ARCHITECTURE AND SELF-ORGANIZATION:

HEADING FOR THE BEST OF BOTH WORLDS

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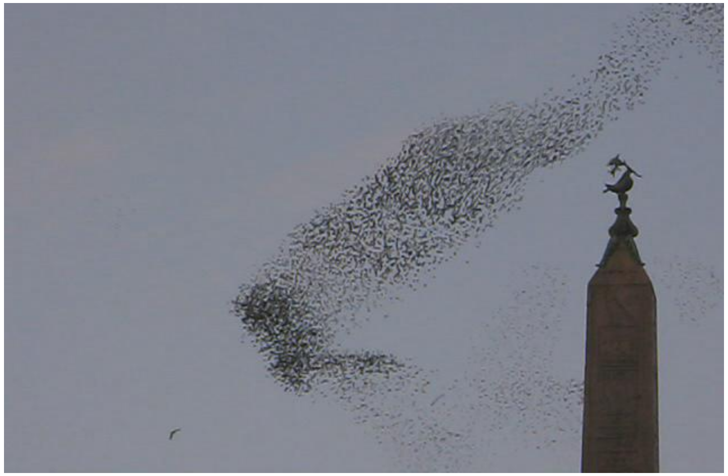
Systems that are self-organized *and* architectured



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

ARCHITECTURE AND SELF-ORGANIZATION

1. What are Complex Systems?

- Decentralization
- Emergence
- Self-organization

2. Architects Overtaken by their Architecture

Designed systems that became suddenly complex

3. Architecture Without Architects

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

but were not

4. Morphogenetic Engineering

From cells and insects to robots and networks

5. The New Challenge of "Meta-Design"

Or how to organize spontaneity

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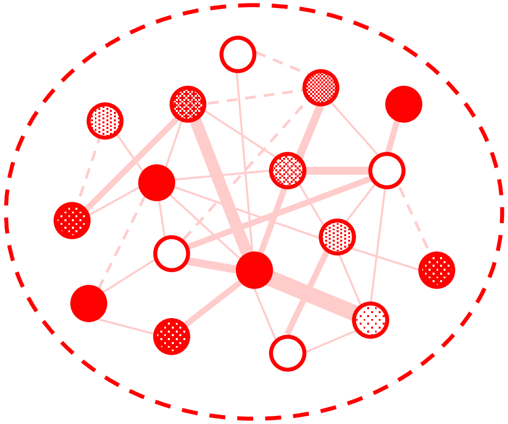
1. What are Complex Systems?

- Complex systems can be found everywhere around us



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

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

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

- Physical, biological, technological, social complex systems

pattern formation
○ = matter

biological development
○ = cell

the brain & cognition
○ = neuron

insect colonies
○ = ant

Internet & Web
○ = host/page

social networks
○ = person

http://fr.wikipedia.org/wiki/Formicidae

MS PowerPoint clips

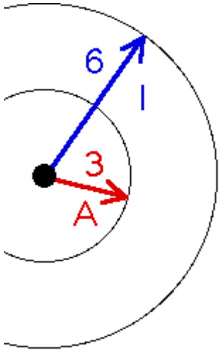
1. What are Complex Systems?

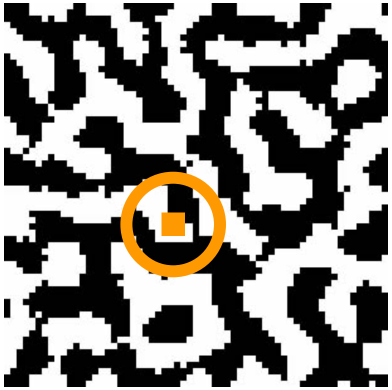
➢ Ex: Pattern formation – Animal colors

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




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



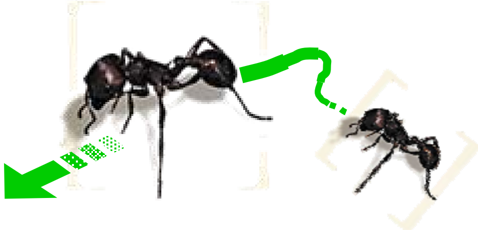


NetLogo Fur simulation

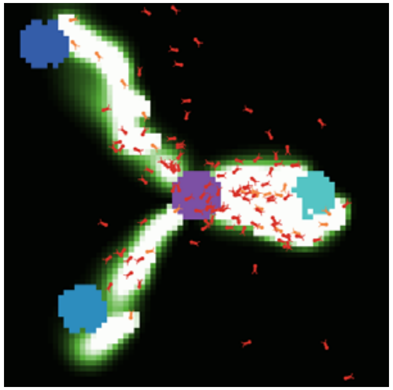
➢ Ex: Swarm intelligence – Insect colonies

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

Matabele snts
http://www.mtkilimanjarologue.com/2008/02



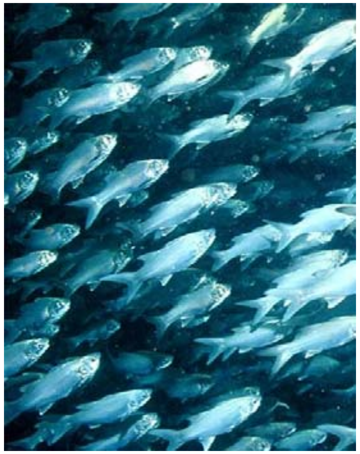
Harvester ants
Deborah Gordon, Stanford University



