema of Drosophila embryo, after Carroll, S. B. (2005) "Endless Forms Most Beautiful", p117

MECAGEN – *Mechano-Genetic Model of Embryogenesis*

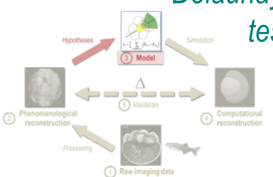
[A] Cell behavior: equations of motion

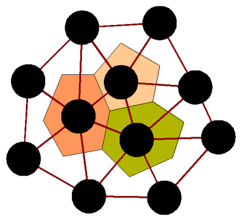
$$\cancel{m\vec{a}_i} + \lambda\vec{v}_i = \sum_{\boxed{j\in\mathcal{N}_i}} \left(\boxed{\vec{F}^{P}_{ij}} + \boxed{\vec{F}^{A,\mathrm{int}}_{ij} + \vec{F}^{A,\mathrm{ext}}_{ij}} \right)$$



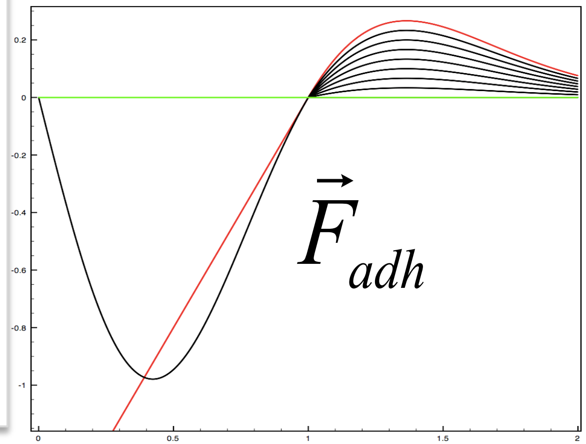
"metric" ***neighborhood*** *(radius-based)*

"topological" neighborhood Delaunay/Voronoi tessellation

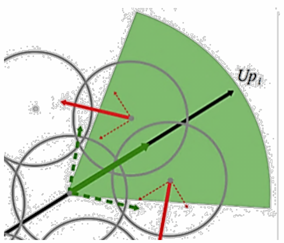


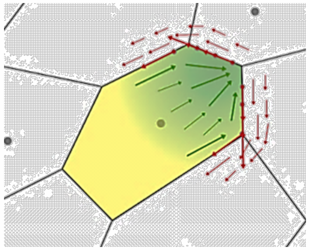


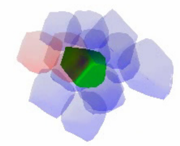
passive ***relaxation forces***



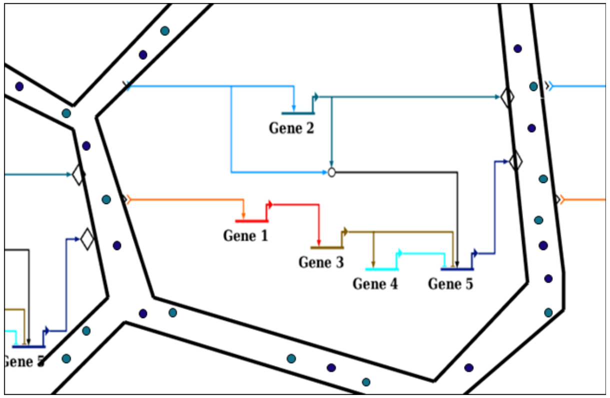
active migration *and swarming forces, by polarized intercalation*

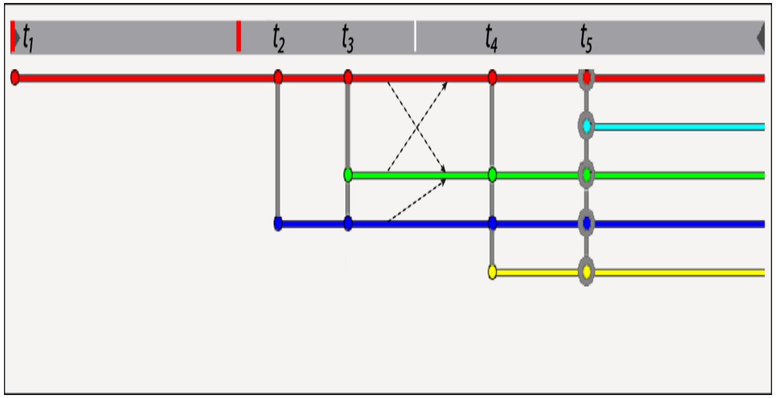






[B] Cell types: GRN or "Waddingtonian" timeline





A

T_{gm}	2	T_{red}	2
3500	-1	3500	+1

T_{gm}	1
1000	0

B

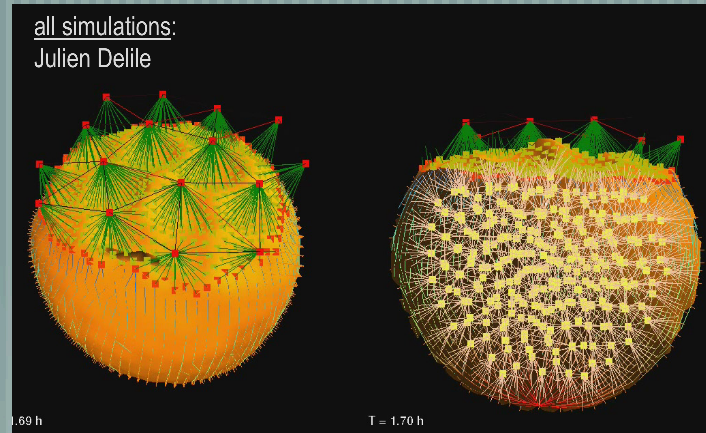
Target cell type *T*	Axis id
Intensity	+1: mono N^+ -1: mono N^- 0: bipolar

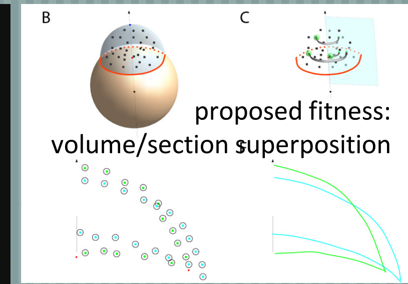
[C] coupling

MECAGEN → Case Studies in the Zebrafish

3. How is the Zebrafish blastula shaped?

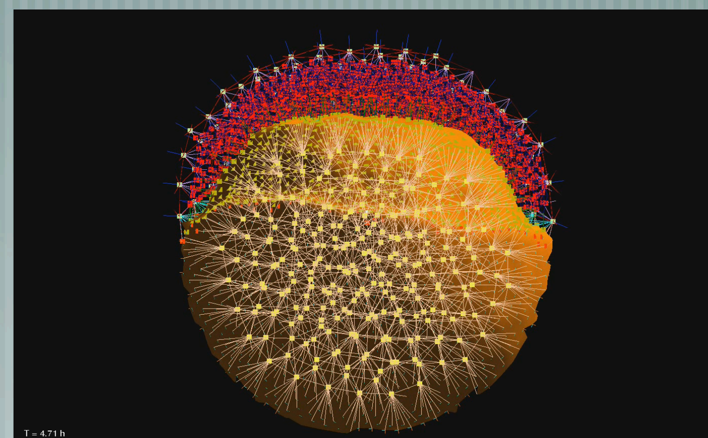
→ *How does blastula shape emerge from cell-cell interactions?*

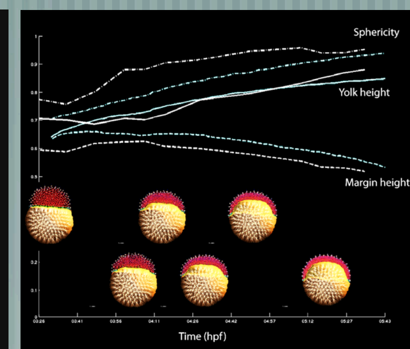




5. Intercalation patterns

→ *Are protrusions sufficient to drive epiboly ?*

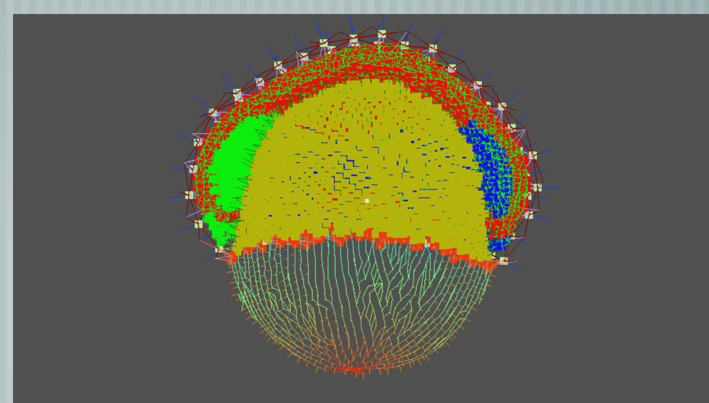




Macroscopic landmarks characterizing epiboly

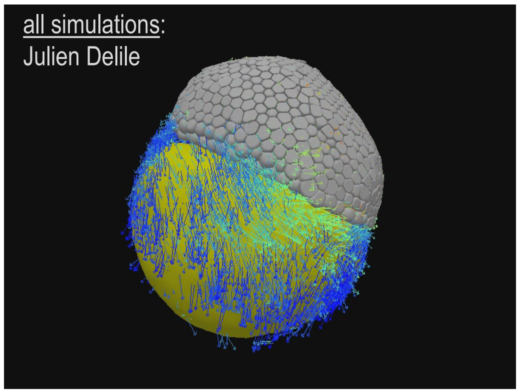
6. Cell behaviors during gastrulation

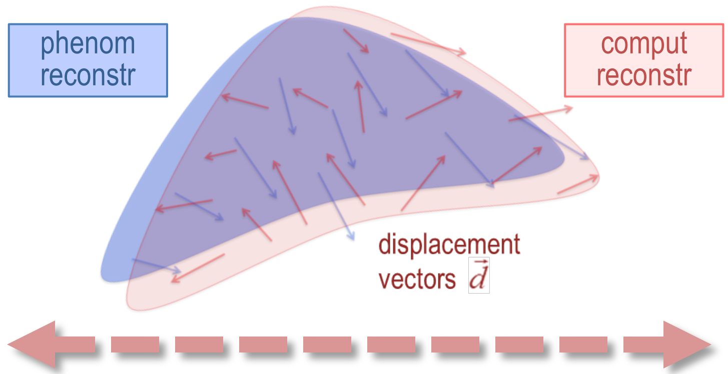
→ *How is cell division orientation and the polarization field during convergence-extension?*

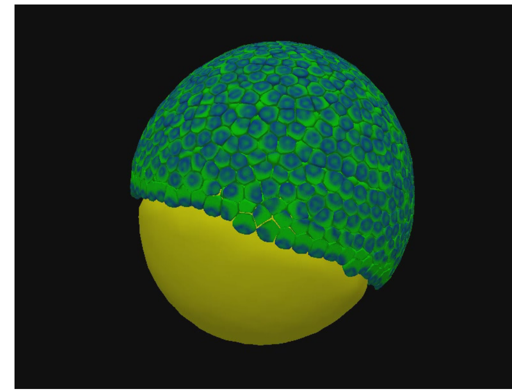


➢ Validation and optimization: fitness and parameter search

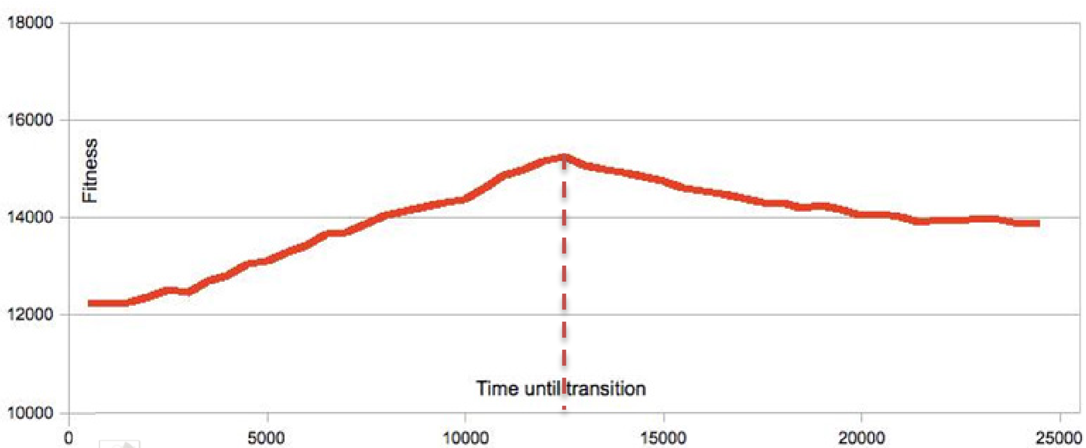
- find the most "realist" simulation, i.e. closest to the phenomenal reconstruction

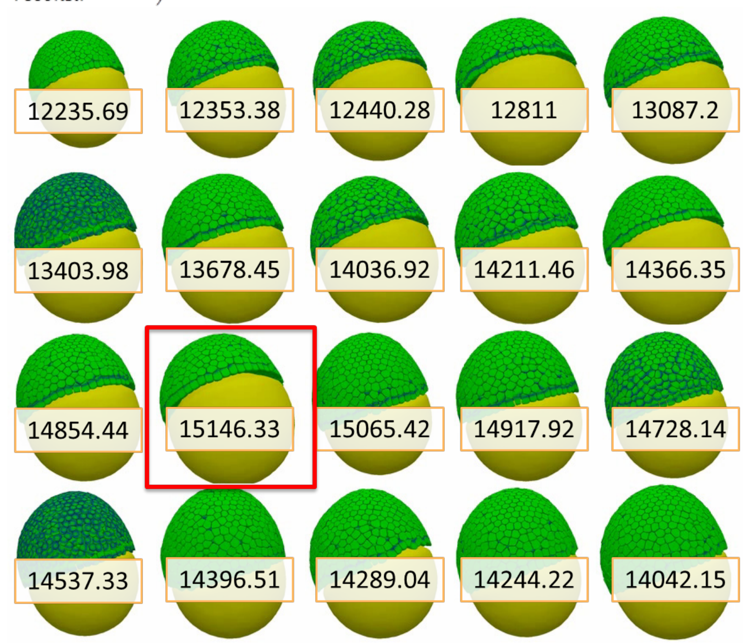


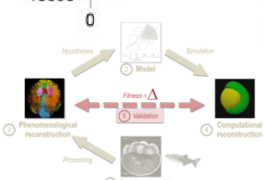




$$Fitness = \sum_{time\,t} \sum_{cells\,i} \max\left(0, \vec{d}_{simul}(i,t) \cdot \vec{d}_{reconstr}(i,t)\right)$$

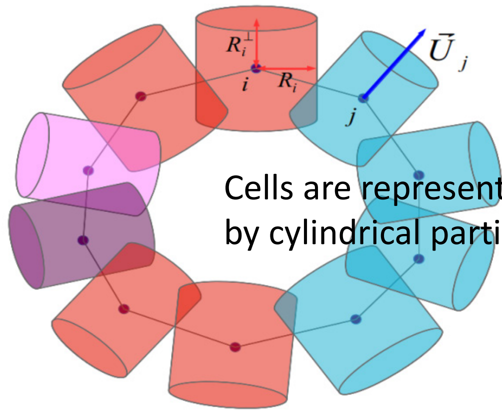




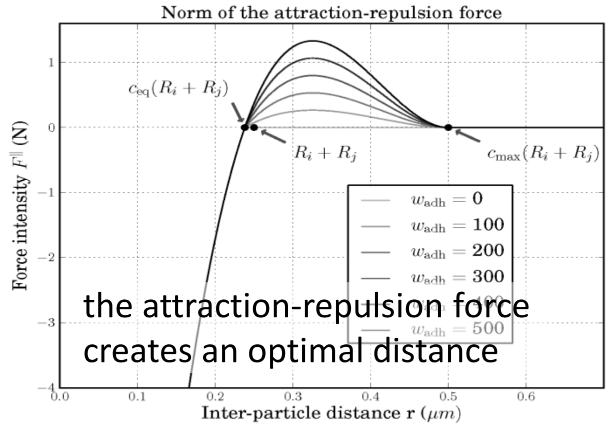


ex. of parameter: time_until_transition_to_epiboly

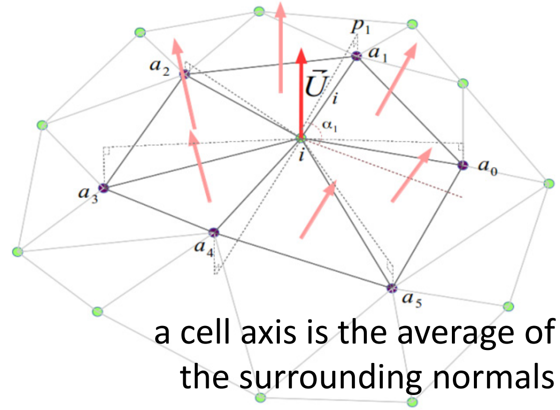
MECAGEN → Case Study in the Sea Urchin



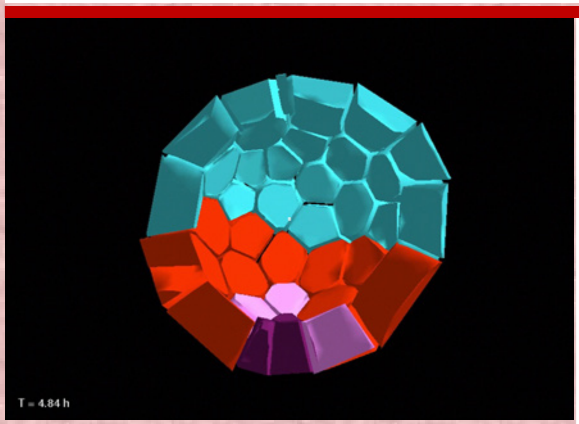
Cells are represented by cylindrical particles

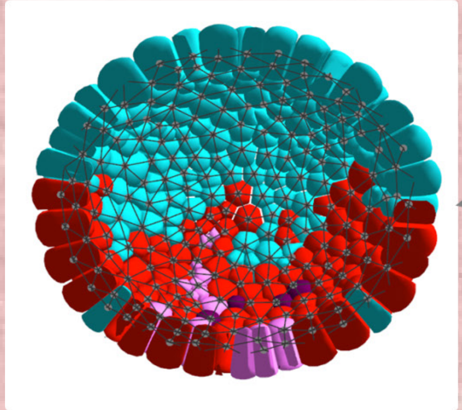


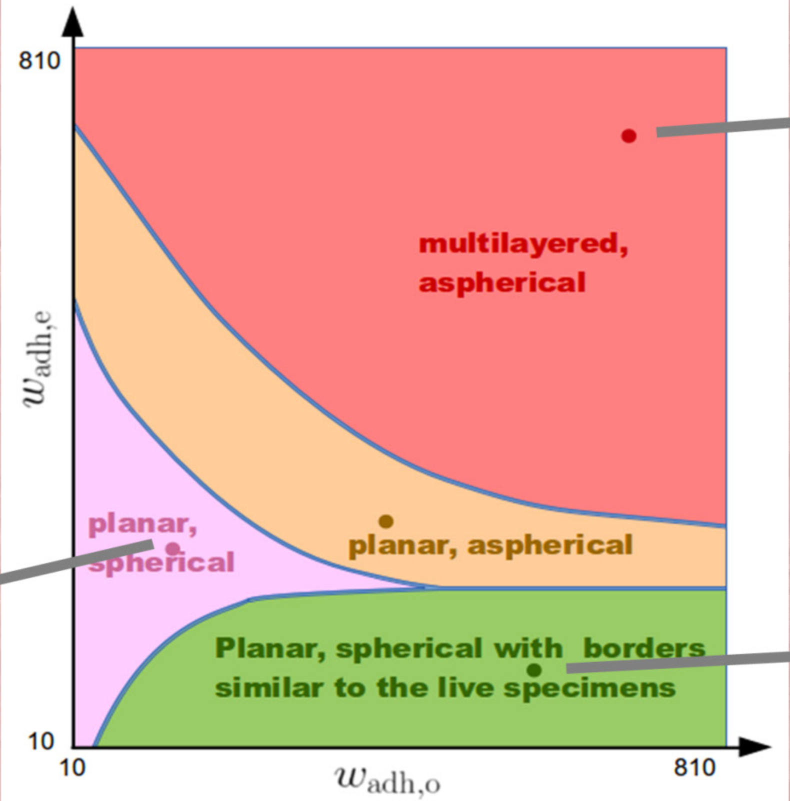
the attraction-repulsion force creates an optimal distance

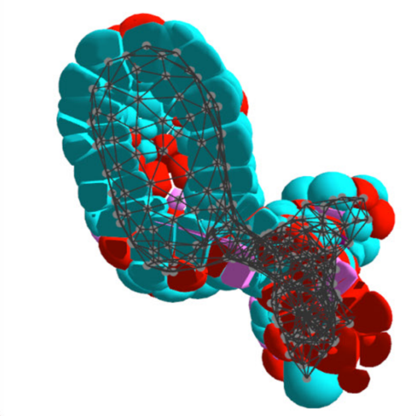


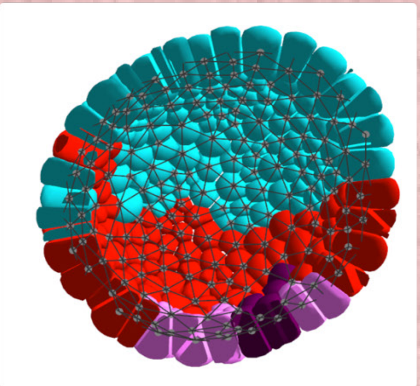
a cell axis is the average of the surrounding normals



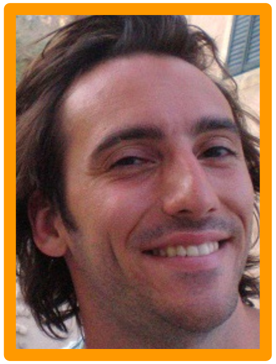








MecaGen Acknowledgments



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MECAGEN

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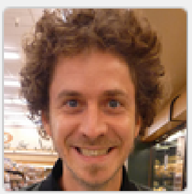
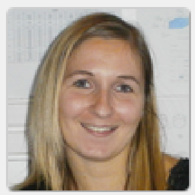
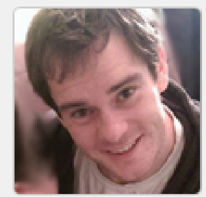
BioEmergences



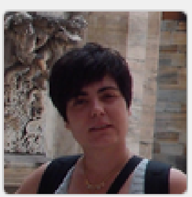
Emmanuel Faure
Research Engineer
Arrived in 2005



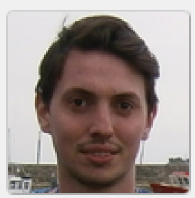
Adeline Boyreau
Engineer/Ingénieure d'Étude
Arrived in 2012



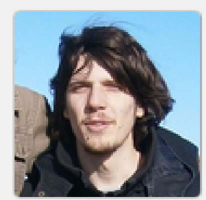
Mathieu Bouyrie
PhD Student/Doctorant
Arrived in 2012



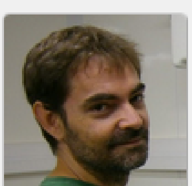
Barbara Rizzi
CNRS TEFOR
Arrived in 2010



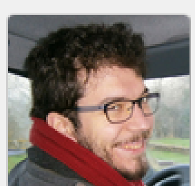
Julien Dumont
Engineer/Ingénieur d'Étude
Arrived in 2013



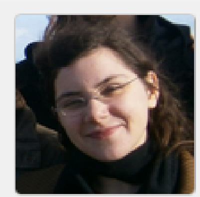
Dimitri Fabrèges
PhD Student/Doctorant
Arrived in November 2010



Thierry Savy
Research Engineer
Arrived in 2006



Paul Villoutreix
PhD Student/Doctorant
Arrived in 2011

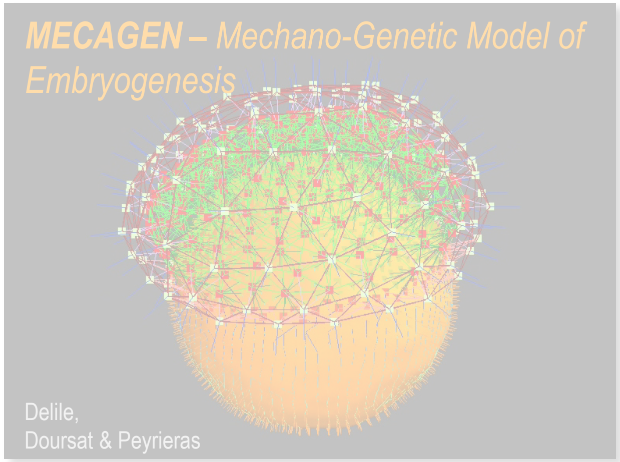


Adeline Rausch
PhD Student/Doctorante
Arrived in April 2013

Systems that are self-organized *and* architectured

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

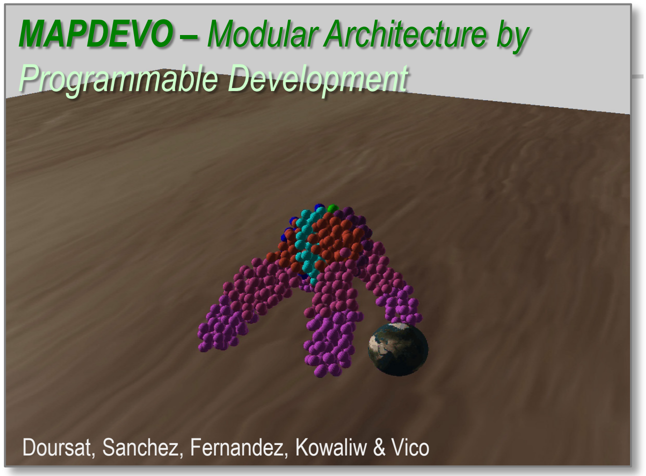
illustration of Morphogenetic Engineering ideas

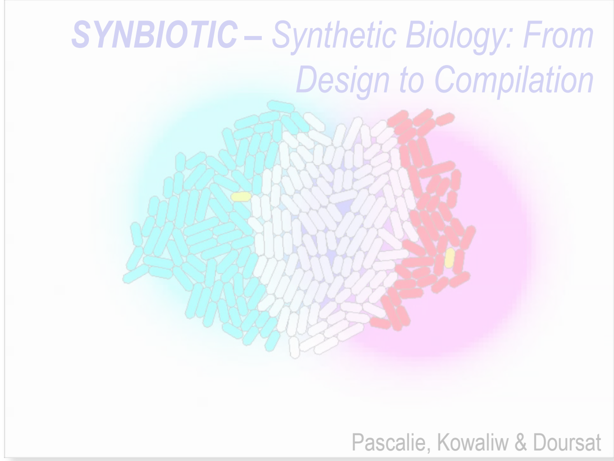


BIOMODELING
(LIFE)

mutually beneficial transfers between biology & CS

BIO-INSPIRED
ENGINEERING (ALIFE)

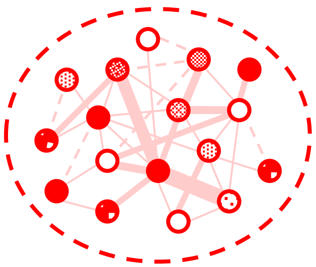




BIOENGINEERING
(HYBRID LIFE)

The challenges of complex systems (CS) research

Transfers
- among systems

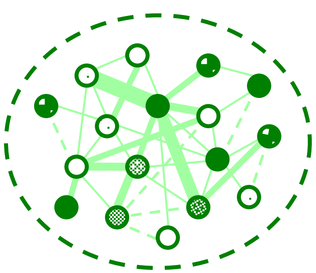


CS science: *understanding & modeling "natural" CS*

(spontaneously emergent, including human-made)

Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

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



CS (ICT) engineering: *designing a new generation of "artificial/hybrid" CS (harnessed & tamed, including nature)*

Bio-Inspired Computation

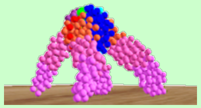
➢ Exporting natural CS to artificial disciplines, such as ICT

ex: brain	specific natural or societal complex system	*ex: genes & evolution*
biological neural models	model simulating this system	*laws of genetics*
binary neuron, linear synapse	generic principles and mechanisms (schematization, caricature)	*genetic program, binary code, mutation*
artificial neural networks (ANNs) applied to machine learning & classification	new computational discipline exploiting these principles to solve ICT problems	*genetic algorithms (GAs), evolutionary computation for search & optimization*

Bio-Inspired Computation

➢ Exporting natural CS to artificial disciplines, such as ICT

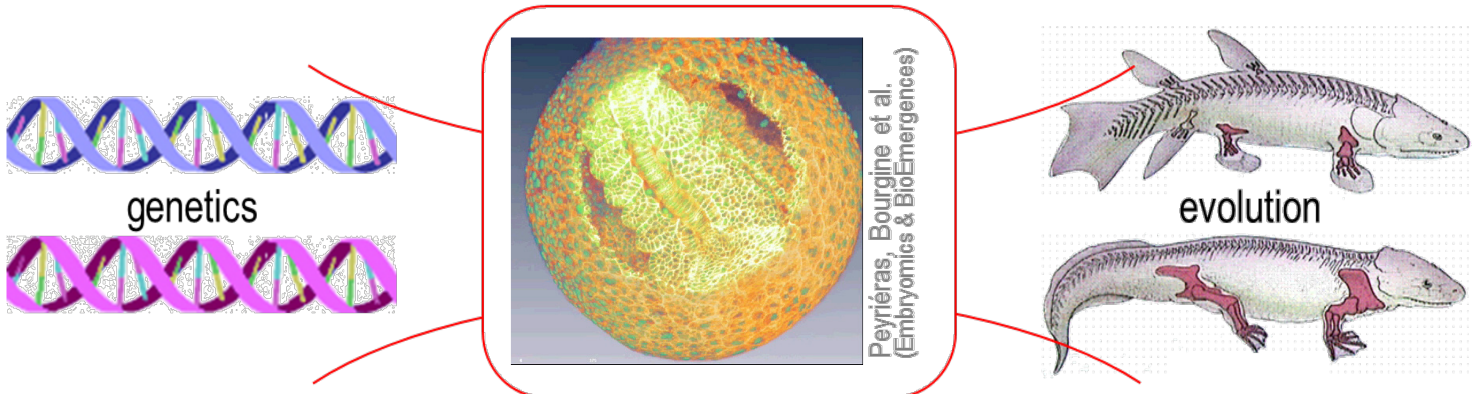
ex: ant colonies	specific natural or societal complex system	ex: bird flocks
⬇	⬇	⬇
trail formation, swarming	model simulating this system	*3-D collective flight simulation*
⬇	⬇	⬇
agents that move, deposit & follow "pheromone"	generic principles and mechanisms (schematization, caricature)	*"boid", separation, alignment, cohesion*
⬇	⬇	⬇
ant colony optimization (ACO) applied to graph theoretic & networking problems	new computational discipline exploiting these principles to solve ICT problems	*particle swarm optimization (PSO) "flying over" solutions in high-D spaces*

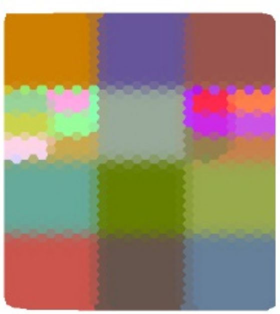


Embryomorphic Engineering

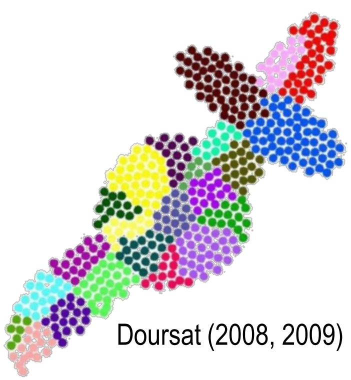
- Exploring the avenue from ***biological*** to ***artificial development***
  - ✓ designing multi-agent models for decentralized systems engineering

Embryogenesis

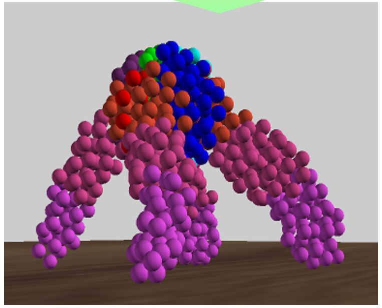




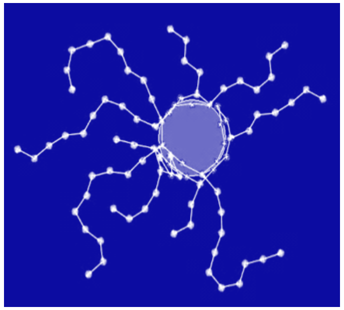
Doursat (2006)



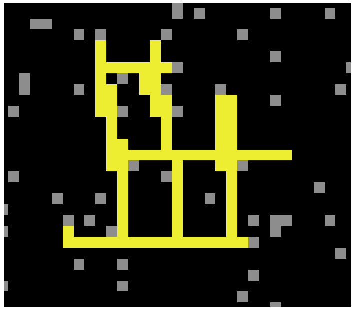
Doursat (2008, 2009)



Doursat, Sanchez, Fernandez Kowaliw & Vico (2012)



Doursat & Ulieru (2009)



Doursat, Fourquet, Dordea & Kowaliw (2012)

Embryomorphic Engineering

Architectures Without Architects

- From "statistical" to "morphological" complex systems

more intrinsic sophisticated architecture, less randomness

Natural Systems

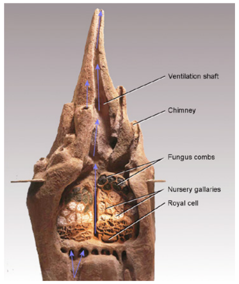
inert matter: pattern formation

social insects: collective constructions

ant trail

network of ant trails

ant nest



termite mound

cells: biological morphogenesis

cells

termites

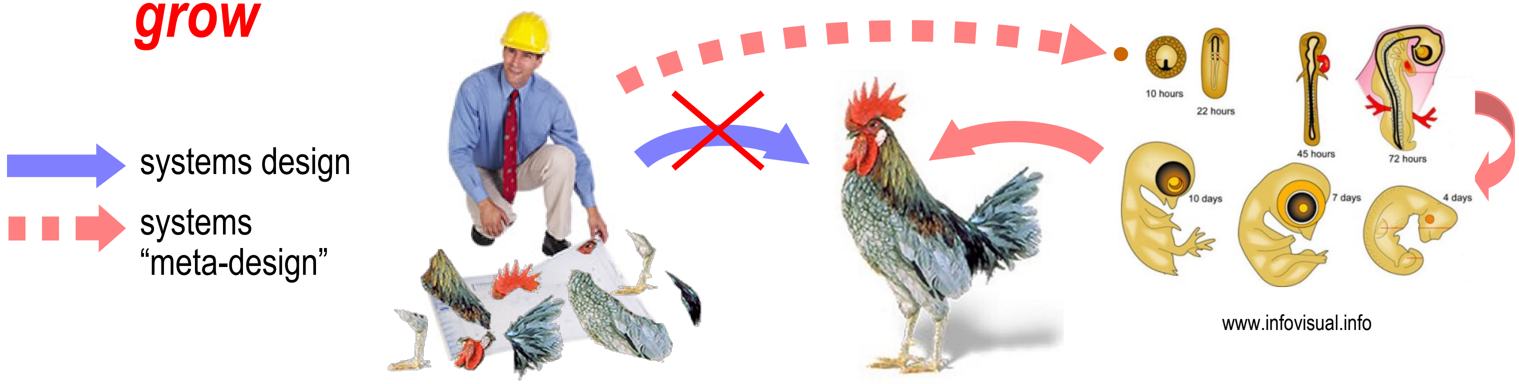
ants

grains of sand + warm air

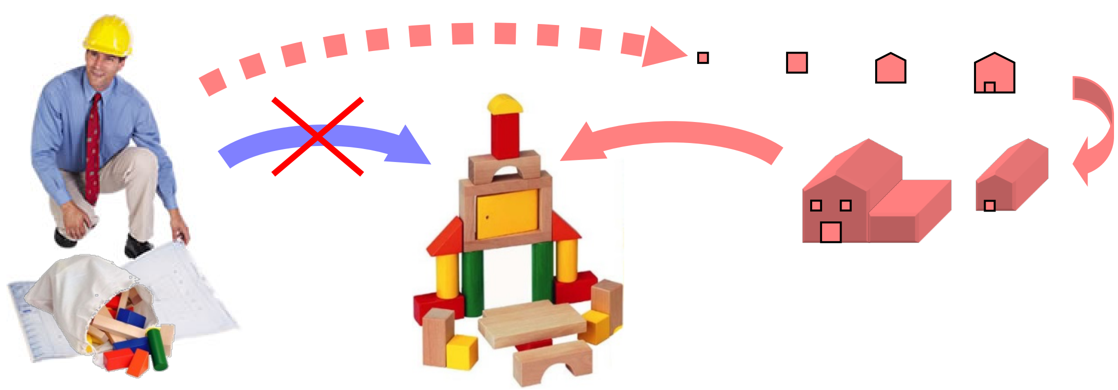
Designing Complexity

➢ 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

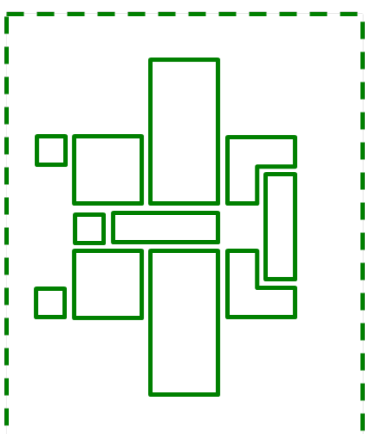


Morphogenetic Engineering

Artificial Systems

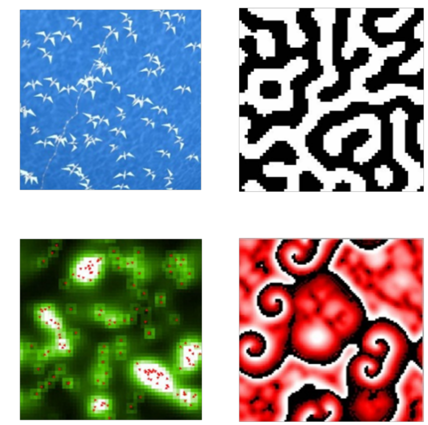
(d)

Architectured Systems
Showing *no* Self-Organization

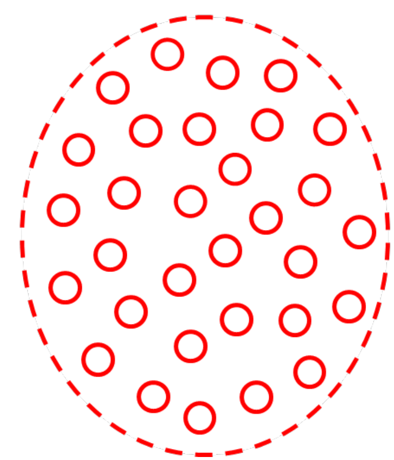


Natural Systems

(a)