NetLogo Ants simulation

1. What are Complex Systems?

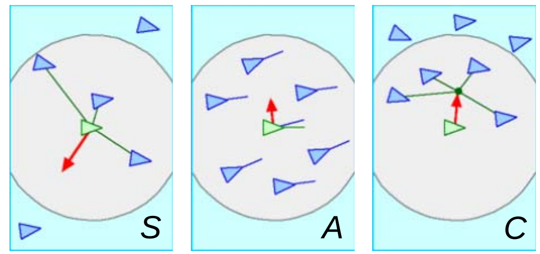
➢ Ex: Collective motion – Flocking, schooling, herding



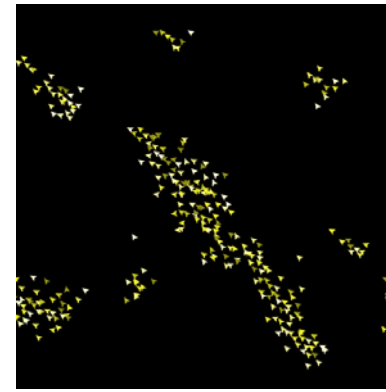
Fish school
http://en.wikipedia.org/wiki/School_(fish)

Cattle
MS PowerPoint clip

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



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

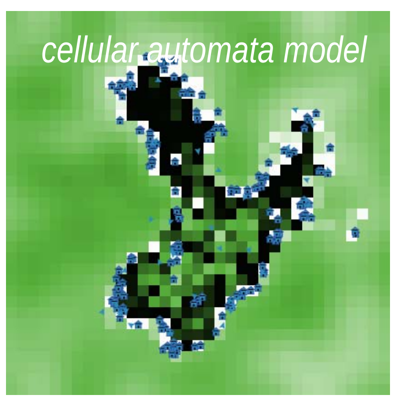


NetLogo Flocking simulation

➢ Ex: Diffusion and networks – Cities and social links

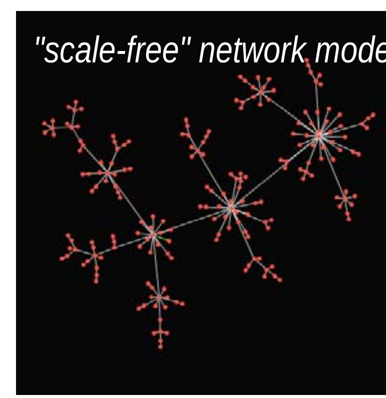
✓clusters and cliques of homes/people that aggregate in geographical or social space