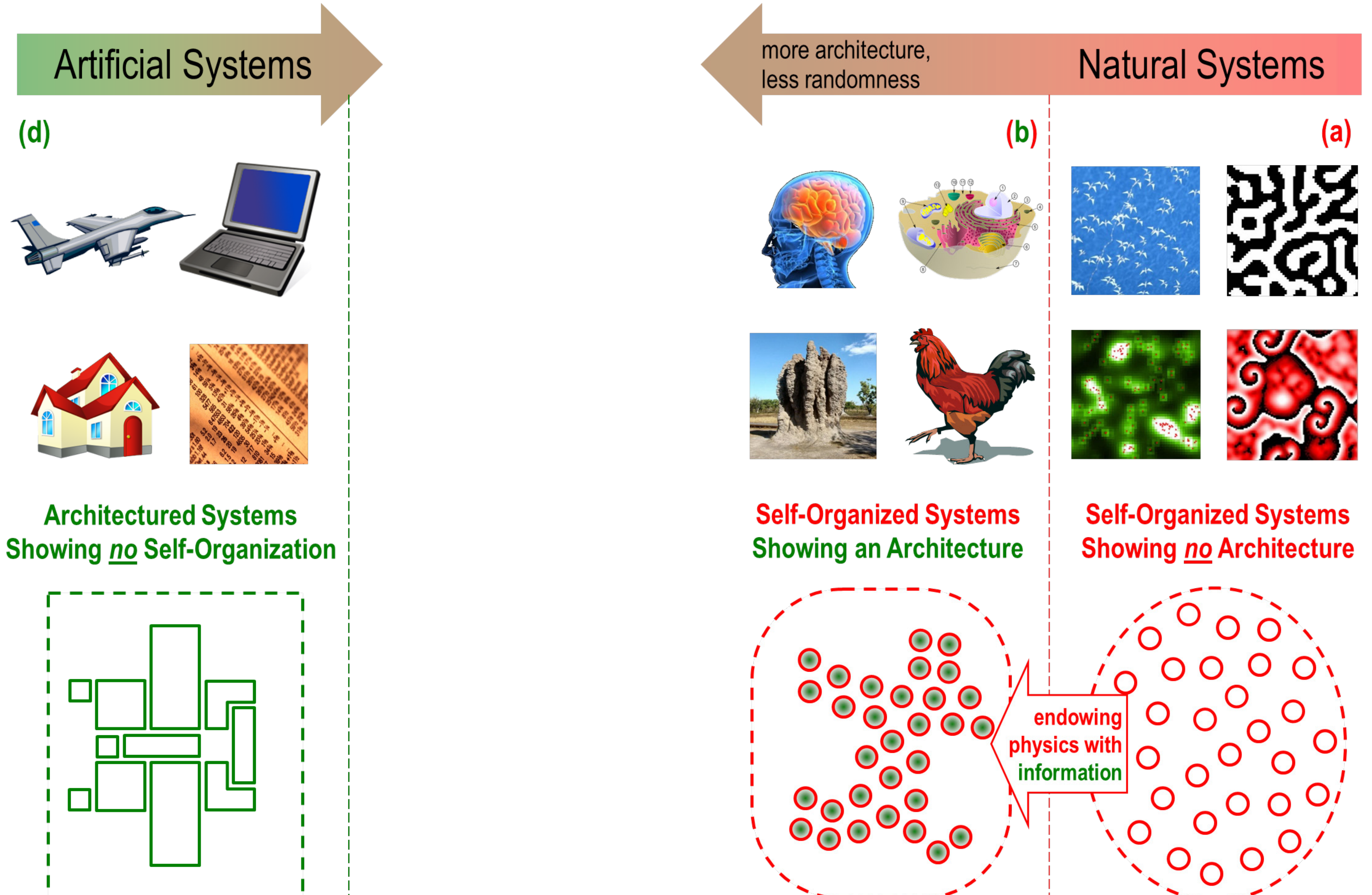


Self-Organized Systems
Showing *no* Architecture



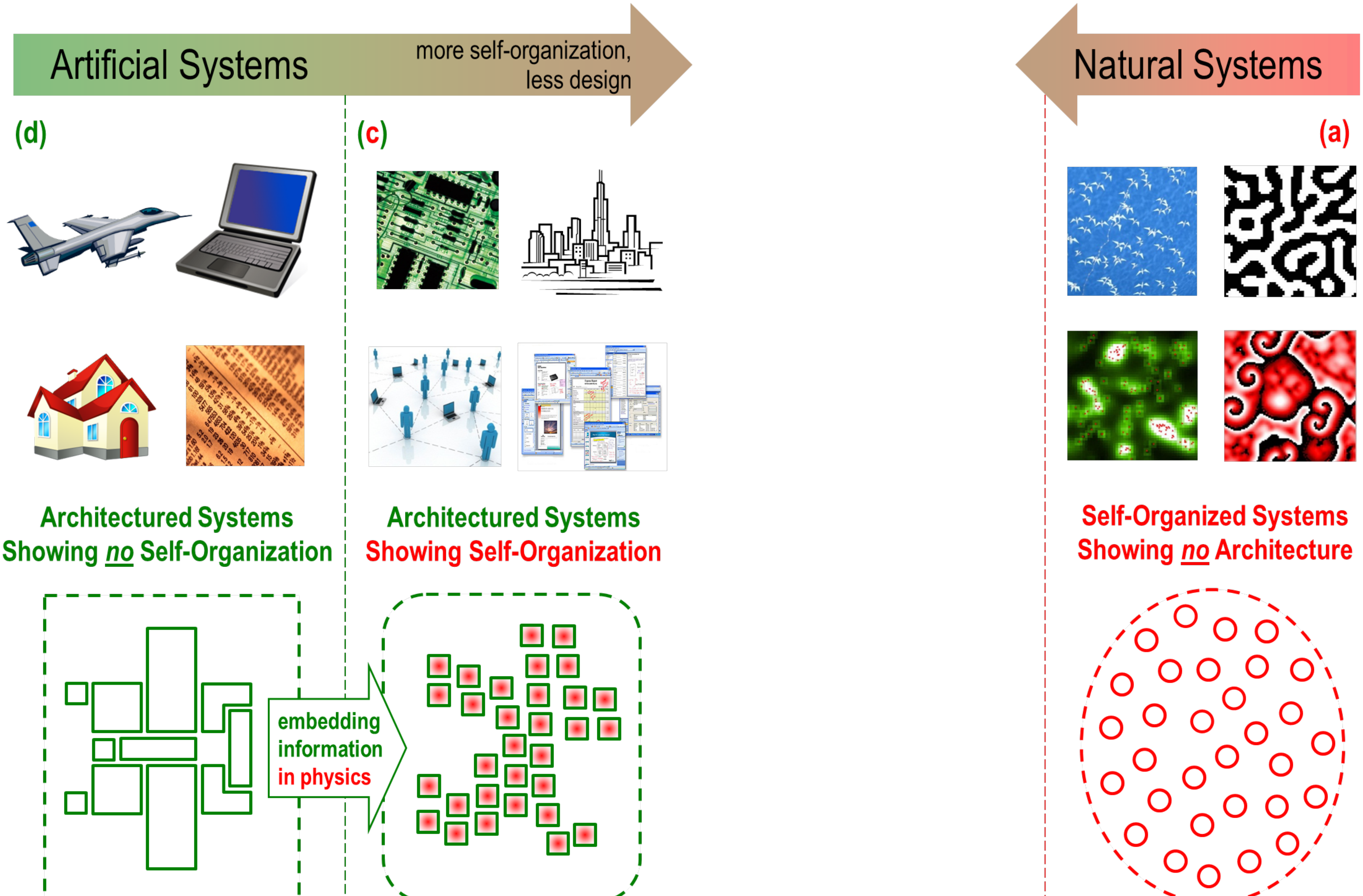
Doursat, Sayama & Michel (2012, 2013)

Morphogenetic Engineering



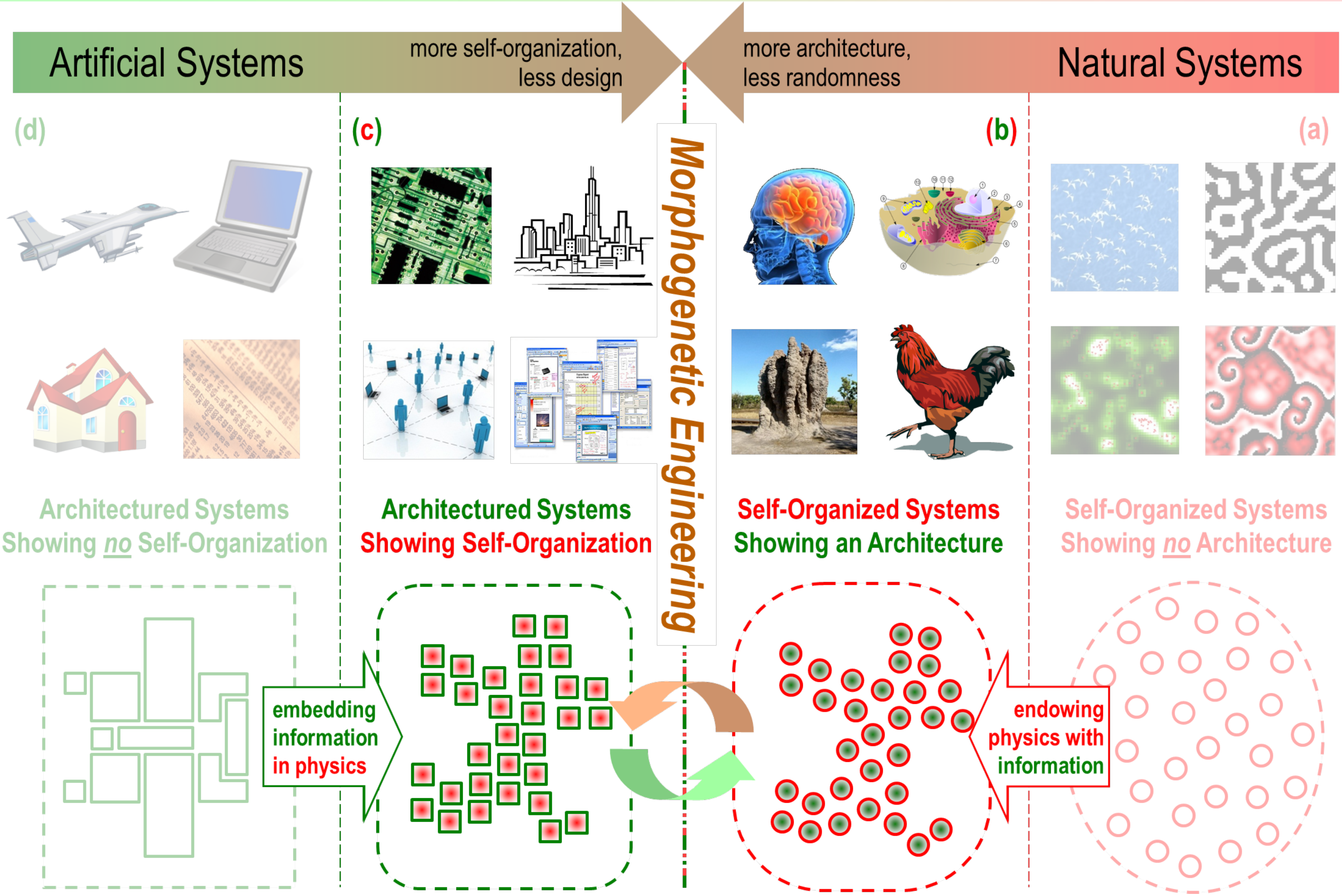
Doursat, Sayama & Michel (2012, 2013)

Morphogenetic Engineering



Doursat, Sayama & Michel (2012, 2013)

⇒ Morphogenetic Engineering



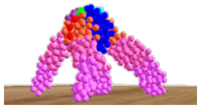
Doursat, Sayama & Michel (2012, 2013)

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

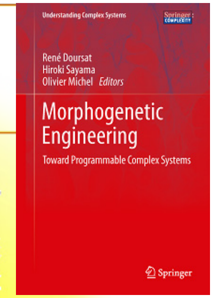
- **ME brings a new focus in complex systems engineering**
  - ✓ exploring the artificial design and implementation of **decentralized systems capable of developing elaborate, heterogeneous morphologies** without central planning or external lead

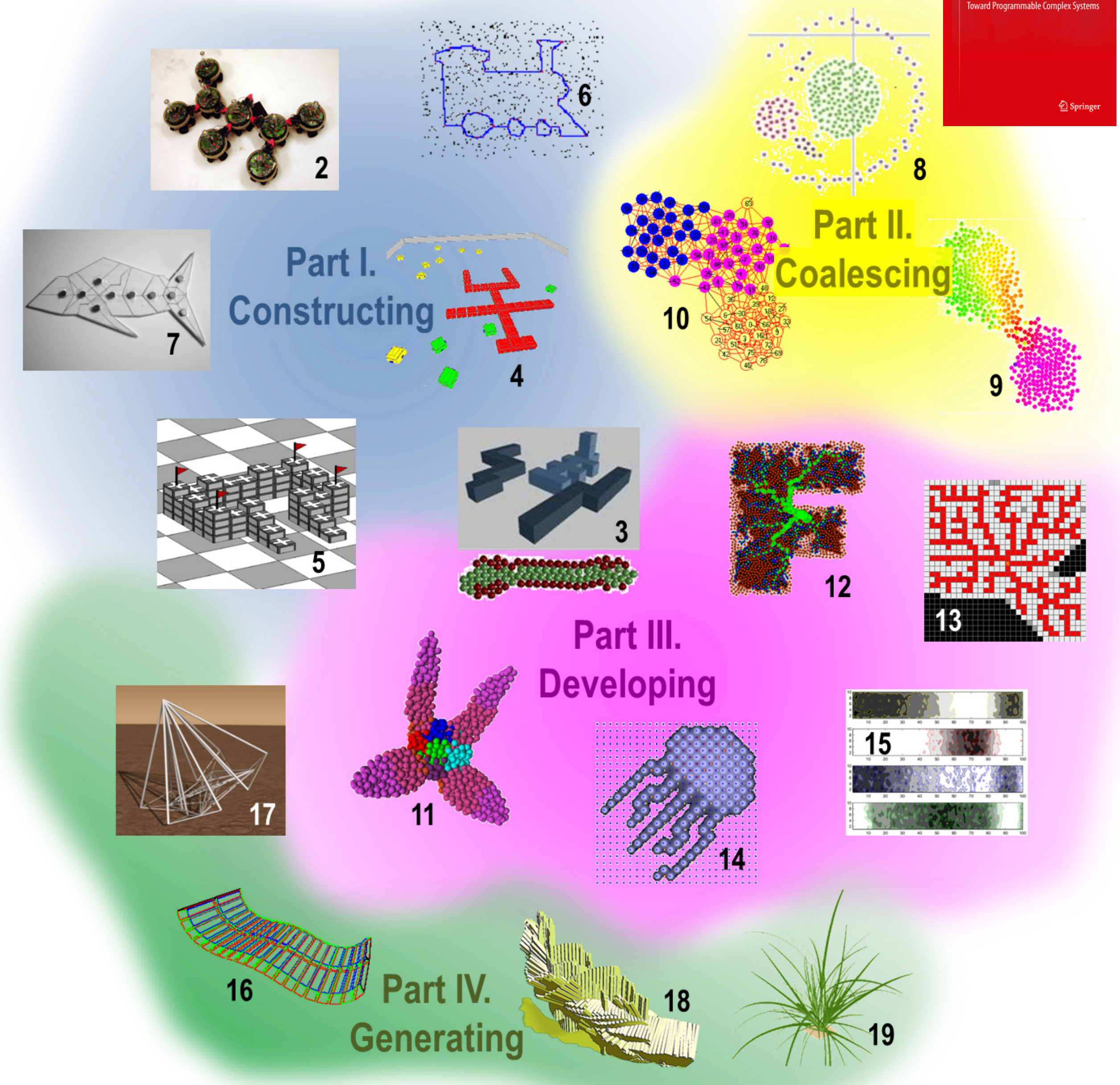
- **Related emerging ICT disciplines and application domains**
  - ✓ *amorphous/spatial computing* (MIT, Fr.)
  - ✓ *organic computing* (DFG, Germany)
  - ✓ *pervasive adaptation* (FET, EU)
  - ✓ *ubiquitous computing* (PARC)
  - ✓ *programmable matter* (CMU)
  - ✓ swarm robotics, modular/reconfigurable 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

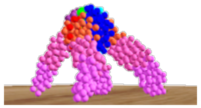


Morphogenetic Engineering:
Toward Programmable Complex Systems

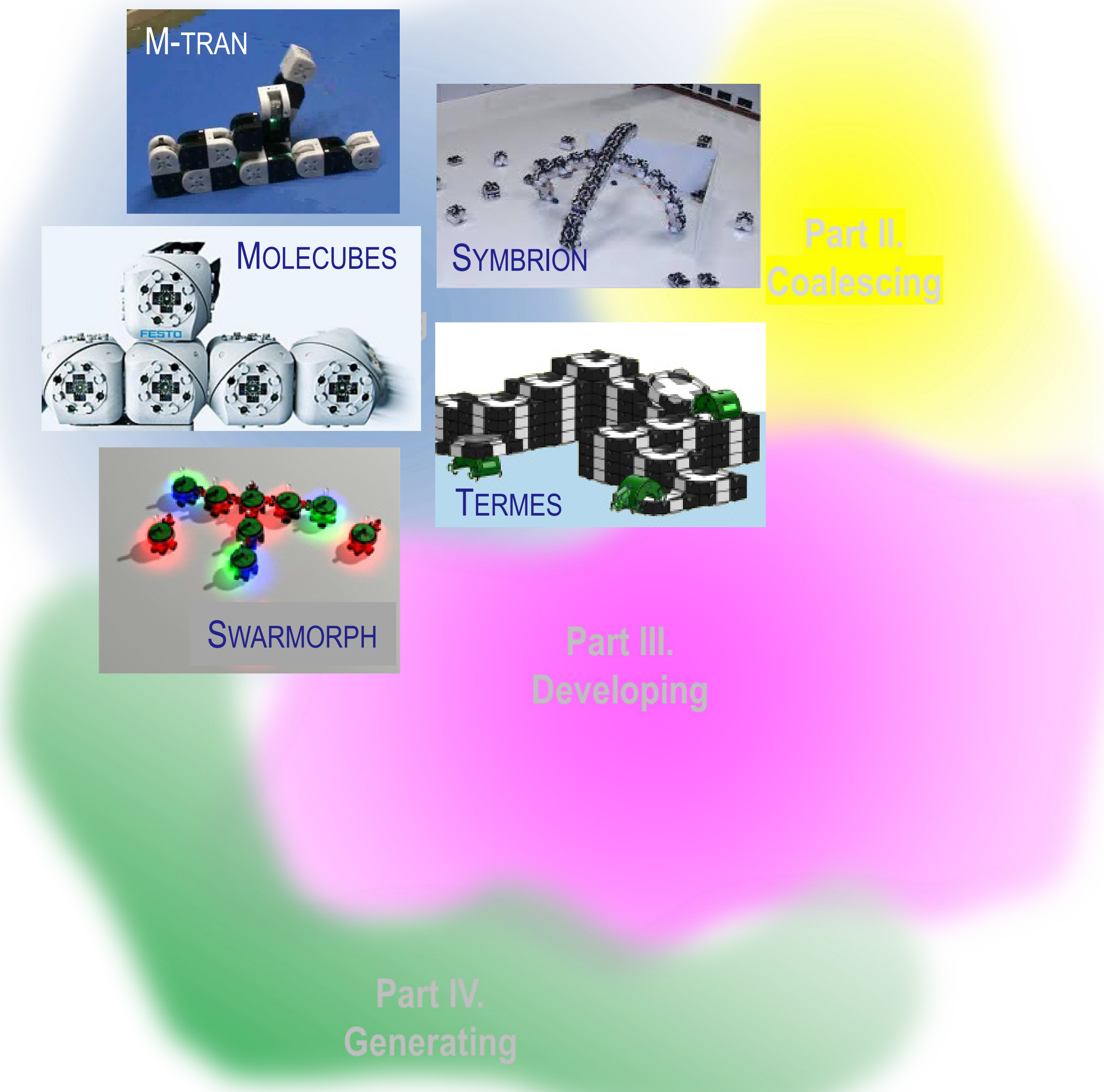




Doursat, Sayama & Michel, eds. (Springer, 2012)



Morphogenetic Engineering



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

Broader Review of ME

Category I. Constructing

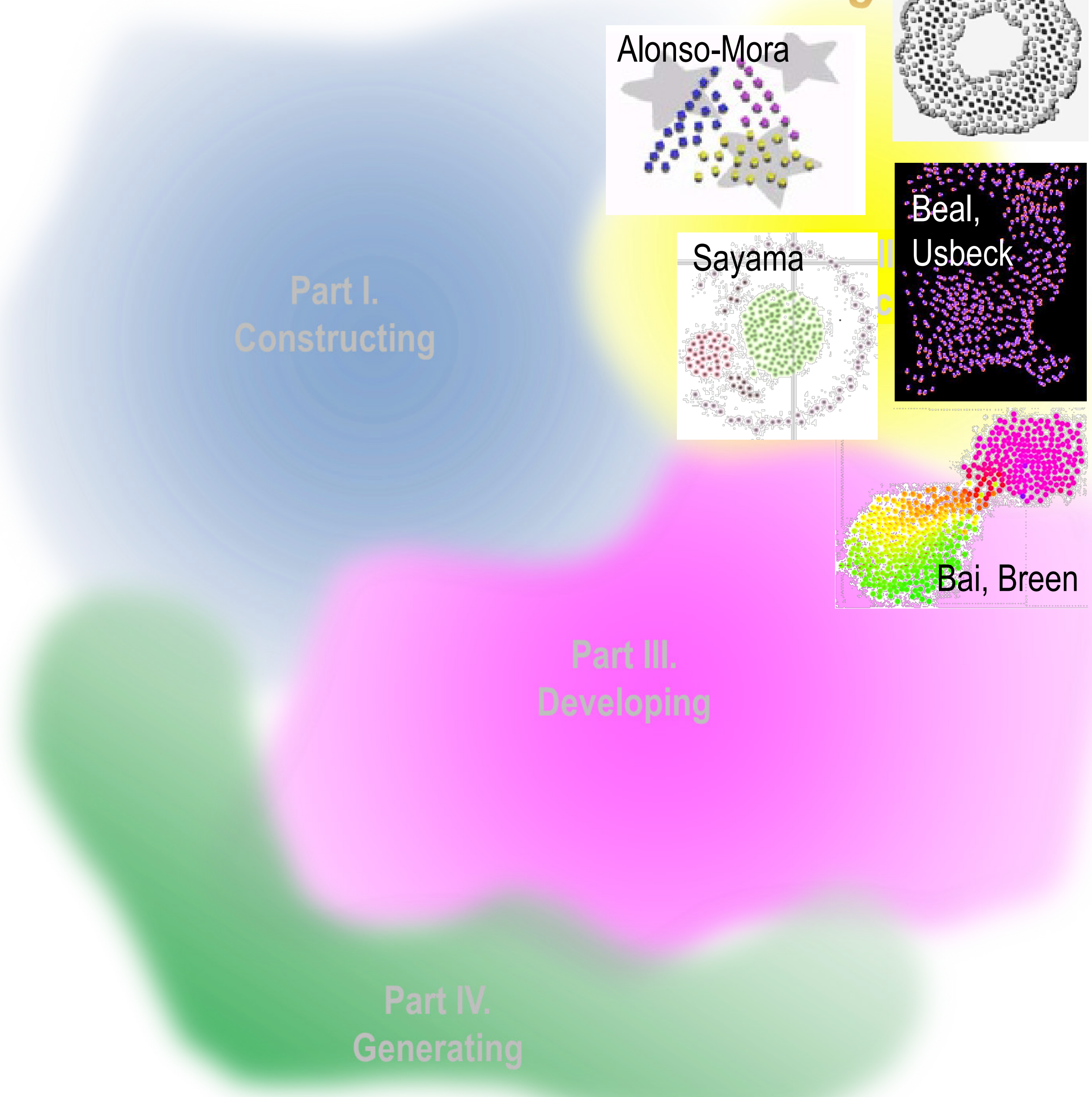
(or "Assembling", "Fitting")

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)

Morphogenetic Engineering



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

Broader Review of ME

Category II. Coalescing

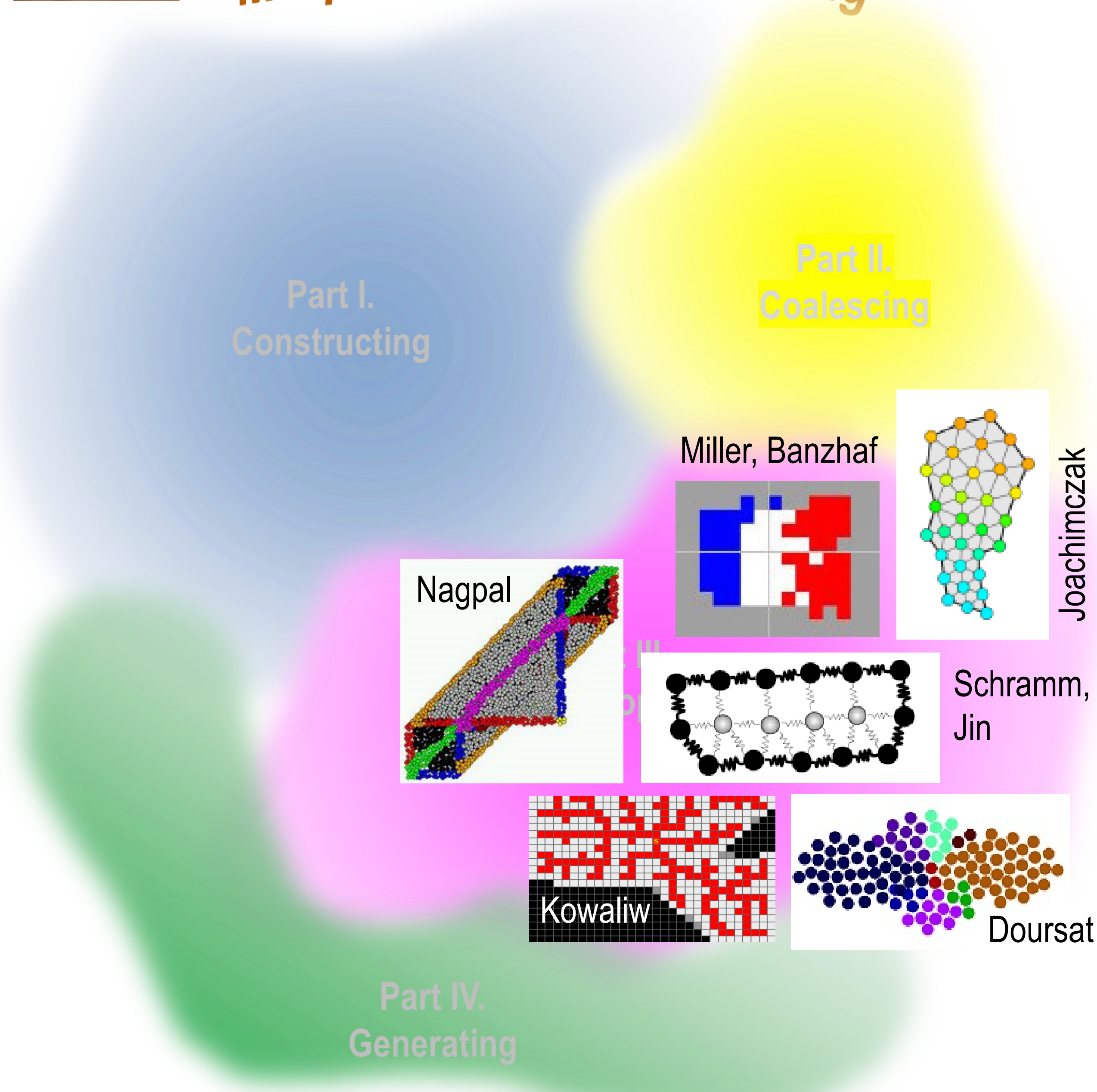
(or “Synchronizing”, “Swarming”)

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)

Morphogenetic Engineering



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

Broader Review of ME

Category III. Developing

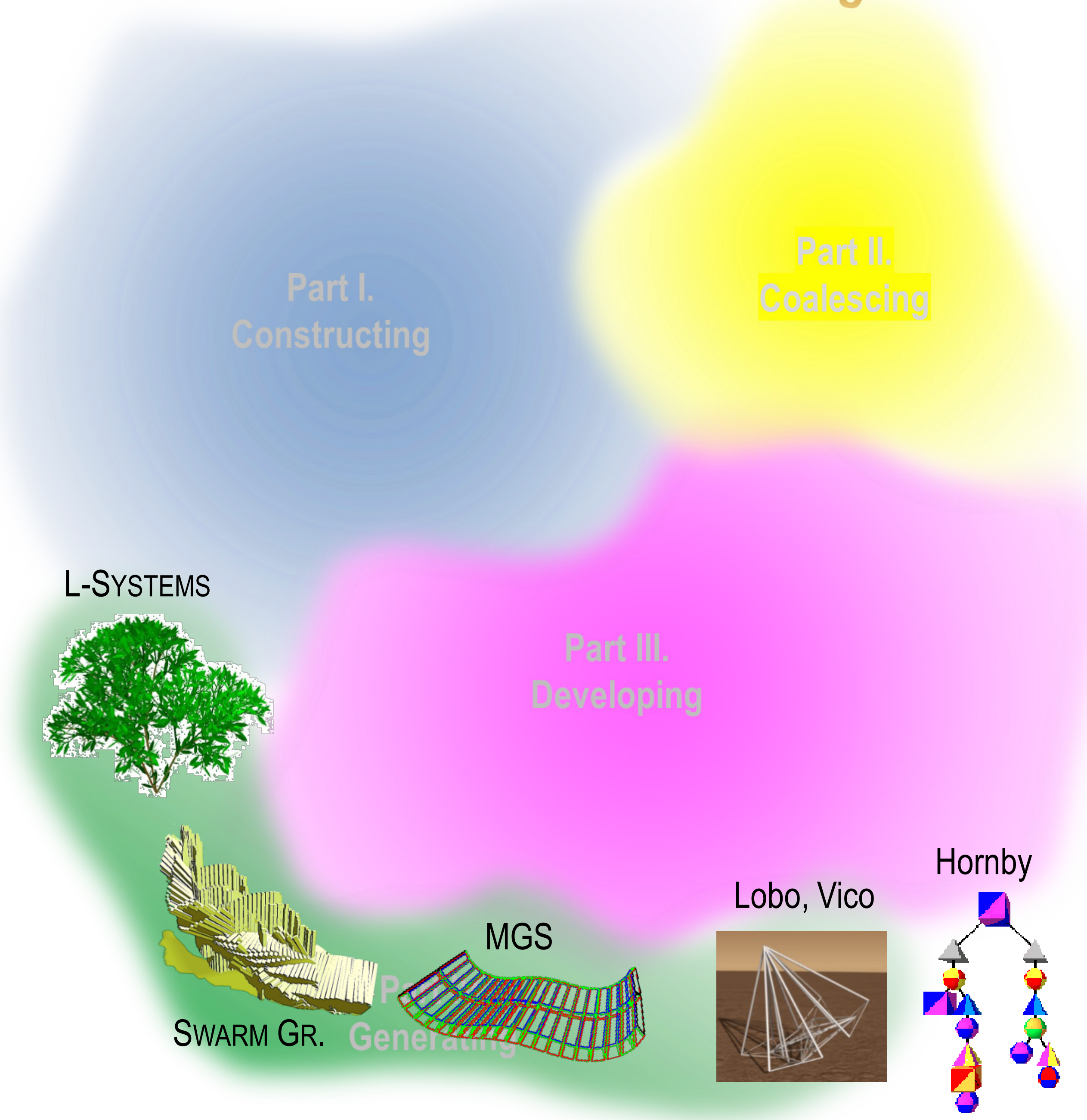
(or “Growing”, “Aggregating”)

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)

Morphogenetic Engineering



Broader Review of ME

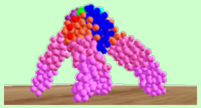
Category IV. Generating

(or "Rewriting", "Inserting")

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

... based on:

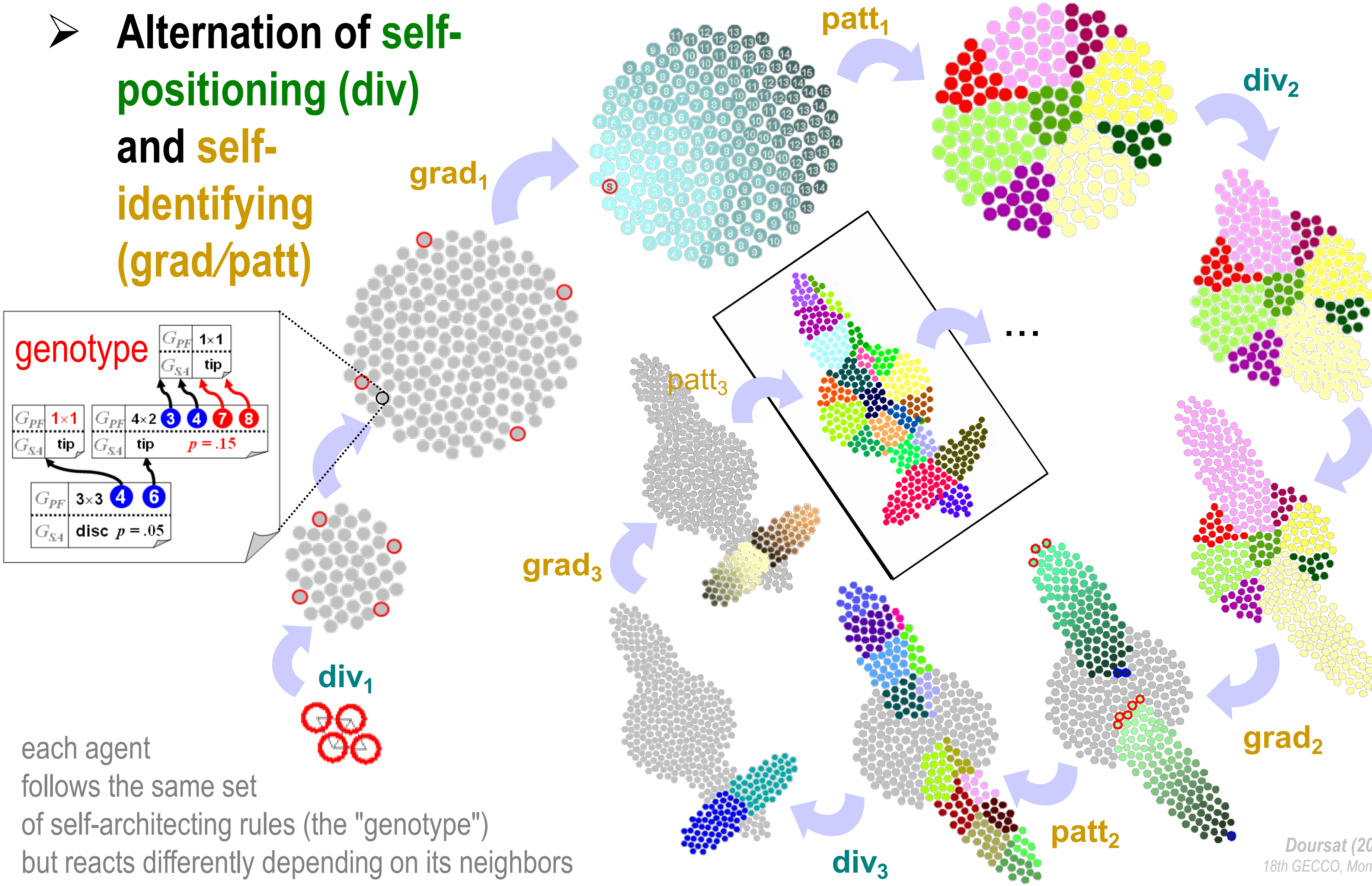
- **Biologically inspired grammars**
  - ex: Lindemayer, Prusinkiewicz (L-Systems)
  - ex: Spicher, Michel, Giavitto (MGS)
- **Graph and swarm grammars**
  - ex: Sayama (GNA)
  - ex: von Mammen
- **Evolutionary grammars**
  - ex: Hornby, Pollack
  - ex: Lobo, Vico



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)

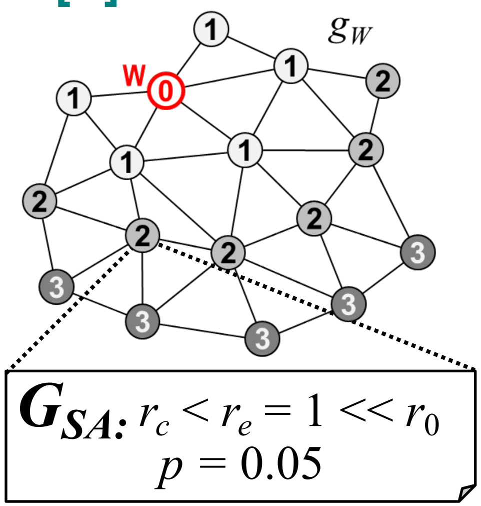


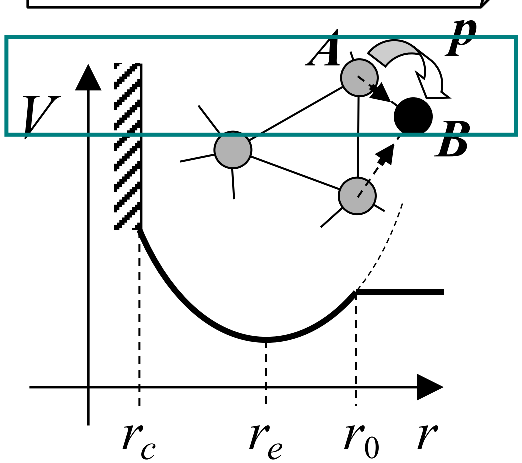
each agent
follows the same set
of self-architecting rules (the "genotype")
but reacts differently depending on its neighbors

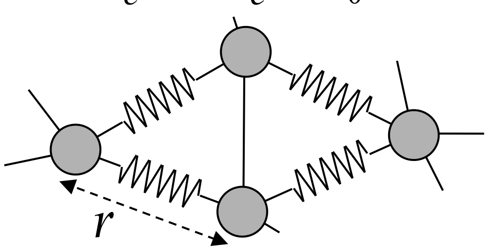
Doursat (2009)
18th GECCO, Montreal

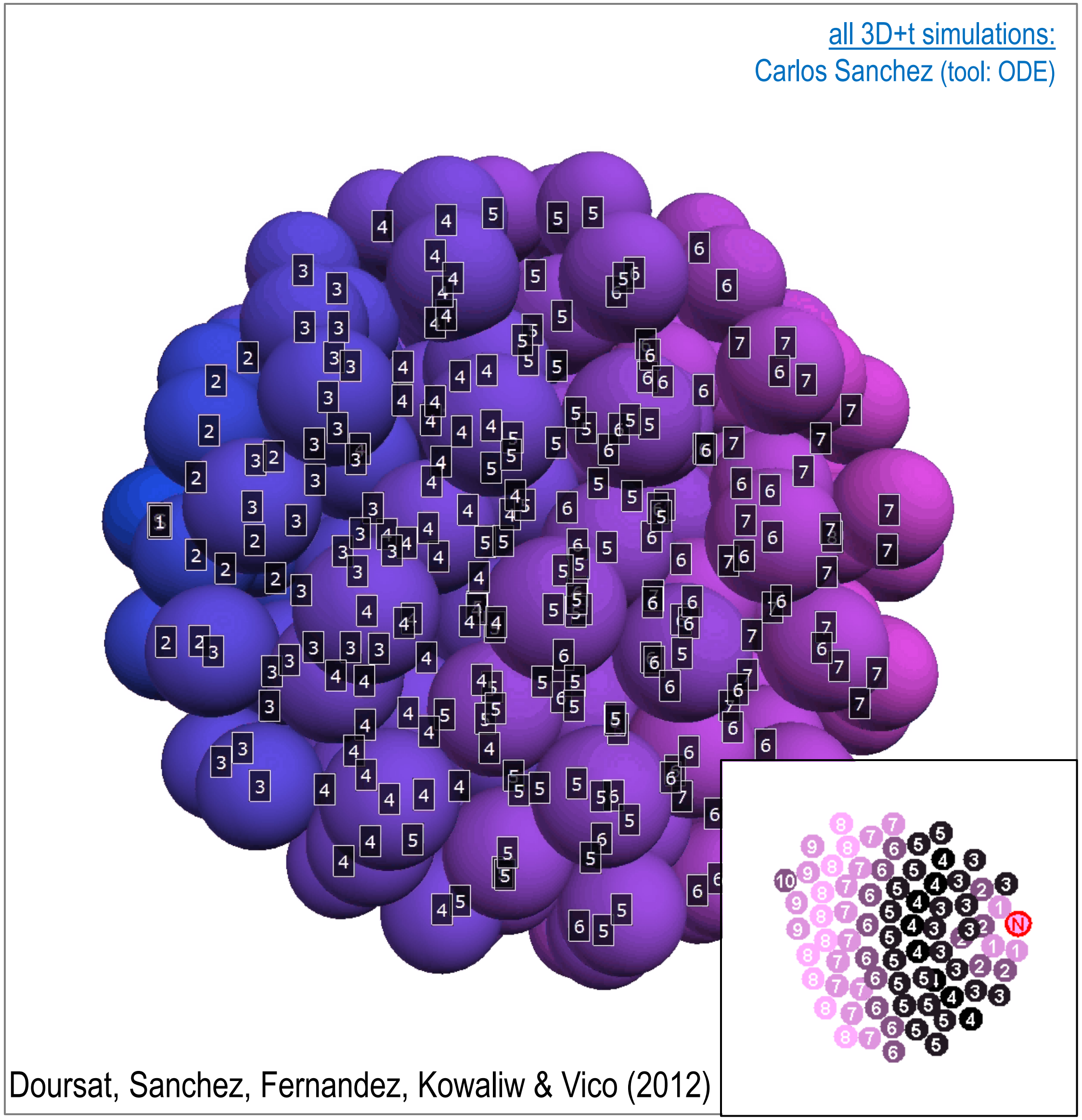
MAPDEVO – Modular Architecture by Programmable Development

[A] "mechanics"

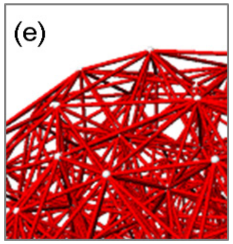


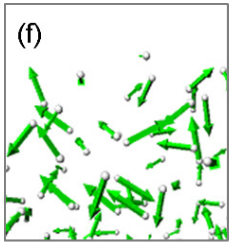


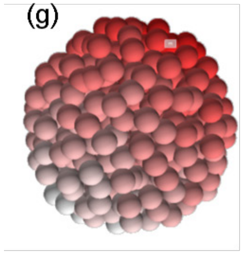


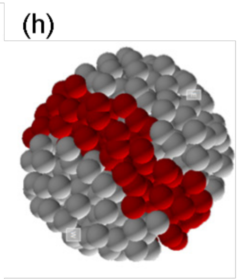


Doursat, Sanchez, Fernandez, Kowaliw & Vico (2012)

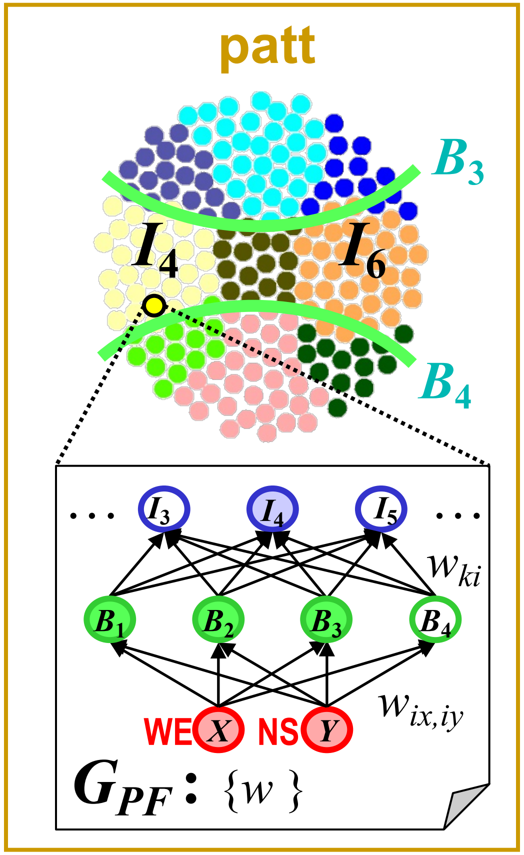


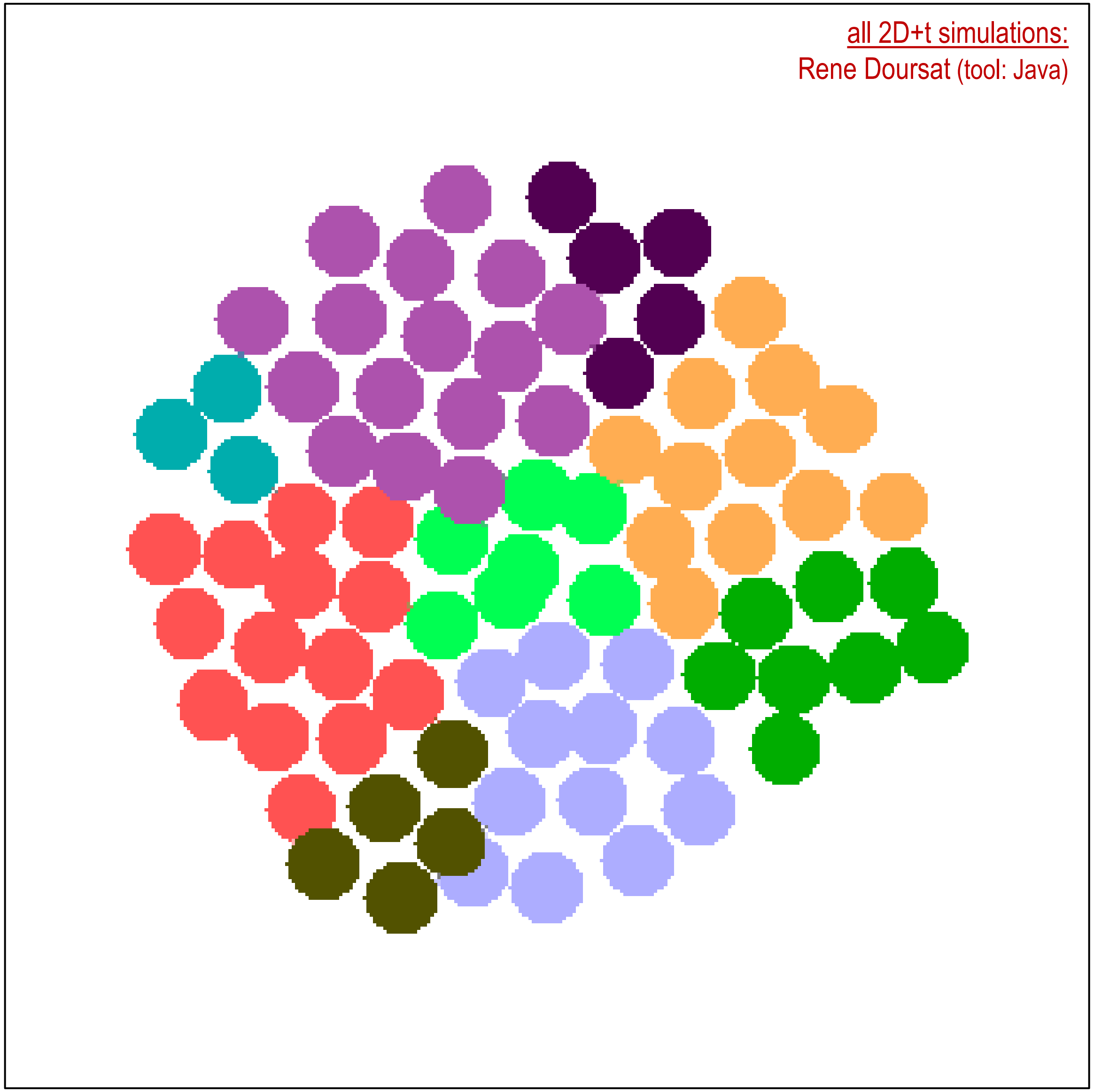






$$m\frac{d^2\vec{r}}{dt^2} = -\frac{dV}{dr}\vec{u} - \lambda\frac{d\vec{r}}{dt}, \quad \Rightarrow \quad \Delta\vec{r} = -k'\Delta t\,(r - r_e)\,\vec{u}$$