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



NetLogo urban sprawl simulation

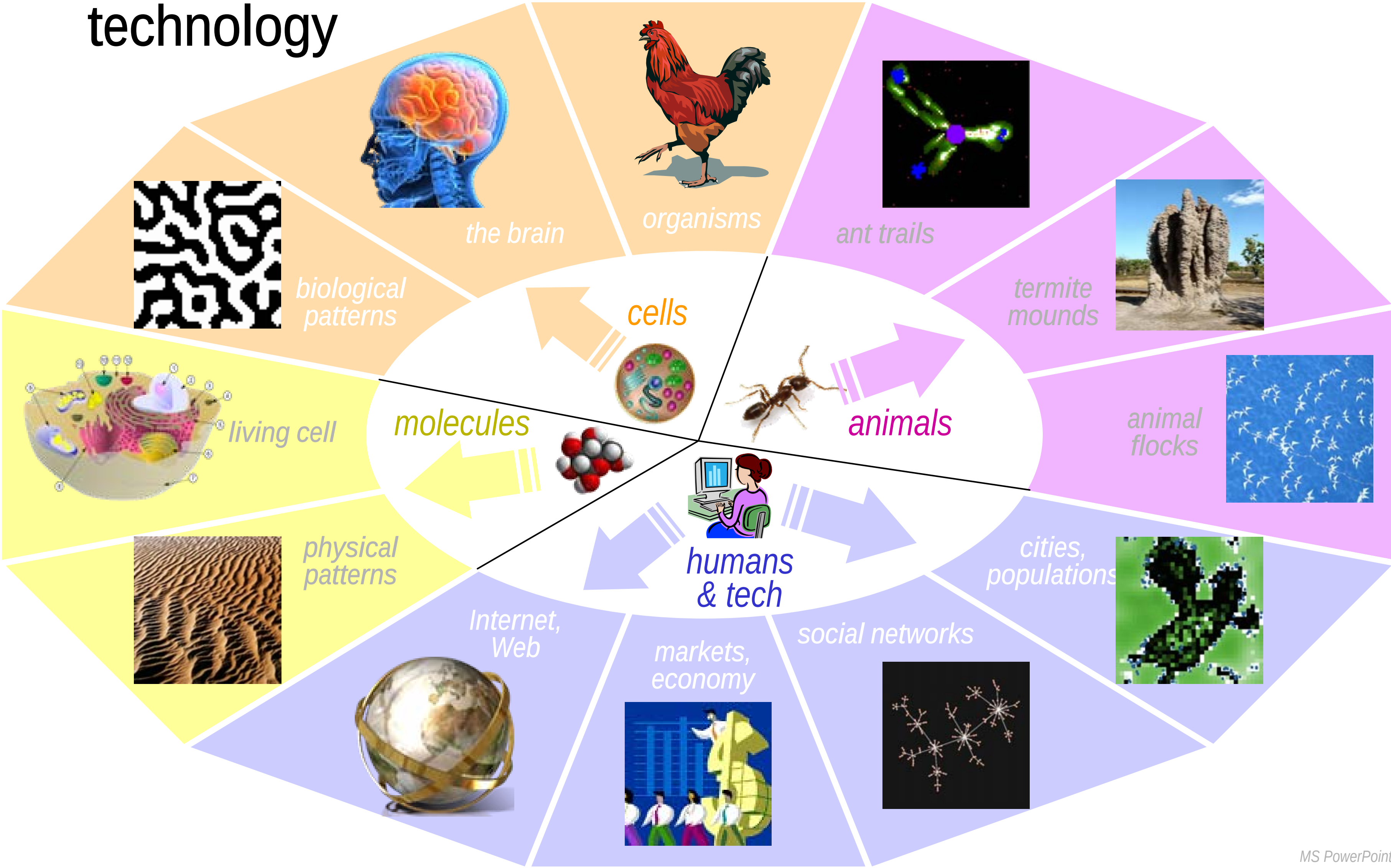
MS PowerPoint clip



NetLogo preferential attachment

1. What are Complex Systems?

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



MS PowerPoint clips
and NetLogo simulations

1. What are Complex Systems?

TAKEAWAY **3 main differences with traditional architecting**

a) Decentralization: the system is made of myriads of "simple" agents

- ✓ **local information** (no group-level knowledge): each agent carries a piece of the global system's state
- ✓ **local rules** (no group-level goals): each agent follows an individual agenda
- ✓ **local interactions** (no group-level scope): each agent communicates with "neighboring" agents, possibly via long-range links

b) Emergence: function is a bottom-up collective effect of the agents

- ✓ **asynchronous dependencies:** agents "threaded" in parallel modify each other's actions (possibly via cues they leave in the environment)
- ✓ **balance:** creation by +feedback (imitation), control by –feedback (inhibition)
- ✓ **combinatorial creativity:** the system exhibits new (surprising) properties that the agents do not have; different properties can emerge from the same agents

1. What are Complex Systems?

TAKEAWAY 3 main differences with traditional architecting

c) **Self-organization:** the system operates *<u>and changes</u>* on its own

- ✓ **autonomy:** there is no external map, grand architect, or explicit leader
- ✓ **robustness:** proper function is maintained despite (some) damage
- ✓ **adaptation:** the system dynamically and "optimally" varies with a changing environment; agents modify themselves to create a new class of functional collective behaviors → *learning and/or evolution*

- decentralized, emergent, self-organized processes are the rule in nature and large-scale human superstructures
- however, they are counterintuitive to our human mind, which prefers central-causal, predictable, planned/rigid systems
- ... and yet again, autonomy, robustness, adaptation are highly desirable properties! *How can we have it both ways, i.e. "care <u>and</u> let go"?*

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2. Architects Overtaken by their Architecture

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

by their unplanned, spontaneous emergence and adaptivity...

... arising from a multitude of traditionally designed artifacts

geography: cities, populations ⇐ houses, buildings

people: social networks ⇐ address books

wealth: markets, economy ⇐ companies, institutions

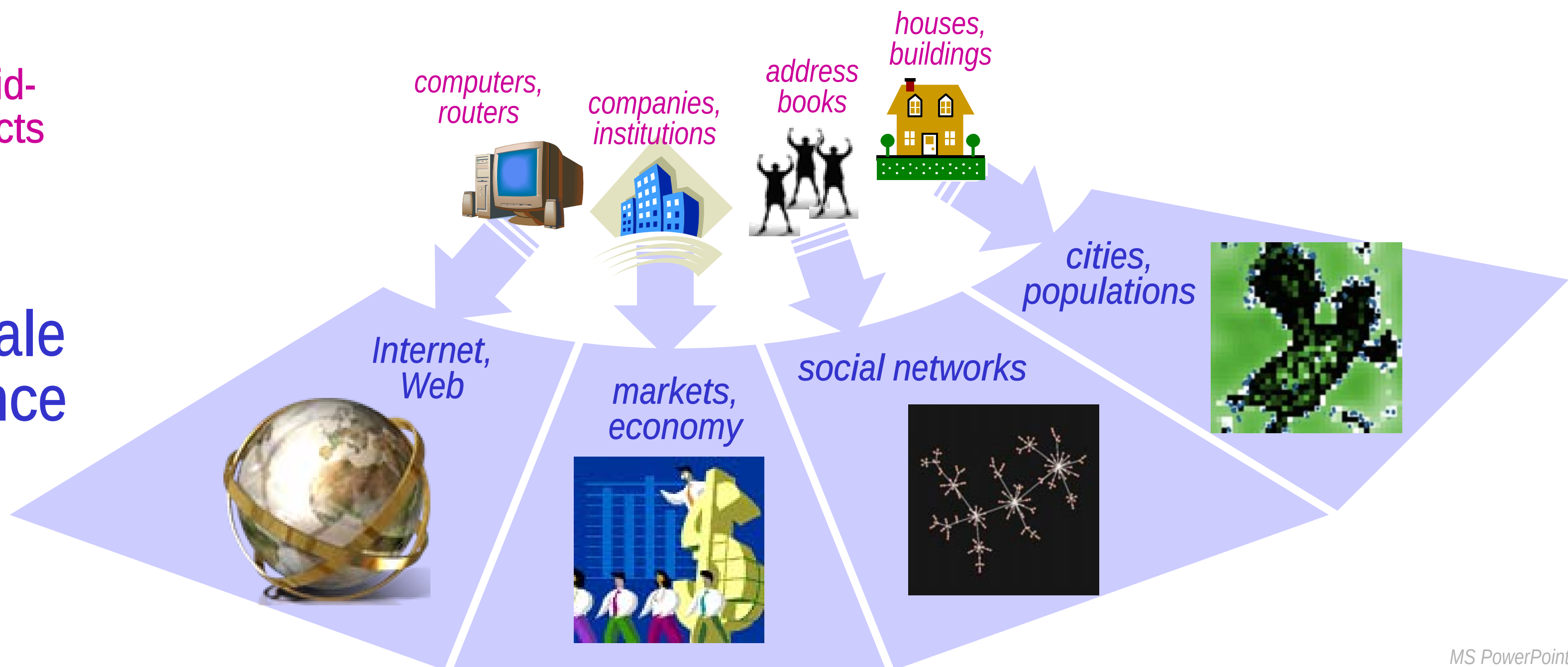
technology: Internet, Web ⇐ computers, routers