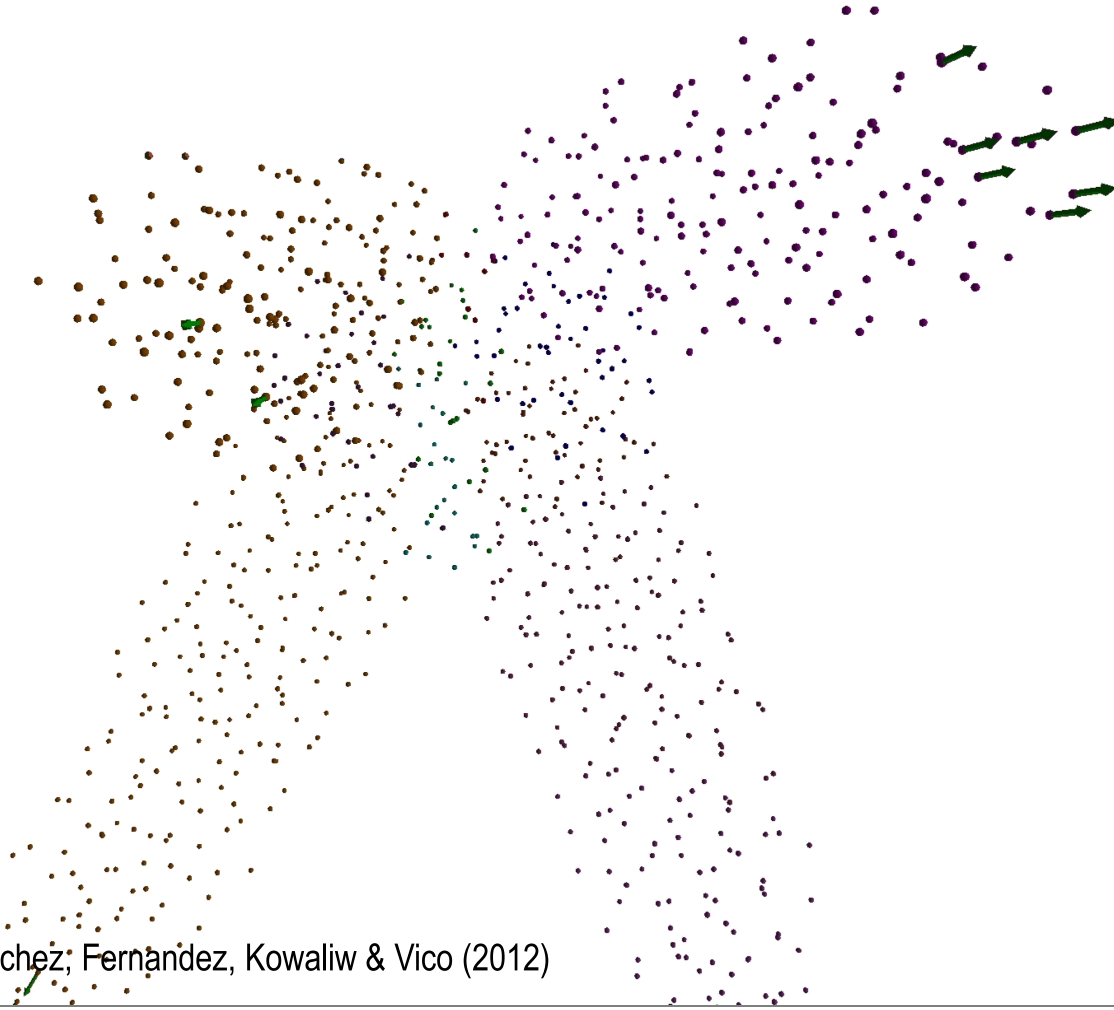


$$B_i = \sigma(L_i(X, Y)) = \sigma(w_{ix}\, X + w_{iy}\, Y - \theta_i)$$

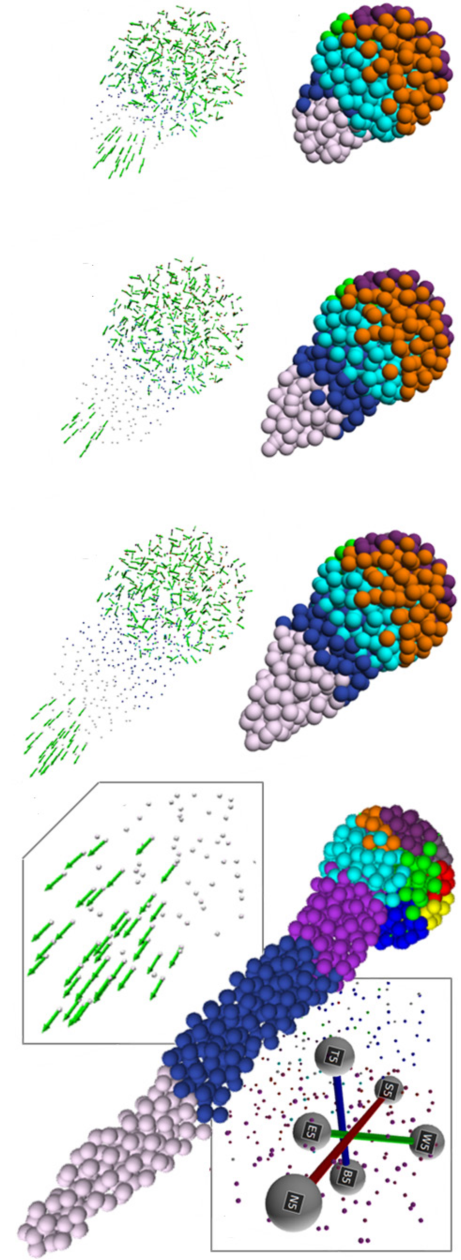
$$I_k = \prod_i |w'_{ki}|(w'_{ki}B_i + (1-w'_{ki})/2)$$

➢ Limbs' development

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

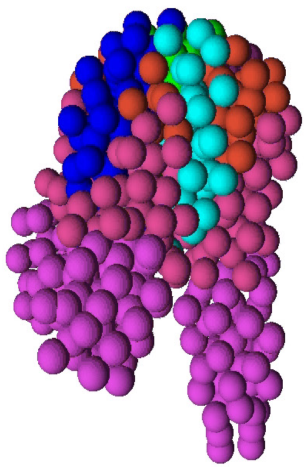


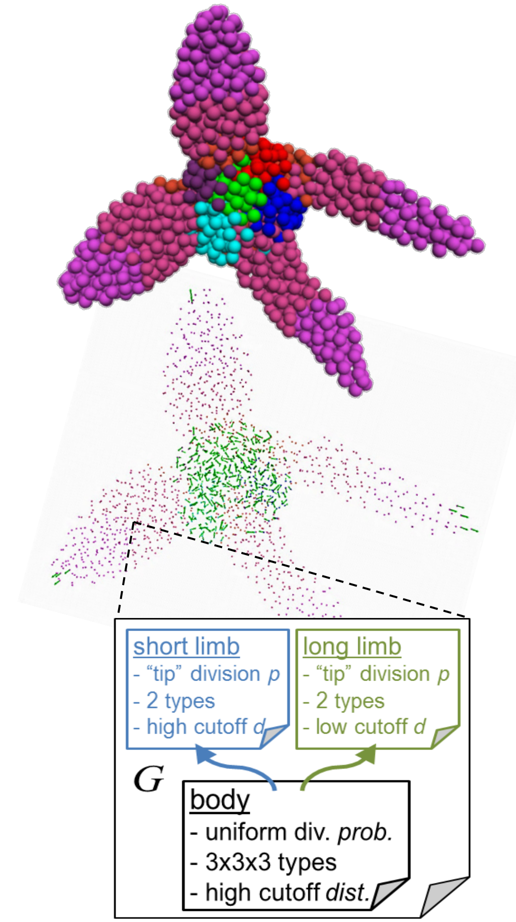
Doursat, Sanchez, Fernandez, Kowaliw & Vico (2012)

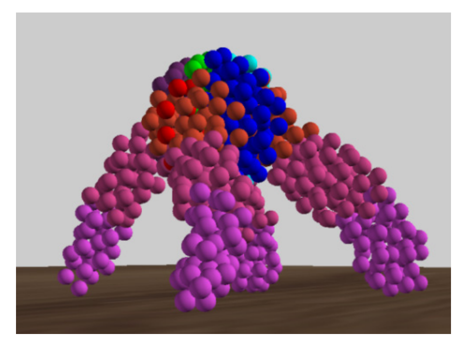


➢ 3D Development

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



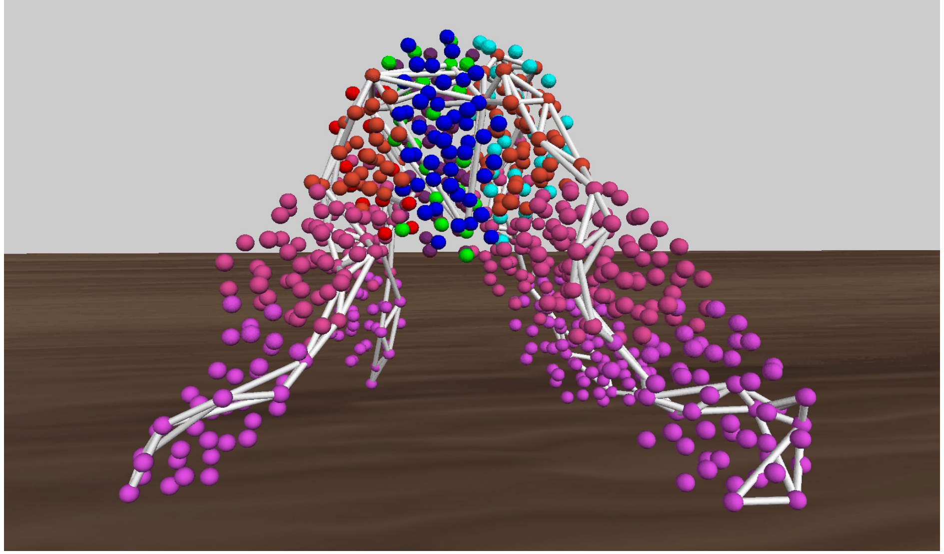


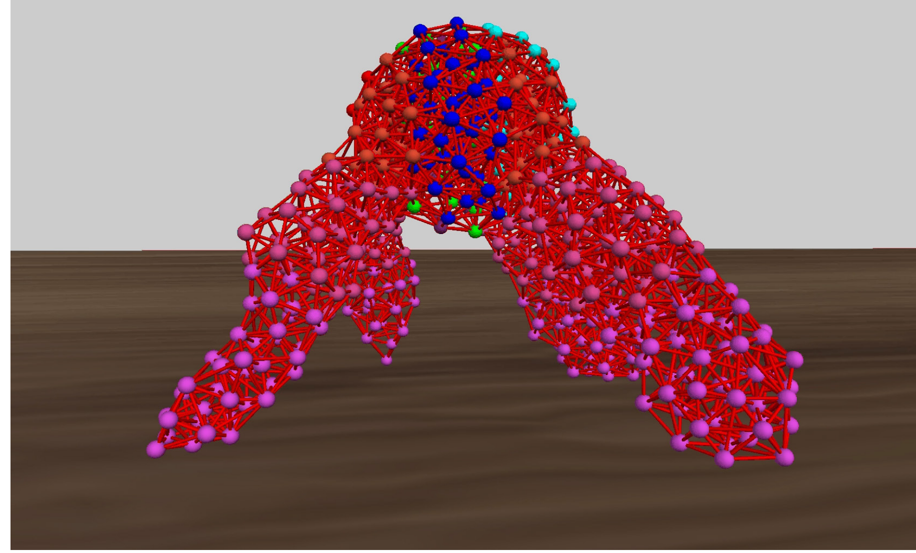


Doursat, Sanchez, Fernandez, Kowaliw & Vico (2012)

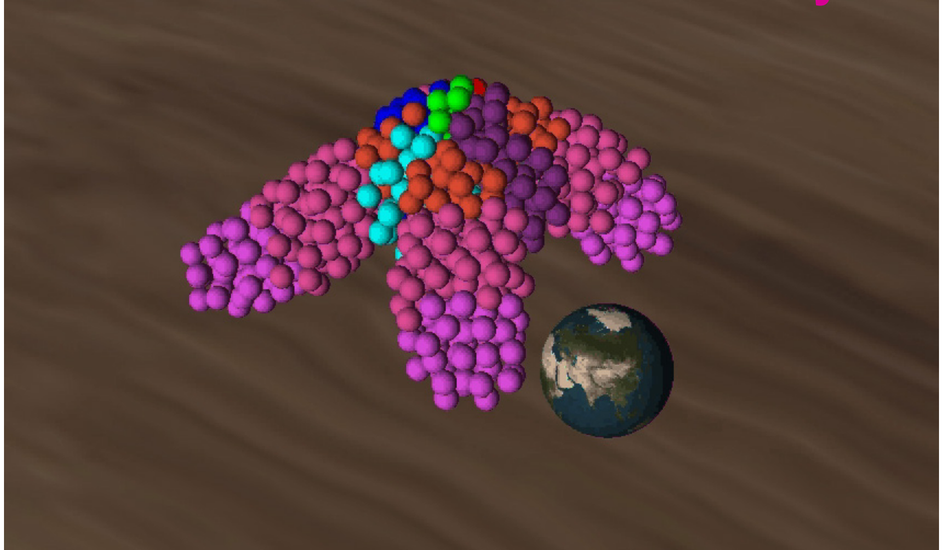
MAPDEVO – Modular Architecture by Programmable Development

➢ Bones & muscles: structural differentiation and properties

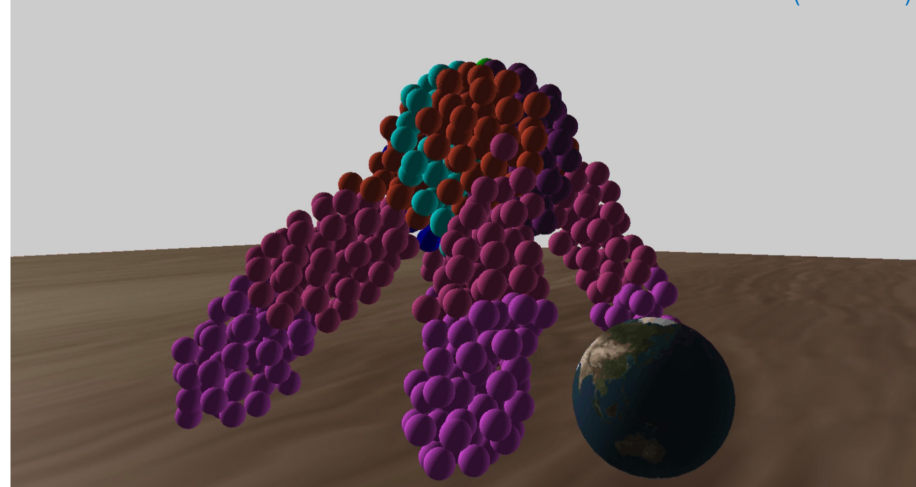




➢ Locomotion and behavior by muscle contraction



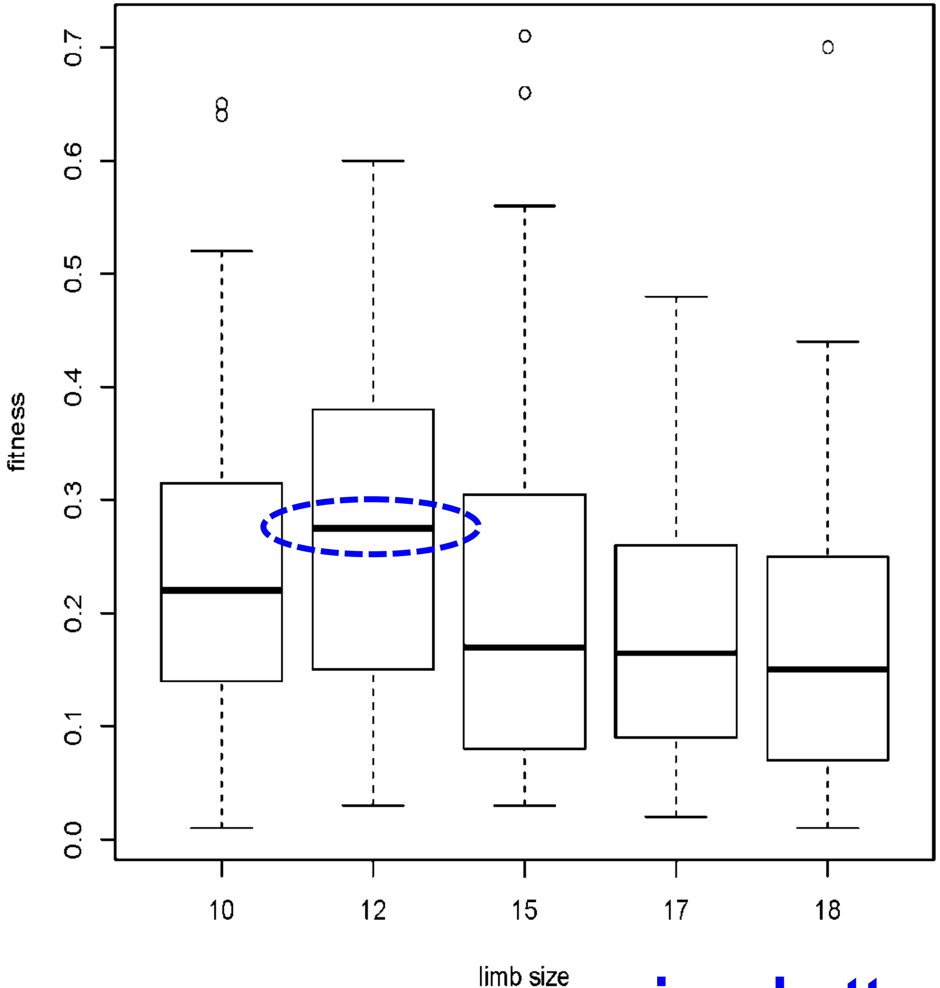
all 3D+t simulations:
Carlos Sanchez (tool: ODE)

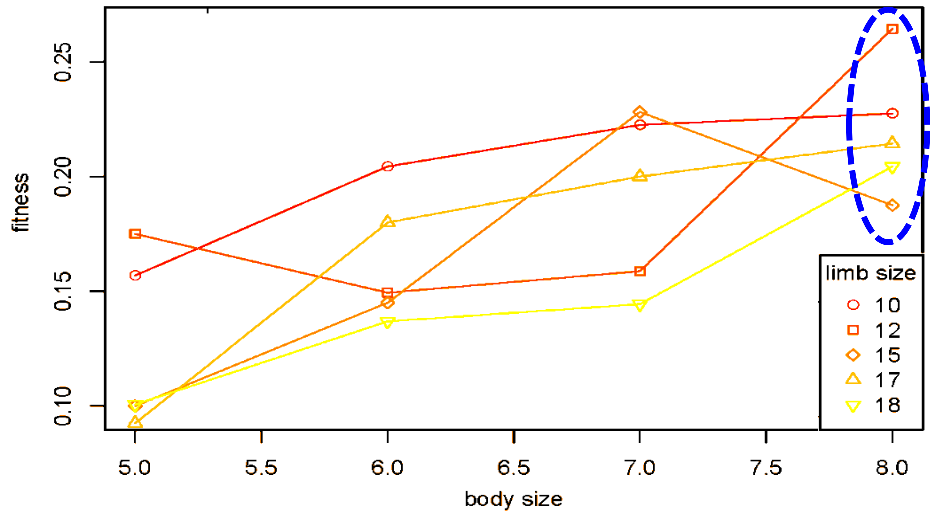


Doursat, Sanchez, Fernandez, Kowaliw & Vico (2012)

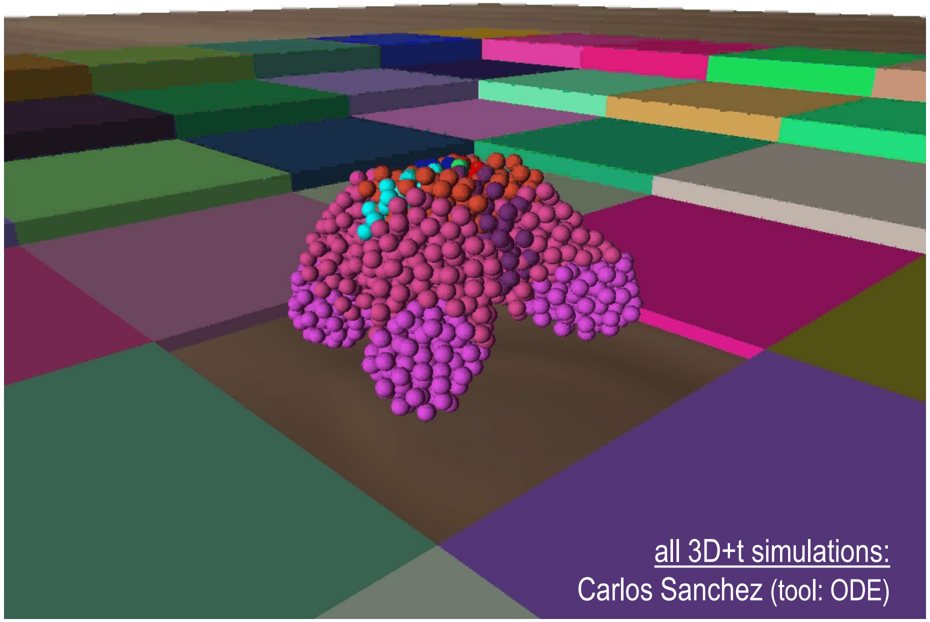
MAPDEVO – Modular Architecture by Programmable Development

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



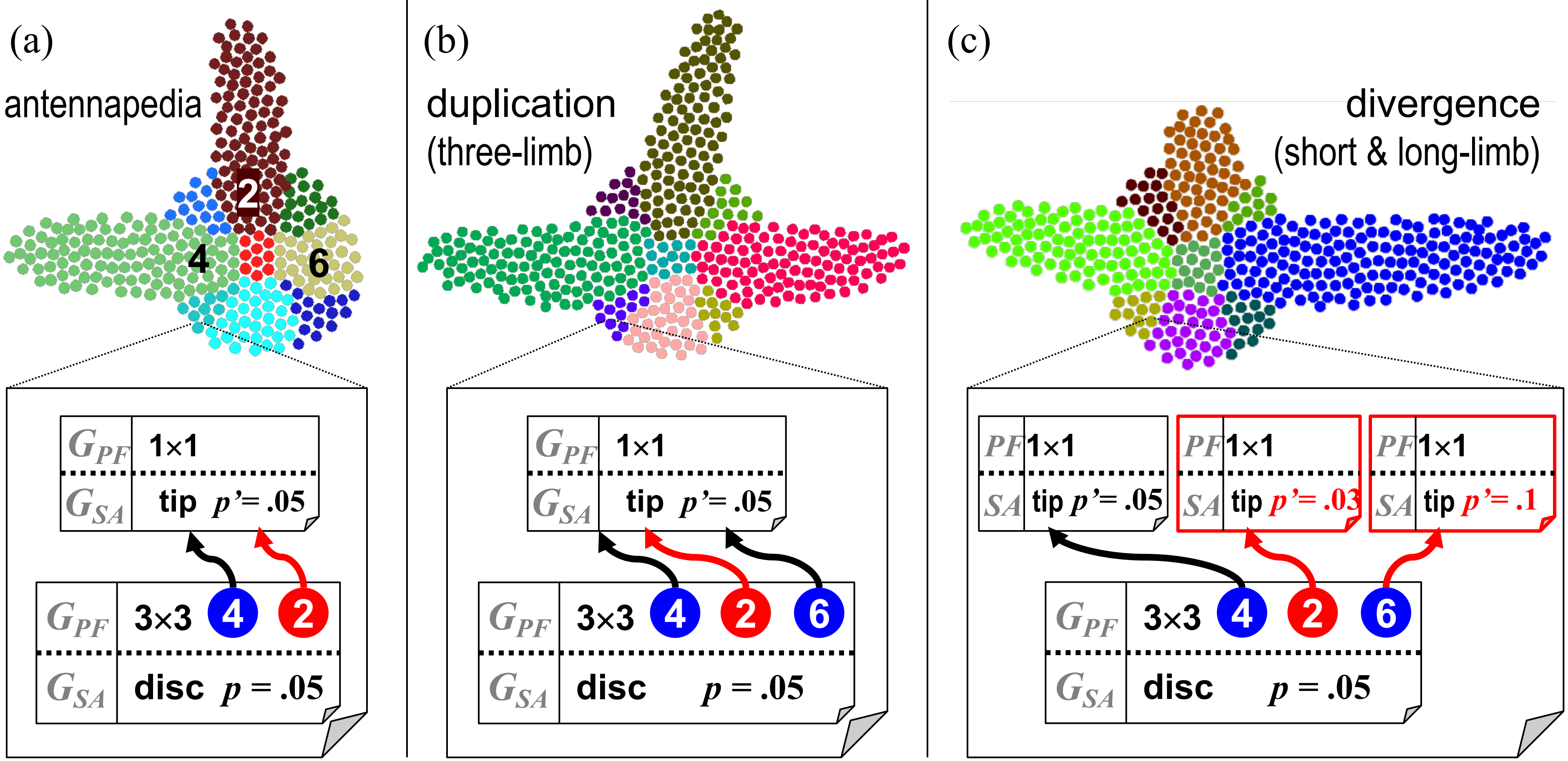


... i.e., better developmental genomes!



➢ To be explored: qualitative mutations in limb structure

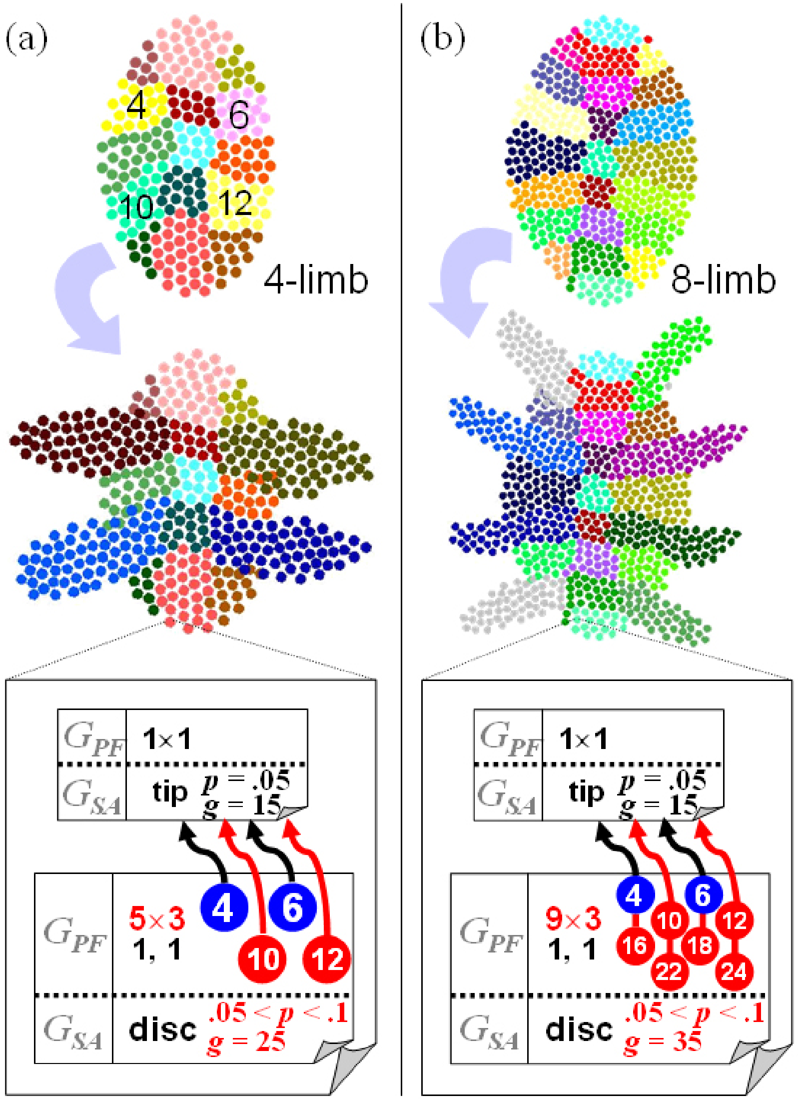
antennapedia | ***homology*** by *duplication* | *divergence* of the homology

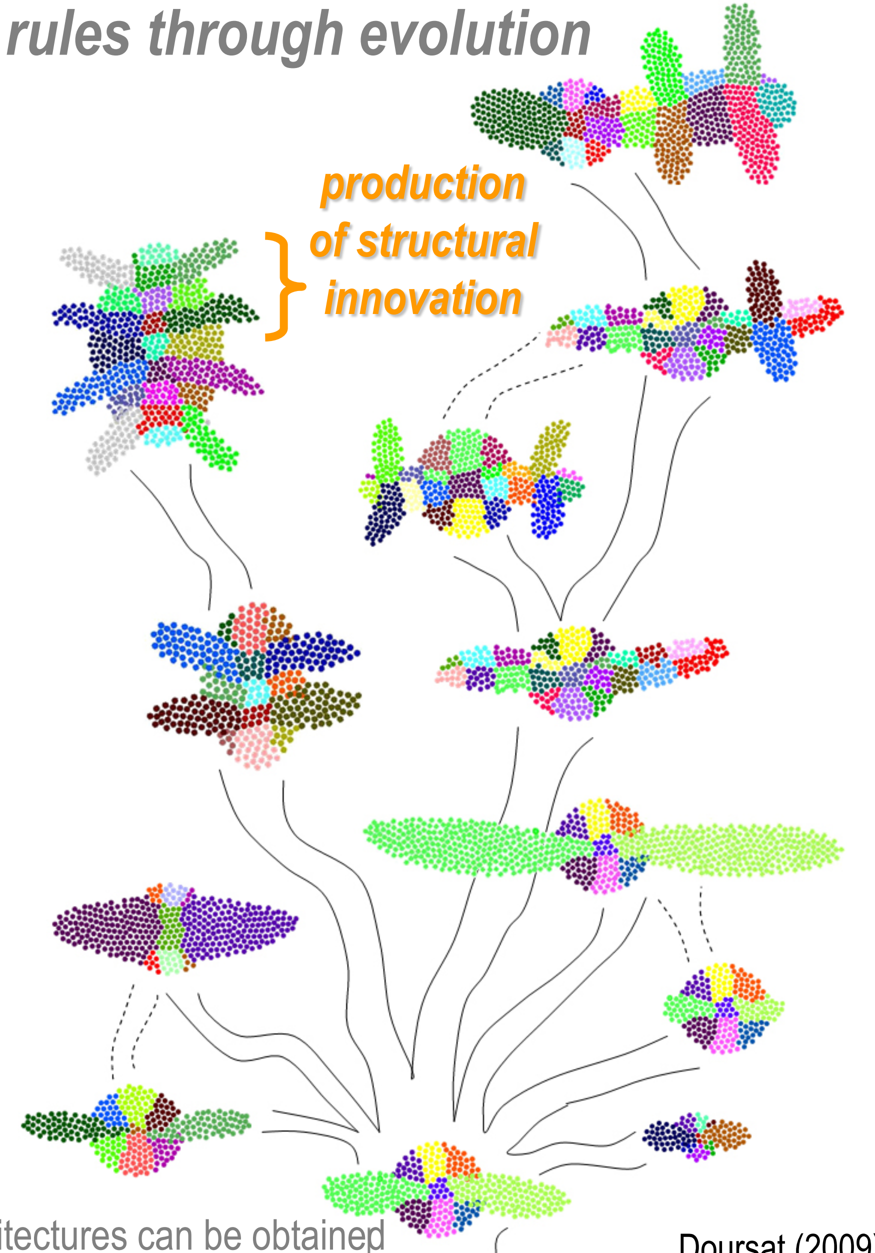


all 2D+t simulations:
Rene Doursat (tool: Java)

Doursat (2009)

Changing the agents' self-architecting rules through evolution





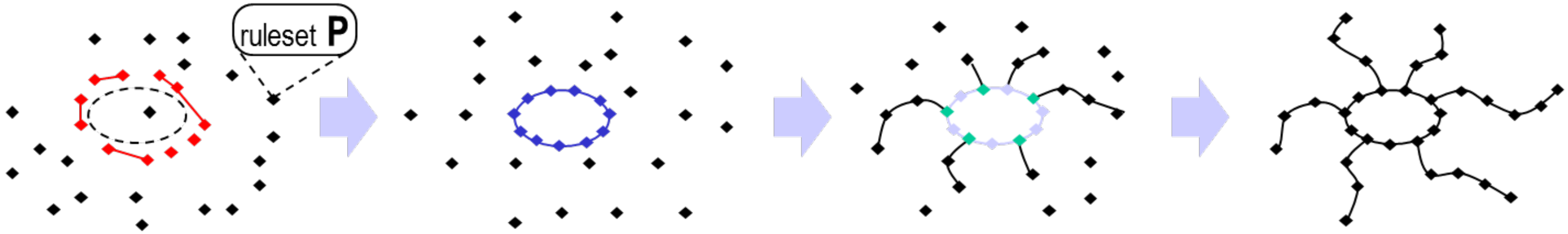
all 2D+t simulations:
Rene Doursat (tool: Java)

by tinkering with the genotype, new architectures can be obtained

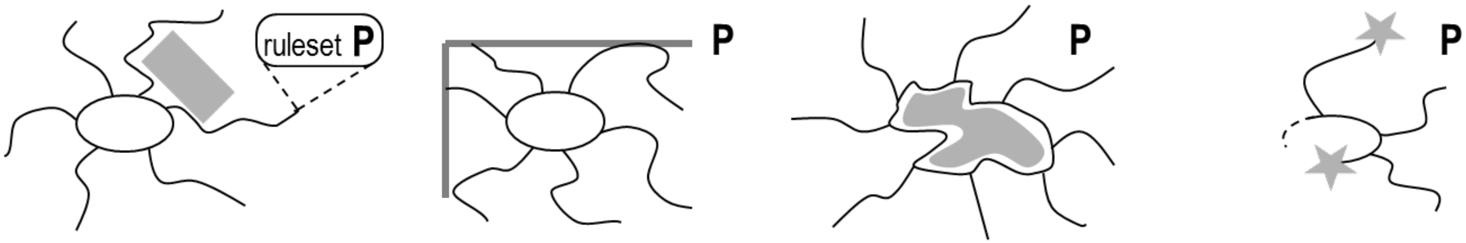
Doursat (2009)

MAPDEVO – Modular Architecture by Programmable Development

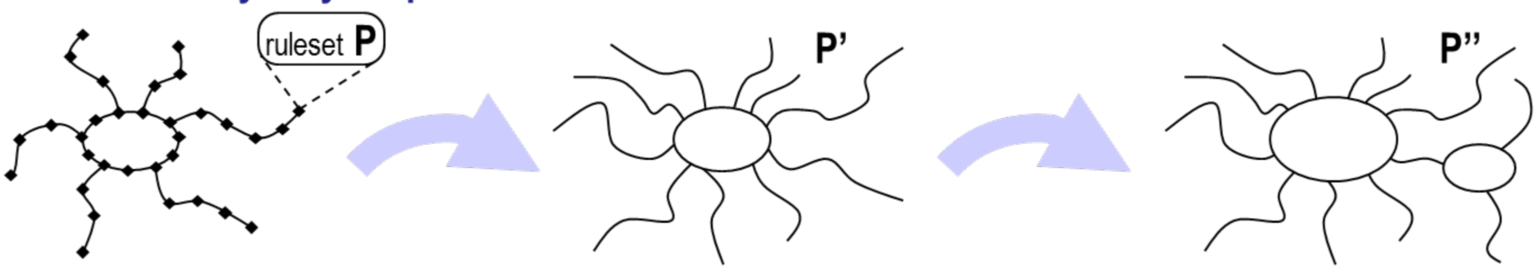
Stereotyped Development



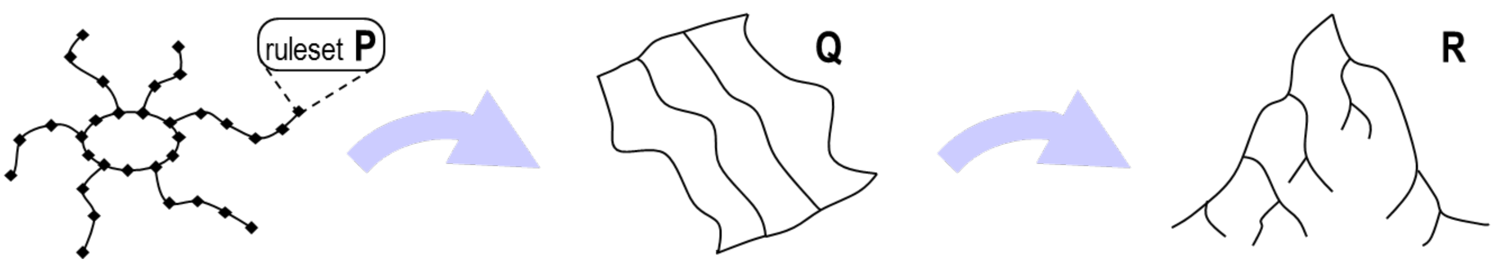
Environment-Induced Polyphenism

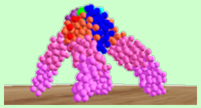


Microevolutionary Polymorphism

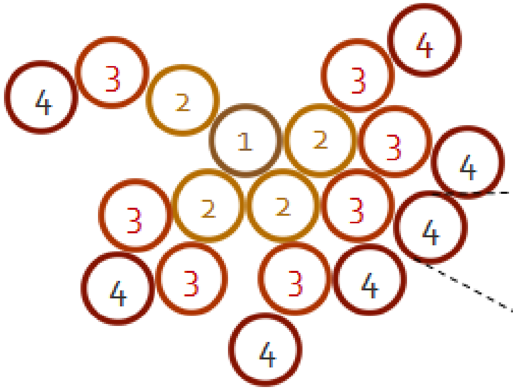


Macroevolution

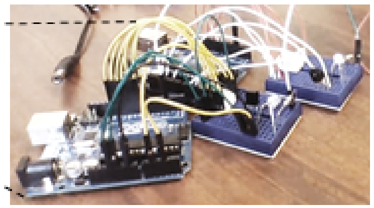


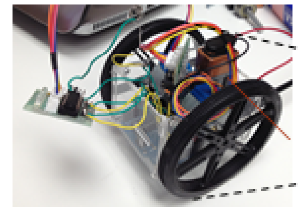


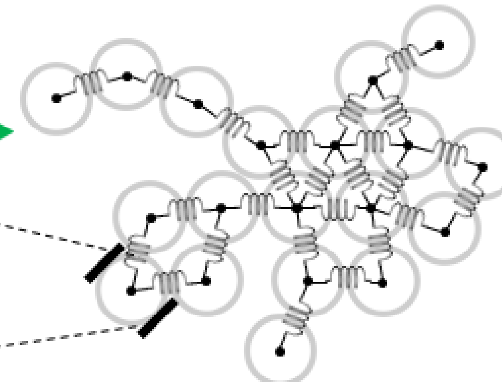
Morphogenetic Engineering Work-bot (MEWbot)



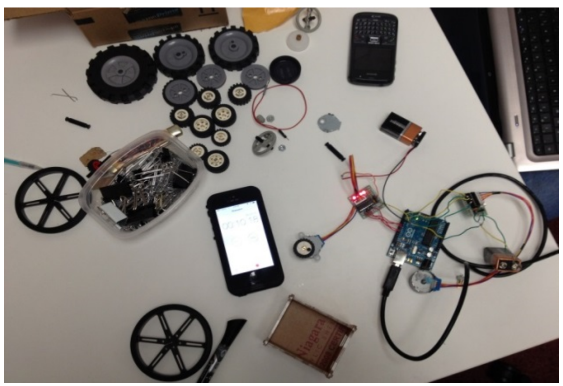
Morphogenesis combines
chemical pattern formation (PF)
and mechanical self-assembly (SA)