---

small to mid-scale artifacts

⇓

large-scale emergence

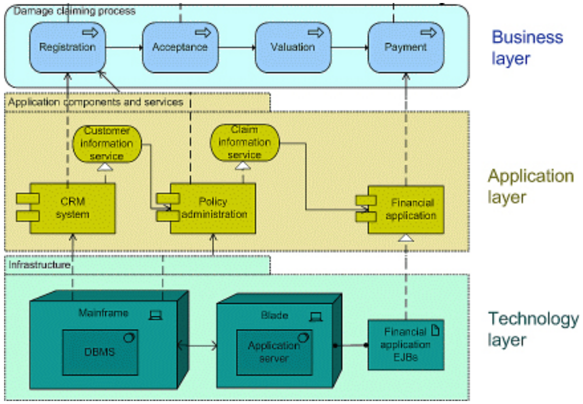


MS PowerPoint clips and NetLogo simulations

2. Architects Overtaken by their Architecture

➢ At mid-scales, human artifacts are classically architected

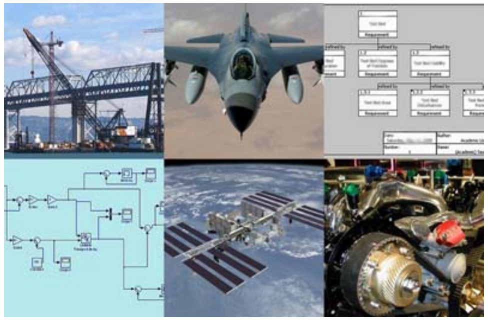
- ✓ a goal-oriented, top-down process toward one solution behaving in a limited # of ways
  - specification & design: hierarchical view of the entire system, exact placement of elts
  - testing & validation: controllability, reliability, predictability, optimality



ArchiMate EA (mockup)

➢ 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



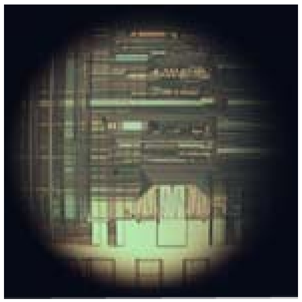
Systems engineering
http://en.wikipedia.org/wiki/Systems_engineering

Military parade
MS PowerPoint clips

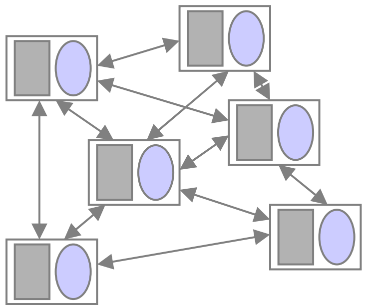
2. Architects Overtaken by their Architecture

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

Intel 80486DX2 chip
http://en.wikipedia.org/wiki/Microprocessor

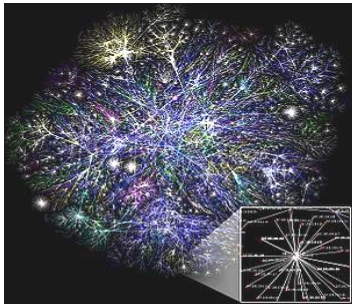


in hardware,

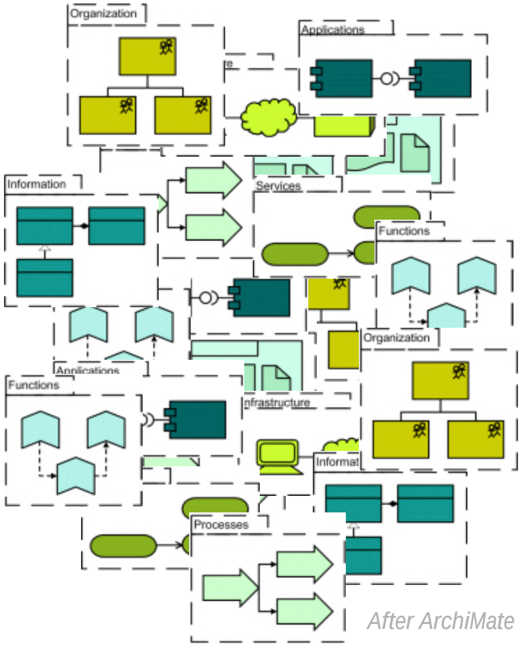


software,

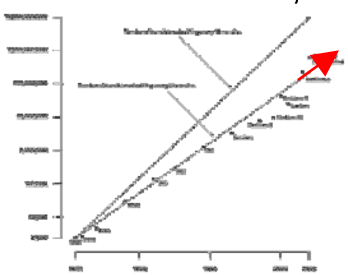
Visualization of Internet
http://en.wikipedia.org/wiki/Internet



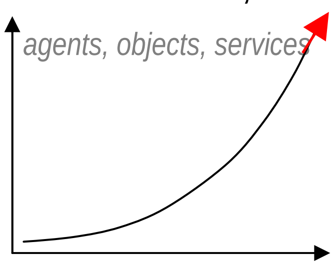
networks...



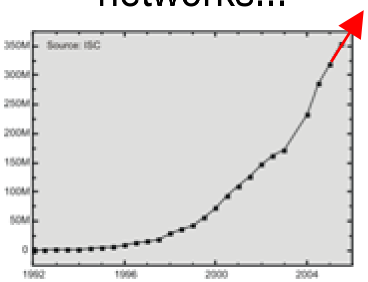
After ArchiMate



number of transistors/year



number of O/S lines of code/year



number of network hosts/year

... and enterprise architecture?

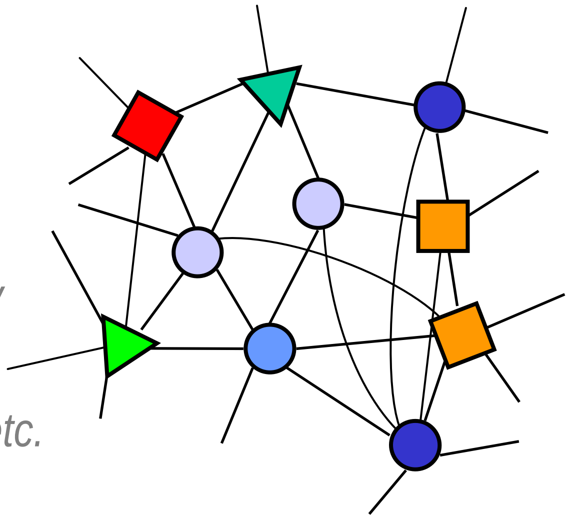
→ *trying to keep the lid on complexity won't work in these systems:*

- cannot place every part anymore
- cannot foresee every event anymore
- cannot control every process anymore

... but do we still *want* to?

2. Architects Overtaken by their Architecture

- Large-scale: *de facto* complexification of organizations, via techno-social networks
  - ✓ ubiquitous ICT capabilities connect people and infrastructure in unprecedented ways
  - ✓ giving rise to complex techno-social "ecosystems" composed of a multitude of human users and computing devices
  - ✓ explosion in size and complexity in all domains of society:
    - healthcare
    - education
    - business
    - energy & environment
    - defense & security
    - finance
  - ✓ from a centralized oligarchy of providers of
    data, knowledge, management, information, energy
  - ✓ to a dense heterarchy of *proactive participants:*
    patients, students, employees, users, consumers, etc.



→ *in this context, impossible to assign every single participant a predetermined role*

2. Architects Overtaken by their Architecture

TAKEAWAY

The "New Deal" of the ICT age

a) Overtaken

- ✓ how things turned around from top-down "architecting as usual" (at mid scales) and went bottom-up (at large-scales)—hopefully not yet belly-up
- ✓ large-scale techno-social systems exhibit spontaneous collective behavior that we don't quite understand or control yet

b) Embrace

- ✓ they also open the door to entirely new forms of enterprise characterized by increasing decentralization, emergence, and **dynamic adaptation**

c) Take over

- ✓ thus it is time to design new collaborative technologies to harness and guide this natural (and unavoidable) force of self-organization
- ✓ try to focus on the agents' potential for self-assembly, not the system

→ 4. Morphogenetic Engineering → 5. "Meta-Design"

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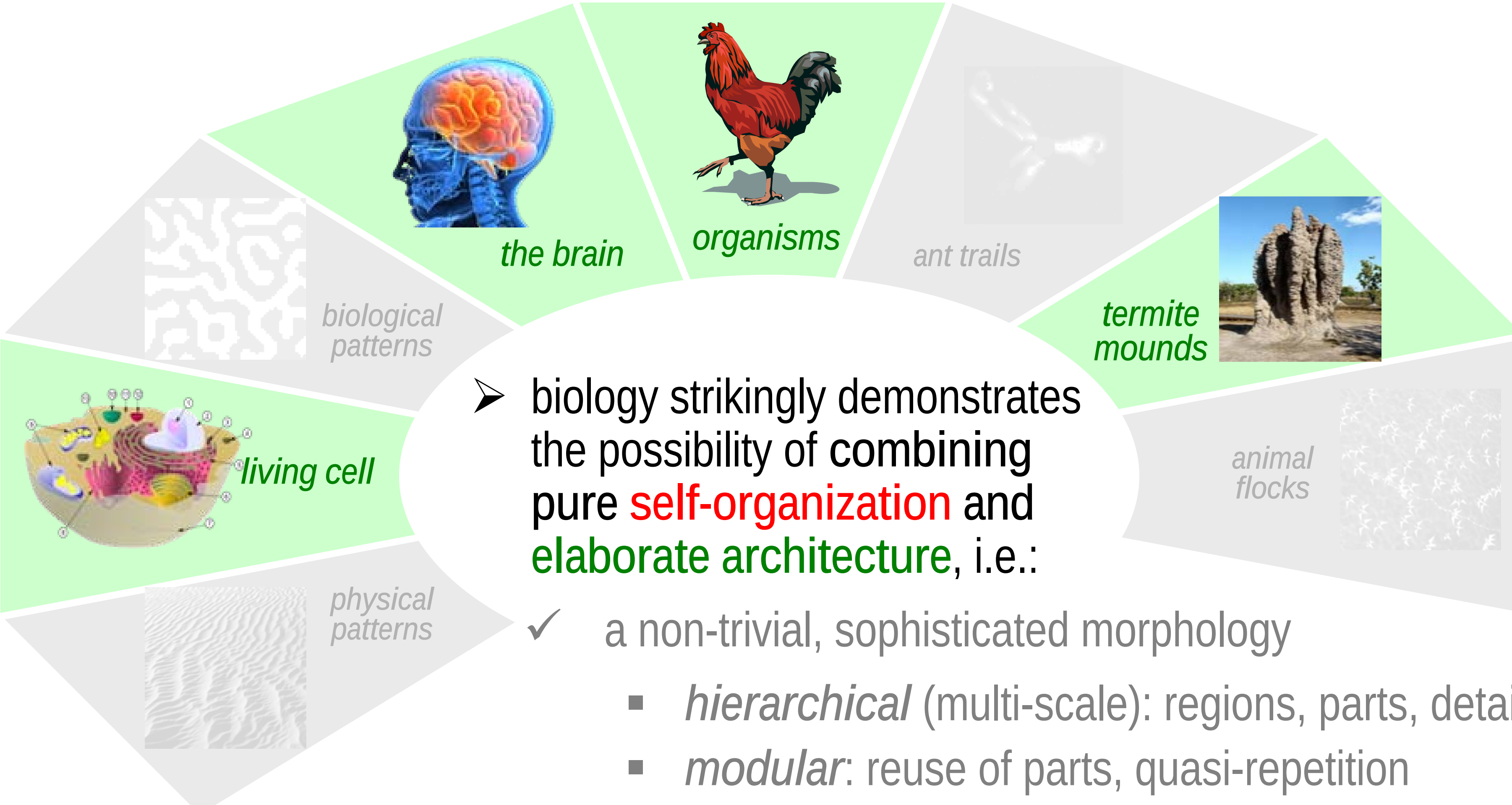
- "Simple"/random vs. architectured complex systems