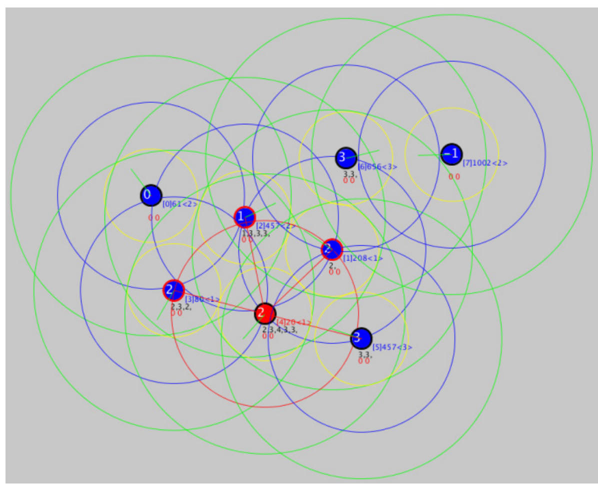


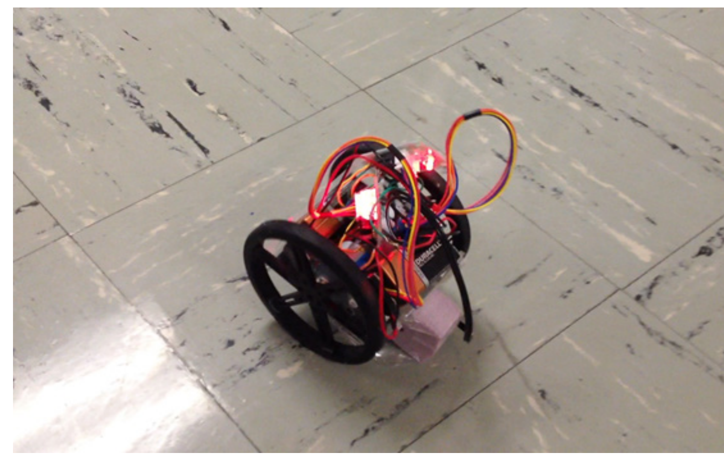




PF: Gradient formation & differentiation + *SA: Virtual multi-spring-mass system*

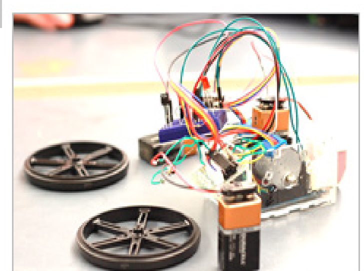


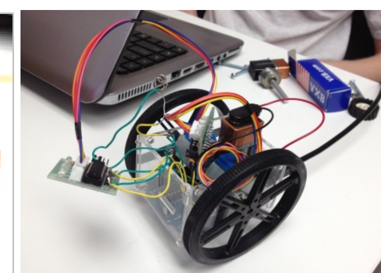


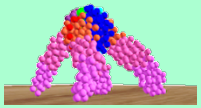


Material used

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







MapDevo / MEWbot Acknowledgments

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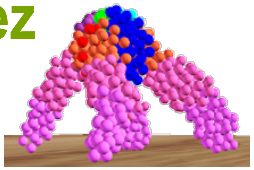

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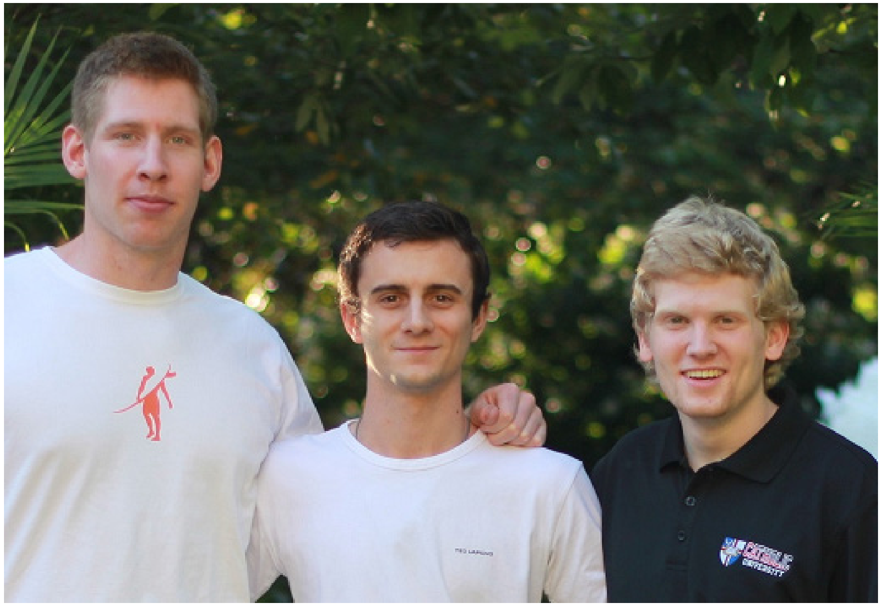
INSTITUT DES SYSTEMES COMPLEXES



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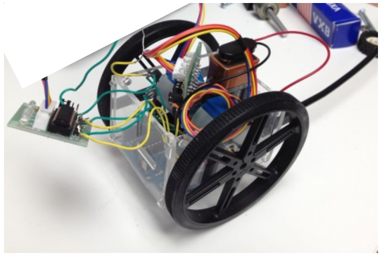
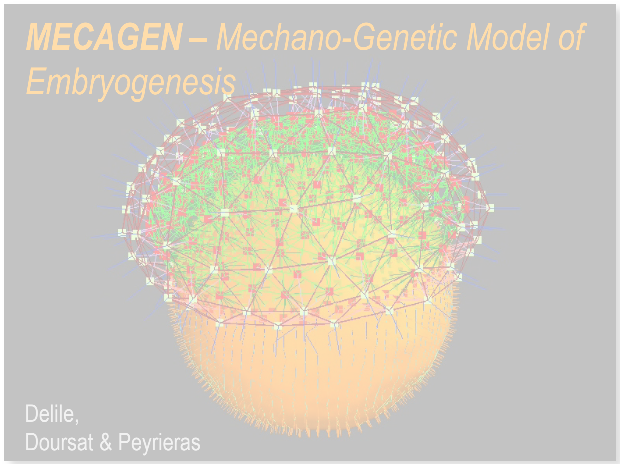


Systems that are self-organized *and* architectured

- **Embryogenesis to Simulated Development to Synthetic Biology**

*illustration of **Morphogenetic Engineering** ideas*

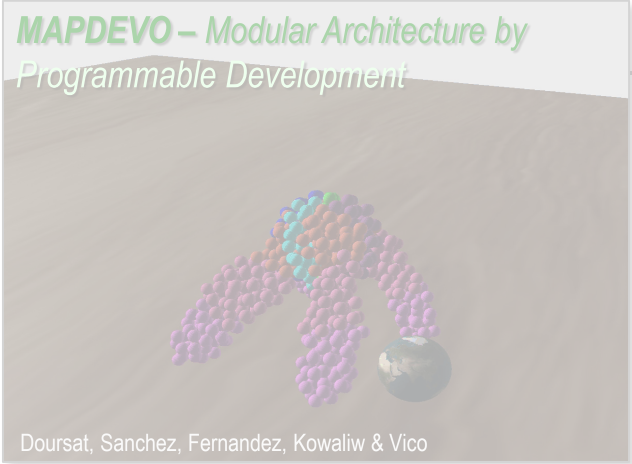
mutually beneficial transfers between biology & CS



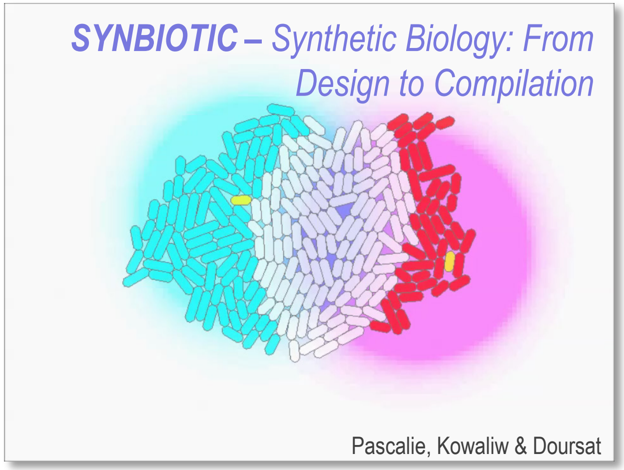
MECAGEN *– Mechano-Genetic Model of Embryogenesis*

BIOMODELING (LIFE)

BIO-INSPIRED ENGINEERING (ALIFE)



MAPDEVO *– Modular Architecture by Programmable Development*

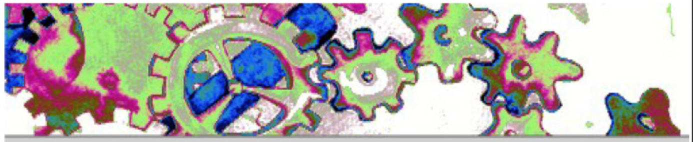


SYNBIOTIC *– Synthetic Biology: From Design to Compilation*

BIOENGINEERING (HYBRID LIFE)

Introduction

- **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**

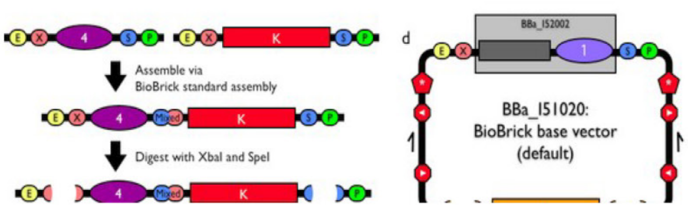


Registry of Standard Biological Parts

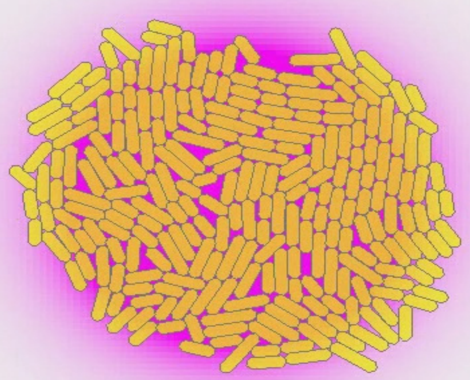
BioBricks FOUNDATION

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

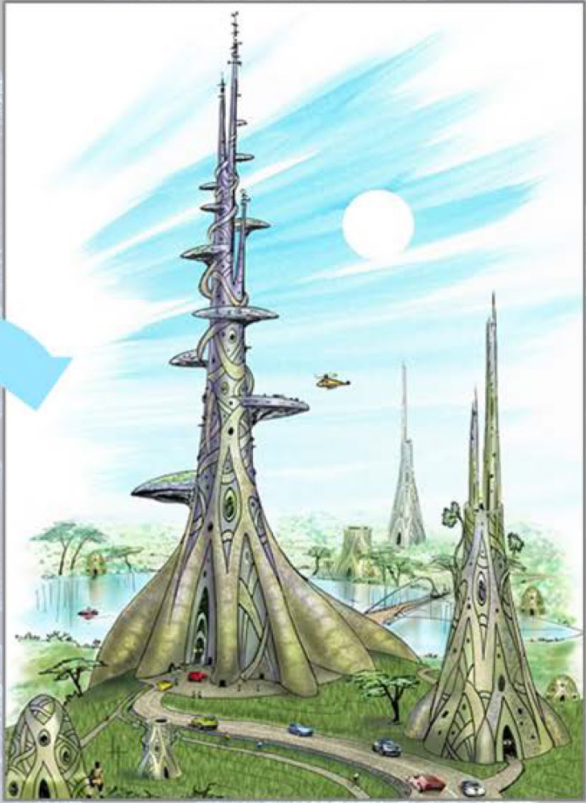
Part Number	Function	Notation
BBa_G00000	BioBrick cloning site prefix	E X
BBa_G00001	BioBrick cloning site suffix	S P
BBa_P1016	ccdB positive selection marker	
BBa_I50022	minimal pUC-derived high copy replication origin	1
BBa_B0042	translational stop sequence	
BBa_B0053 & BBa_B0054	forward transcriptional 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



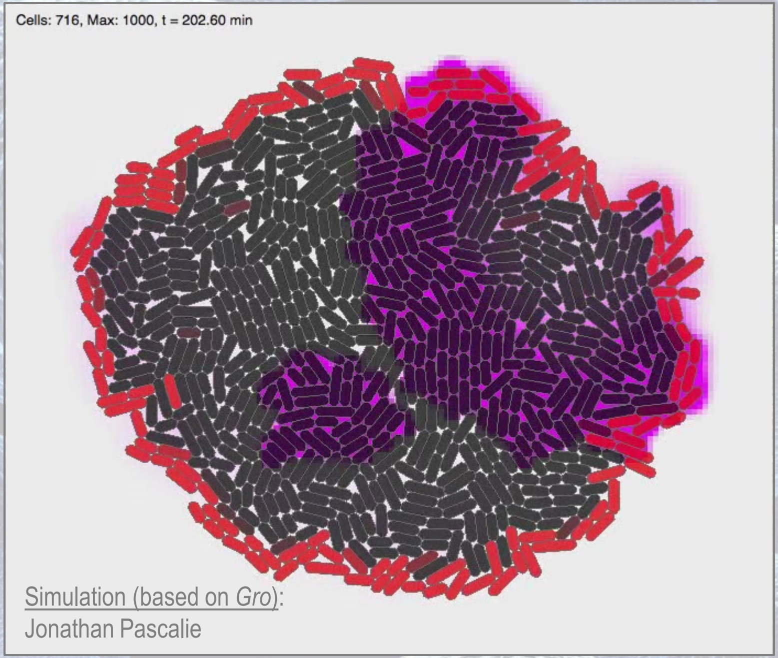
Jang, Oishi, Egbert, Klavins, "Specification and simulation of multicelled behaviours", ACS Synthetic Biology, 2012.



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

Gro Programming Language

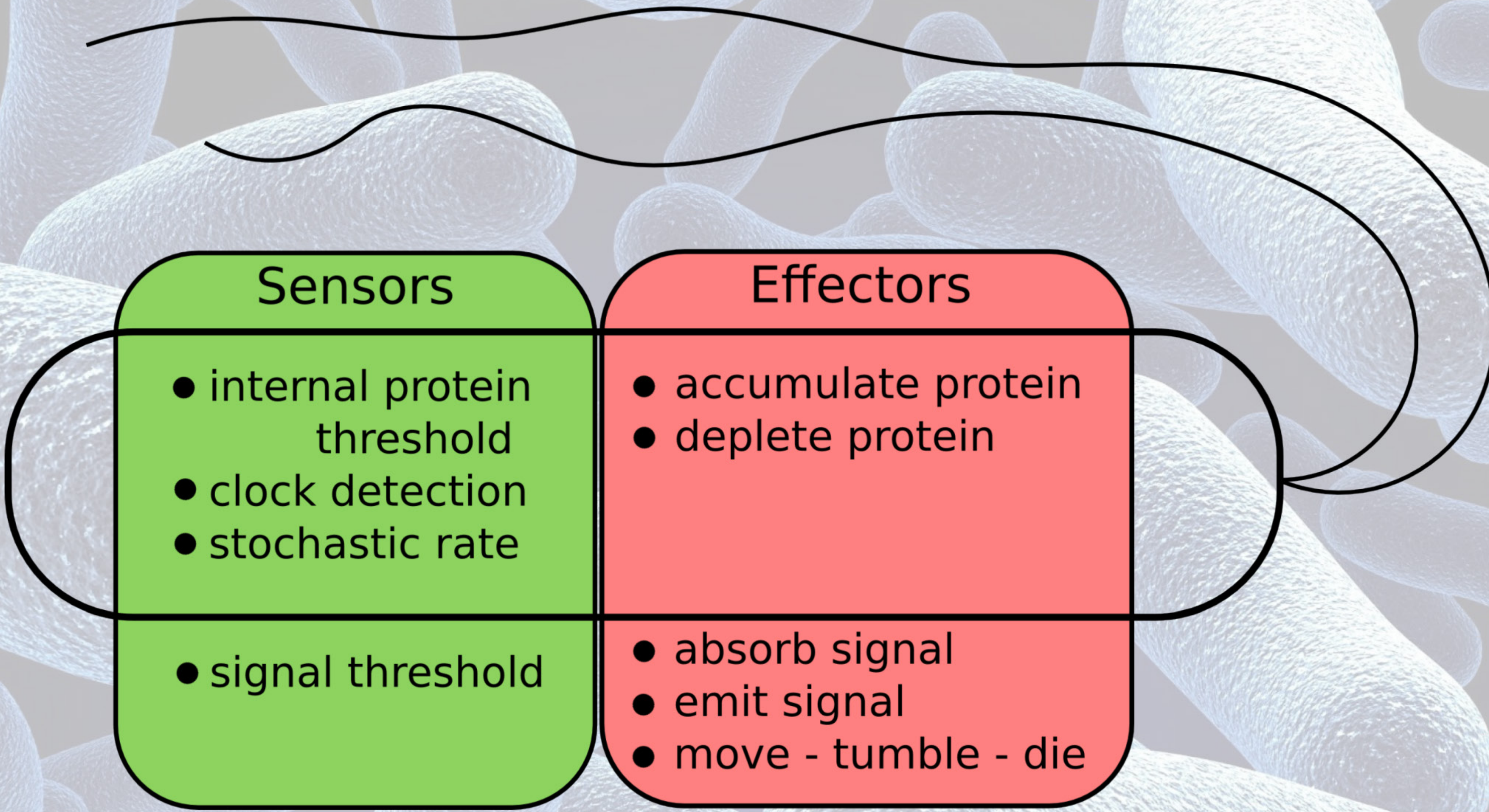
- The **Gro** language (E. Klavins) includes pre-programmed capabilities such as bacterial physics, cell behaviors, and diffusive chemical signals
- Capable of simulating experiments involving the growth and self-organization of *E. Coli* colonies on agar dishes




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

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

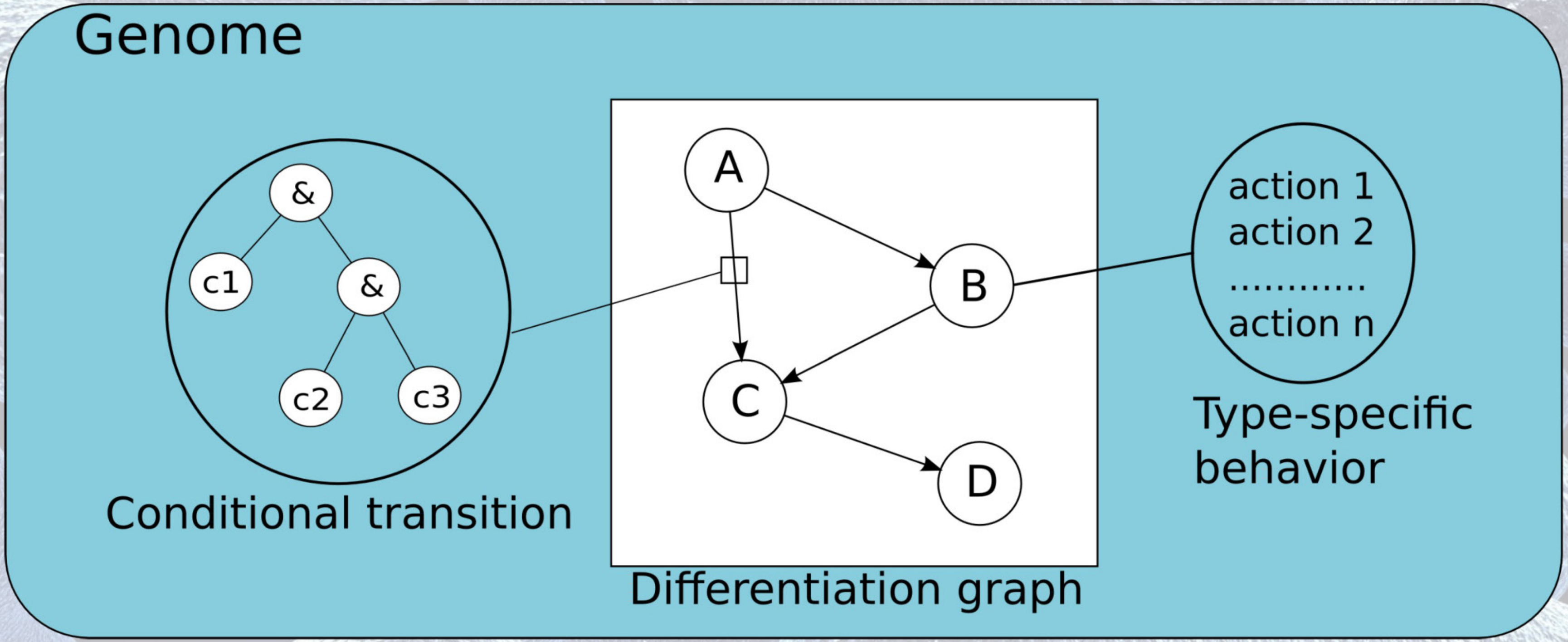
Our Model – Virtual *E. coli*

- 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

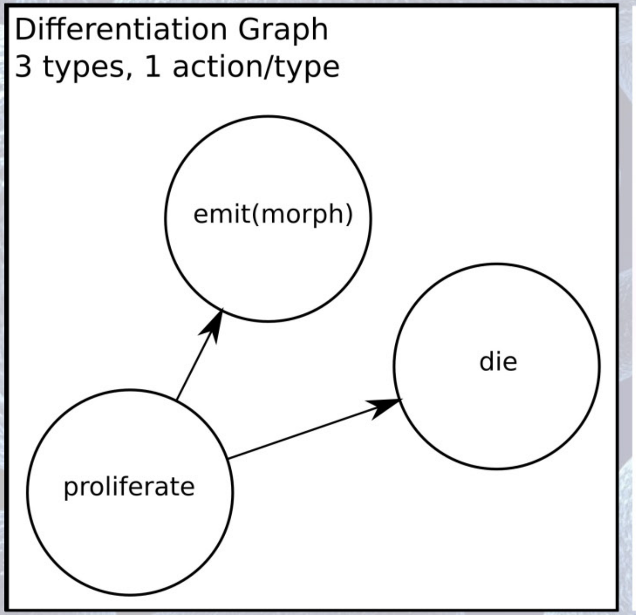
- The **Synthetic Biology Genetic Programming** (SBGP) declarative language describes bacterial dynamics and environmental chemistry