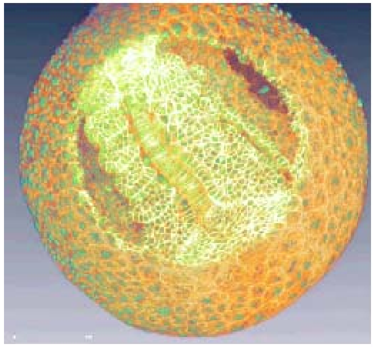


- biology strikingly demonstrates the possibility of combining pure self-organization and elaborate architecture, i.e.:
  - ✓ a non-trivial, sophisticated morphology
    - *hierarchical* (multi-scale): regions, parts, details
    - *modular*: reuse of parts, quasi-repetition
    - *heterogeneous*: differentiation,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

3. Architecture Without Architects

➢ Ex: Morphogenesis – Biological development

Chick embryo development
after Ernst Haeckel

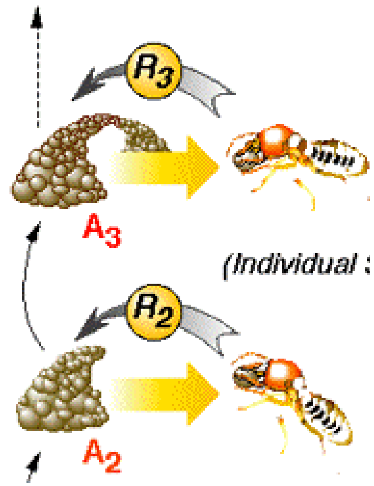


Nadine Peyriéras, Paul Bourgine et al.
Embryomics & BioEmergences FP6 projects

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

➢ Ex: Swarm intelligence – Termite mounds

Termite mound
en.wikipedia.org/wiki/Termite#Mounds

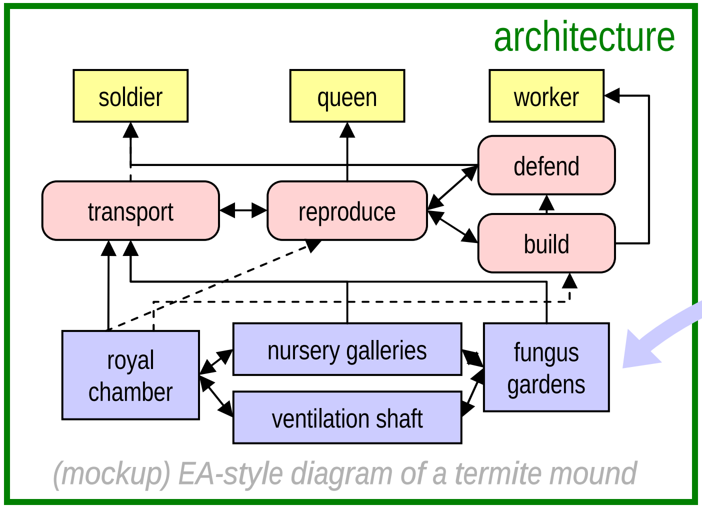


Termite stigmergy
(after Paul Grassé; from Solé and Goodwin, "Signs of Life", Perseus Books)

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

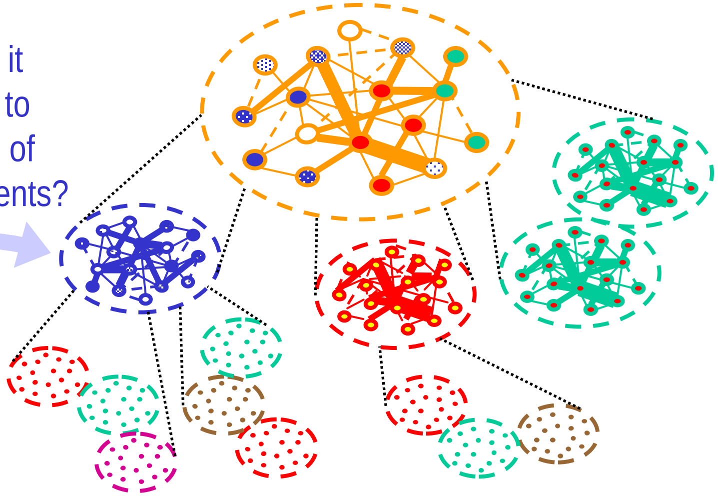
3. Architecture Without Architects

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



(mockup) EA-style diagram of a termite mound

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



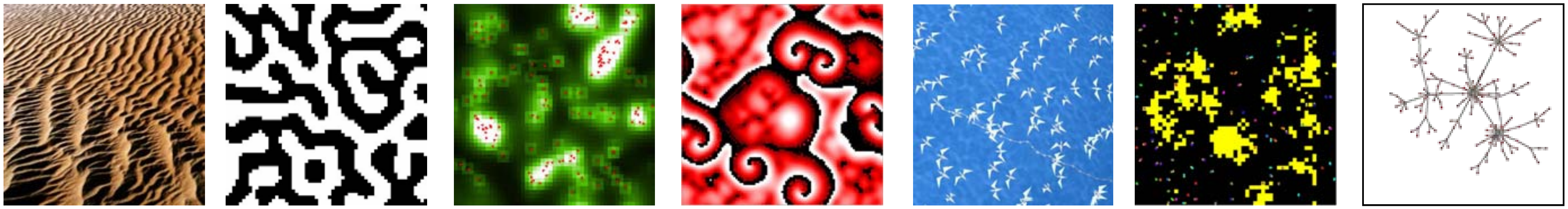
→ *cells and social insects have successfully "aligned business and infrastructure" for millions of years without any architect telling them how to*

3. Architecture Without Architects

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

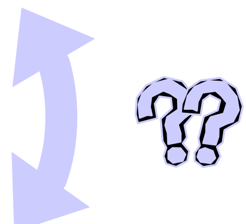
(a) "simple"/random self-organization

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



more architecture

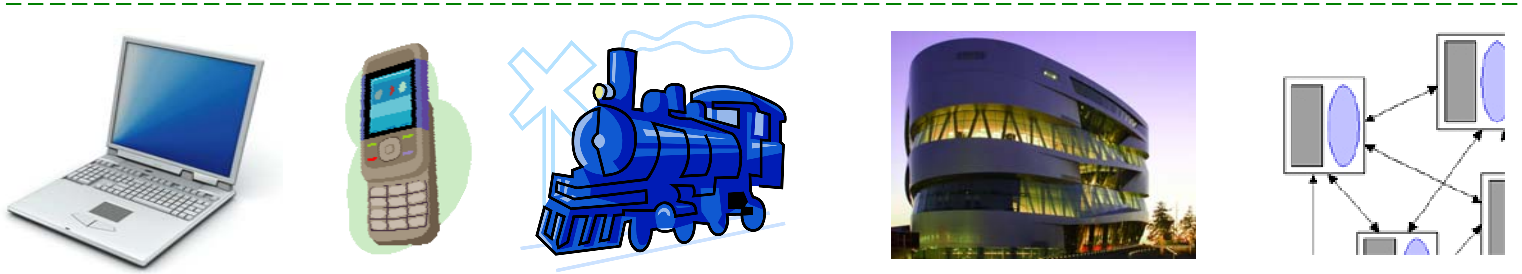
gap to fill



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

more self-organization

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

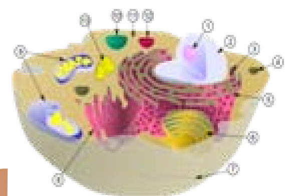


MS PowerPoint clips

3. Architecture Without Architects

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

(b) natural self-organized architecture

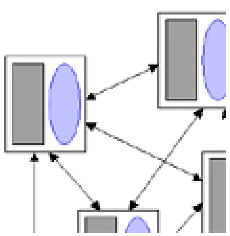


natural

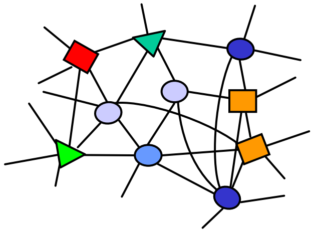
more architecture

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

. . . .



SYMBRION Project



. . . .

artificial

more self-organization

- self-forming robot swarm
- self-programming software
- self-connecting micro-components
- self-reconfiguring manufacturing plant
- self-stabilizing energy grid
- self-deploying emergency taskforce

. . . self-architecting enterprise?

3. Architecture Without Architects

RECAP Toward a reconciliation of complex systems and ICT

3. Architecture Without Architects: ICT-like CS

✓ Some natural complex systems strikingly demonstrate the possibility of combining pure self-organization and elaborate architectures

→ *how can we extract and transfer their principles to human artifacts—such as EA?*

2. Architects Overtaken by their Architecture: CS-like ICT

✓ Conversely, mid- to large-scale techno-social systems already exhibit complex systems effects—albeit still uncontrolled and, for most of them, unwanted at this point

→ *how can we regain (relative) control over these "golems"?*

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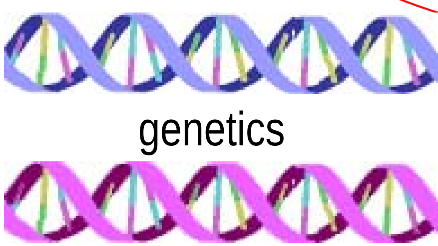
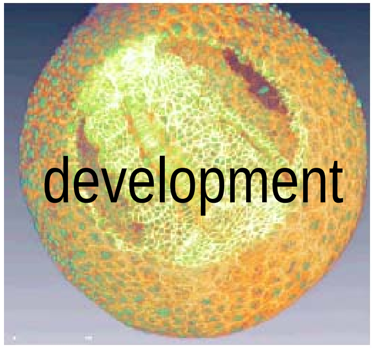
Or how to organize spontaneity