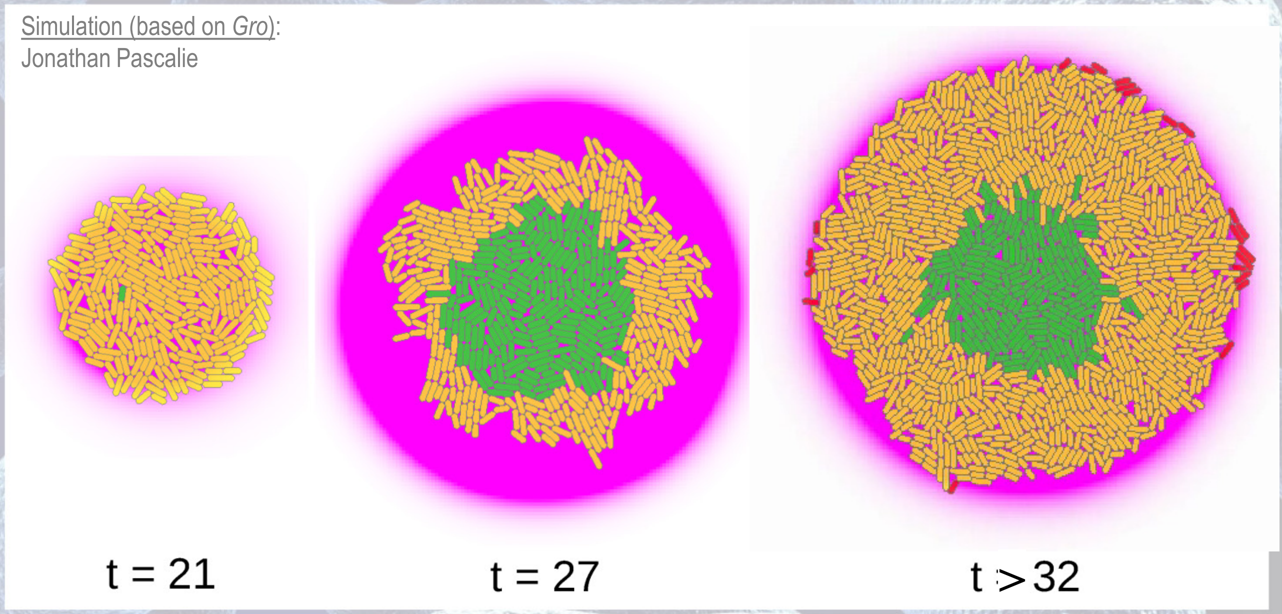
```
"signals" : [
  ["A", 3, 0.4],
  ["B", 5, 0.01],
  ["C", 6, 0.5],
  ["D", 6, 0.5],
  ["E", 6, 0.5],
  ["F", 6, 0.5],
  ["G", 6, 0.5]
],

"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

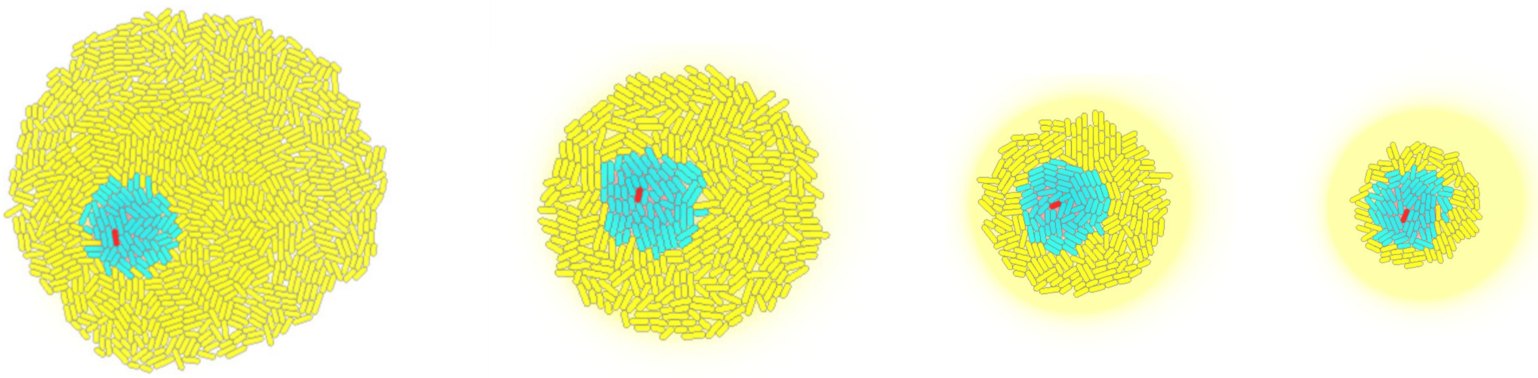
- A leader cell (green cell) emits a diffusive morphogen
- Followers cells (yellow) divide while above a certain threshold
- Death occurs if followers detect morphogens below the threshold



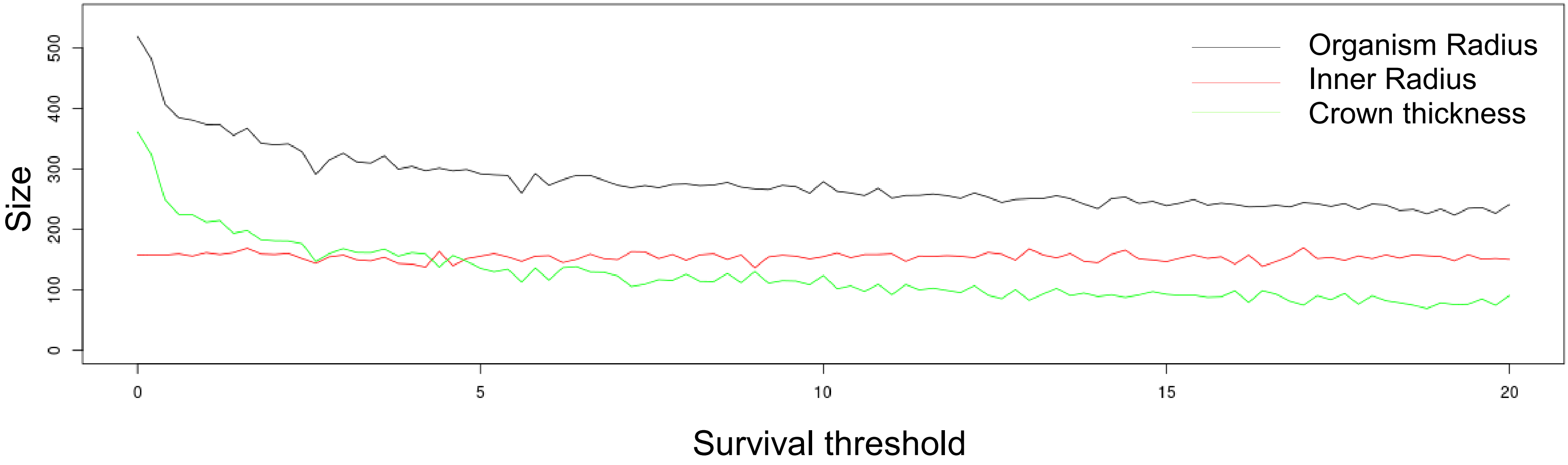


Quantitative variations

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

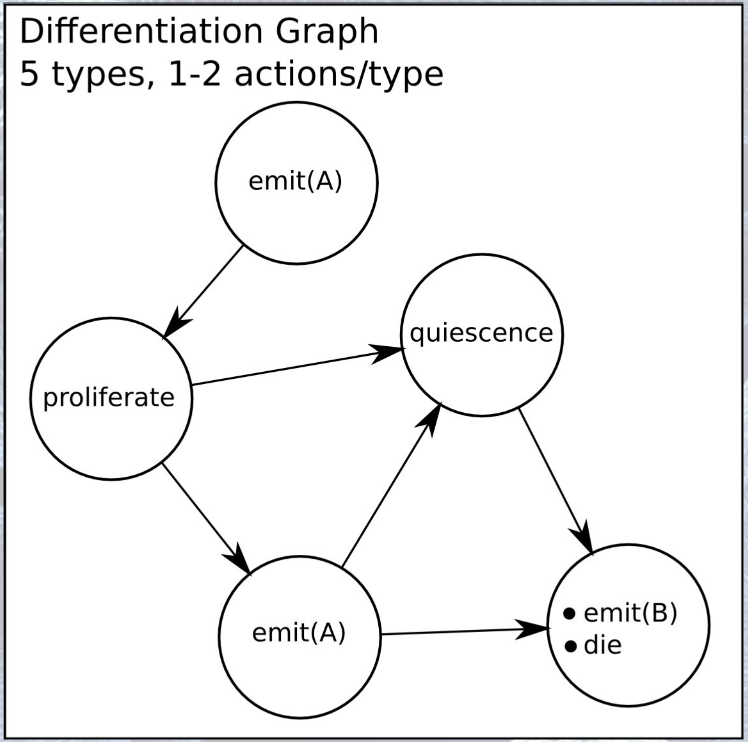


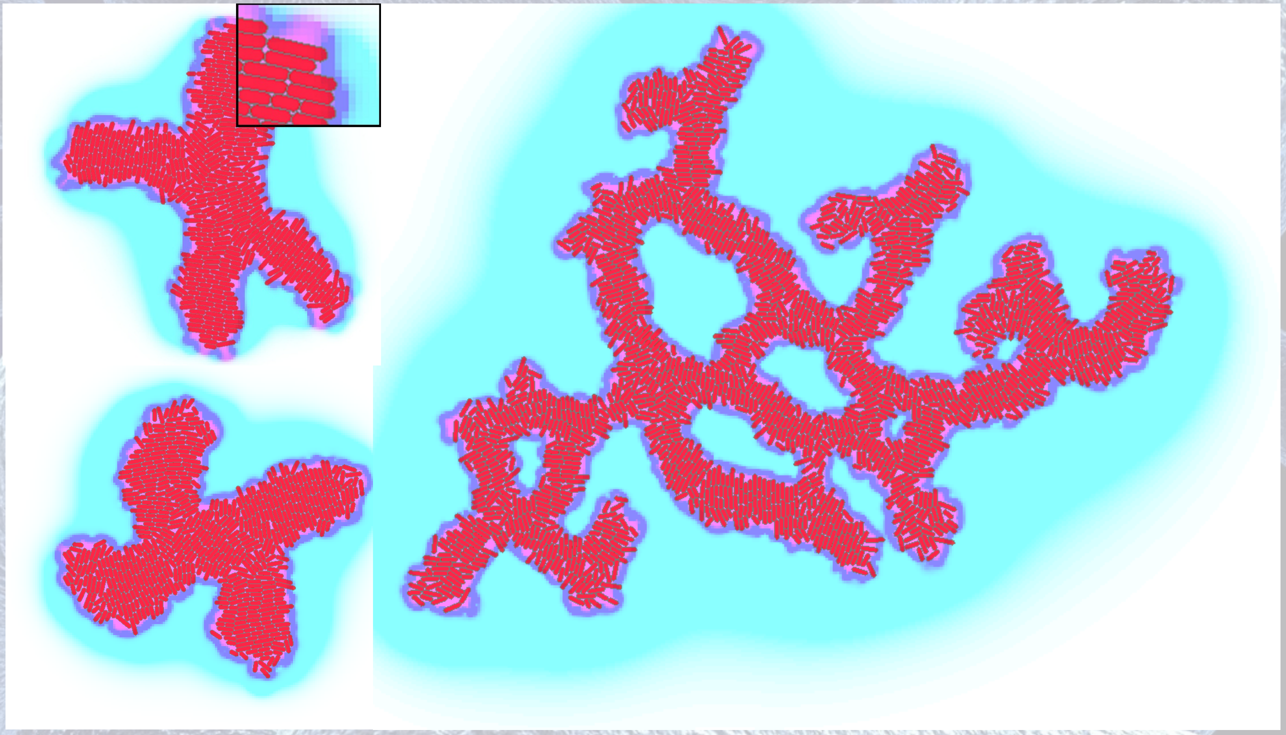
th = 0   th = 0.6   th = 3.4   th = 18



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

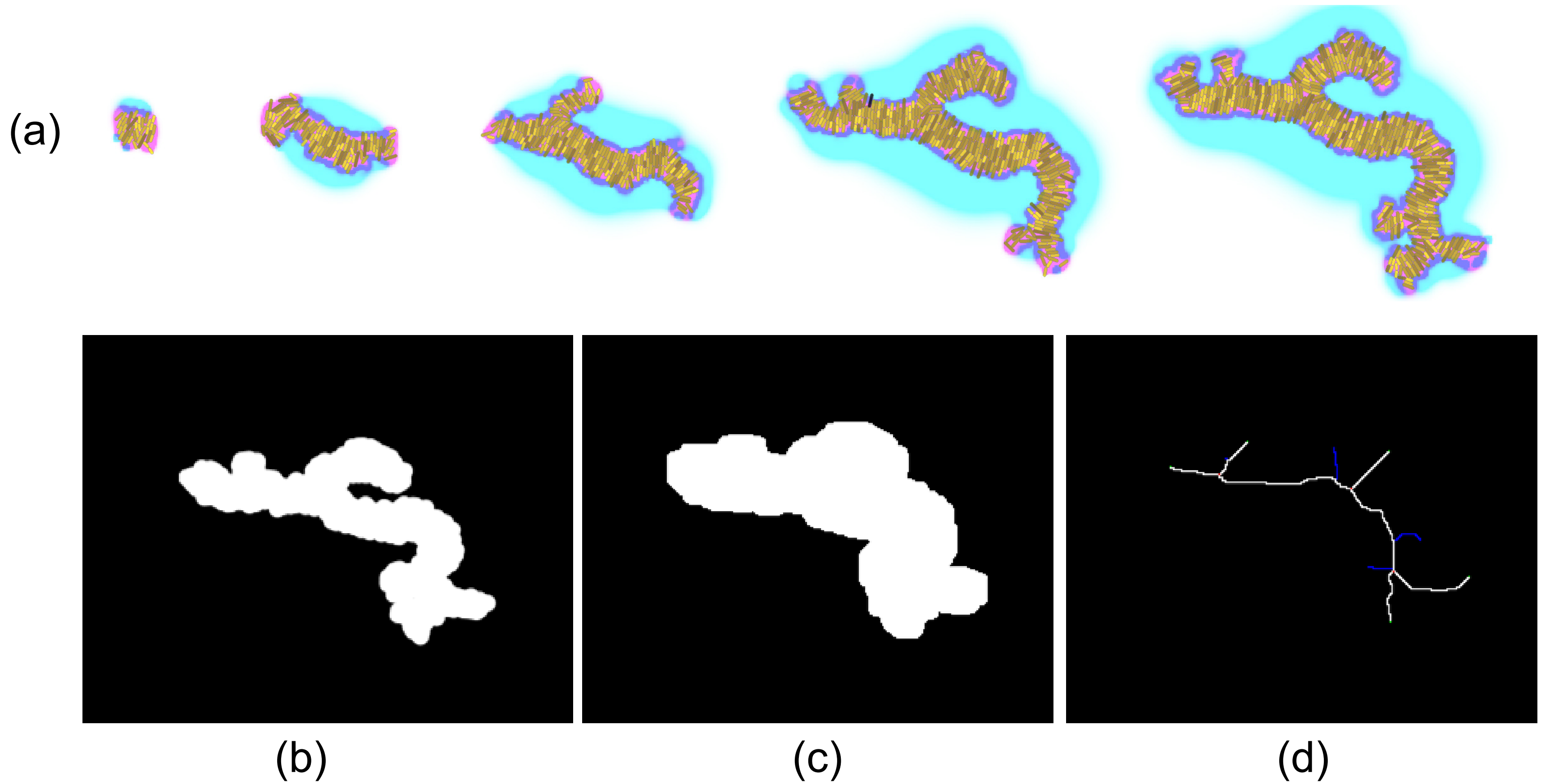




Morphological Analysis

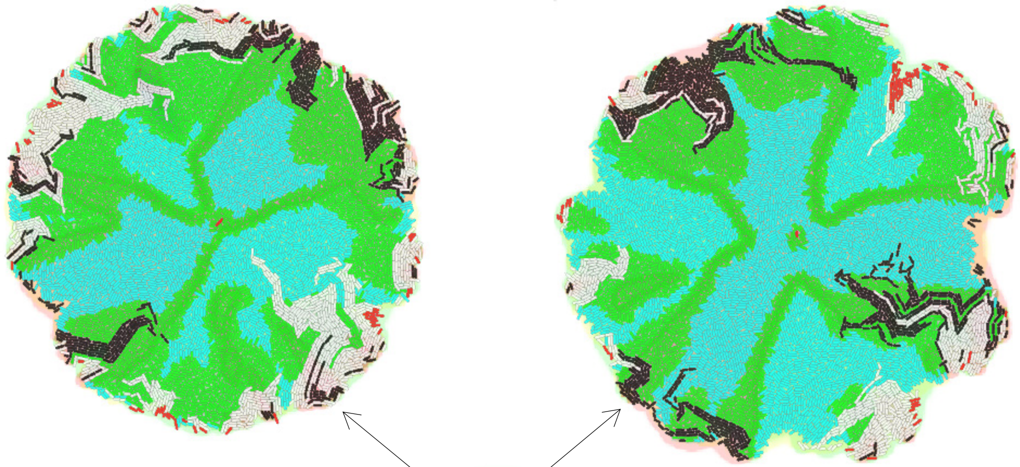
After growth (a), organism morphology can be characterized by image analysis:

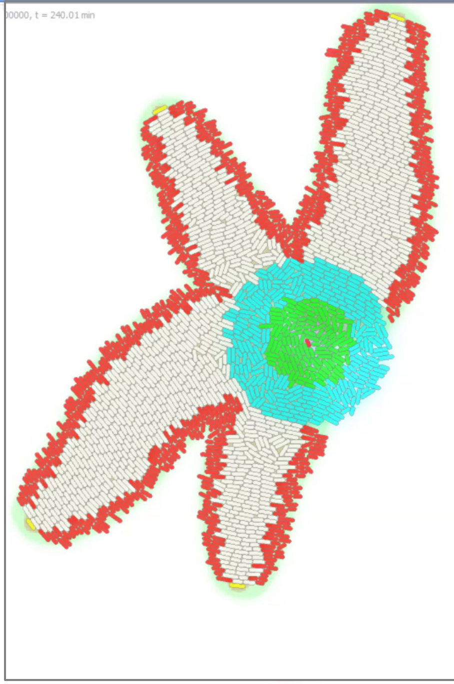
- (b) binary image and (c) Gaussian convolution to reduce contour irregularities
- (d) skeletonization, then pruning of short branches



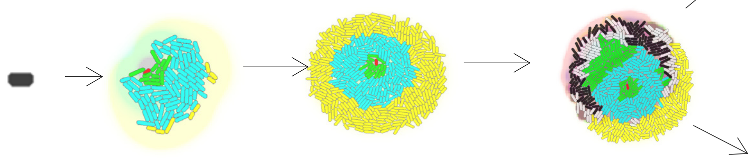
Toward Building Complex Shapes

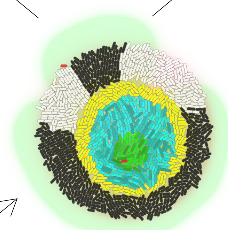
Chemical species emitted by **black** cells react with ones emitted by **white** cells to product **green** cells' survival signals



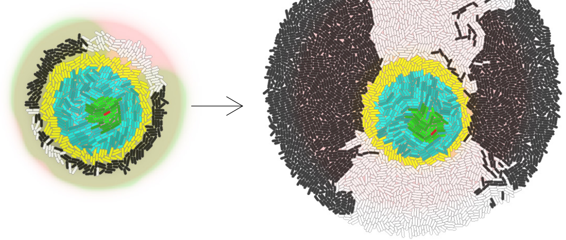


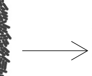
Example of (guided) evolutionary bifurcations

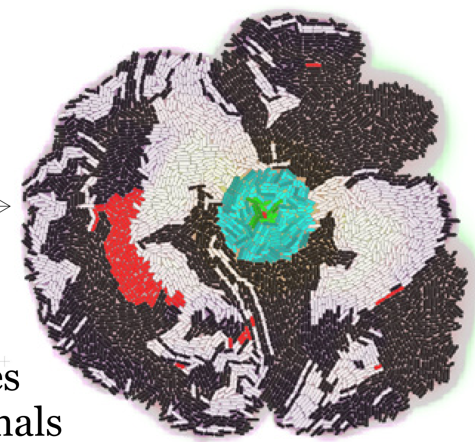




Random changes in spontaneous crown segmentation lead to differences in growth dynamics







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

Simulation (based on *Gro*): Jonathan Pascalie

SynBioTIC Acknowledgements

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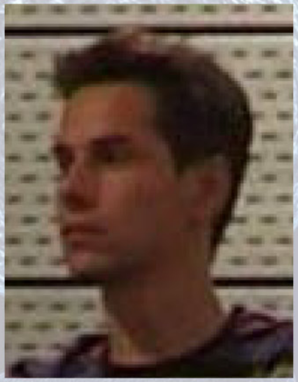
UPEC - LACL



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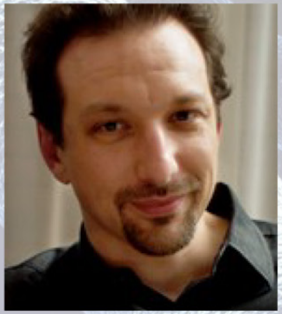

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