4. Morphogenetic Engineering (ME)

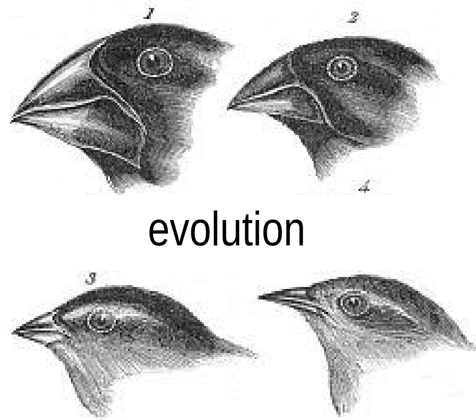
- A major source of inspiration: biological morphogenesis— the epitome of a self-architecting system

  → *thus, part of ME: exploring computational multi-agent models of evolutionary development ...*

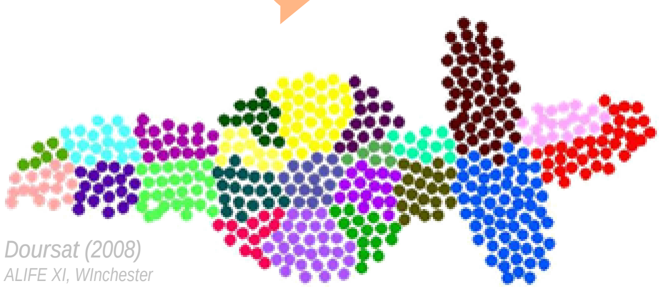




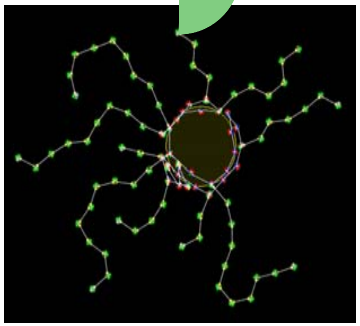
Nadine Peyriéras, Paul Bourgine et al. (Embryomics & BioEmergences)



Darwin's finches http://en.wikipedia.org/wiki/Evolution



Doursat (2008) ALIFE XI, Winchester



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

... toward possible outcomes in distributed, decentralized engineering systems

4. Morphogenetic Engineering

A closer look at morphogenesis: it couples assembly and patterning

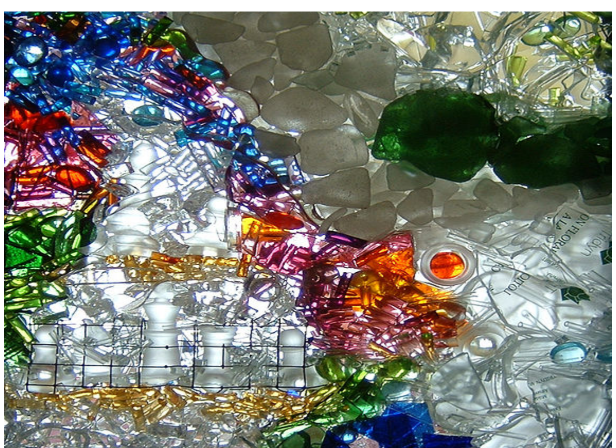
➢ Sculpture → forms

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

"shape from patterning"

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

➢ Painting → colors



Guy Simard, Vitrail à verre libre
http://fr.wikipedia.org/wiki/Vitrail

"patterns from shaping"

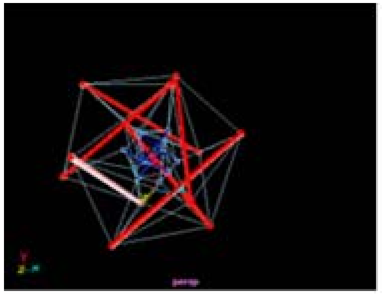
- ✓ new color regions appear (domains of genetic expression) triggered by deformations

4. Morphogenetic Engineering

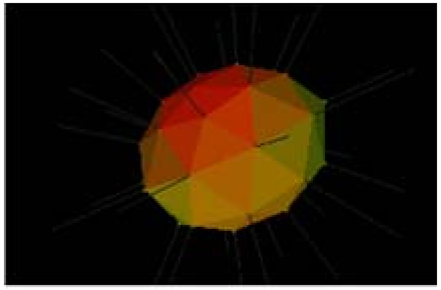
A closer look at morphogenesis: ⇔ it couples mechanics and genetics

➢ Cellular mechanics

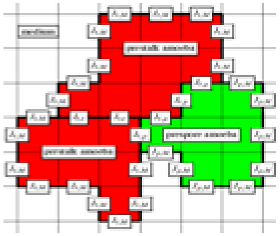
- ✓ adhesion
- ✓ deformation / reformation
- ✓ migration (motility)
- ✓ division / death



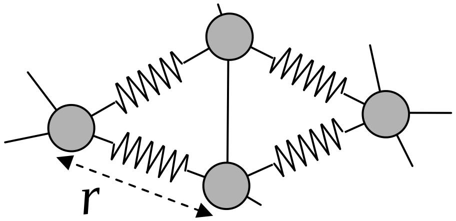
Tensional integrity
Donald Ingber, Harvard



Deformable volume
Doursat, simul. by Delile

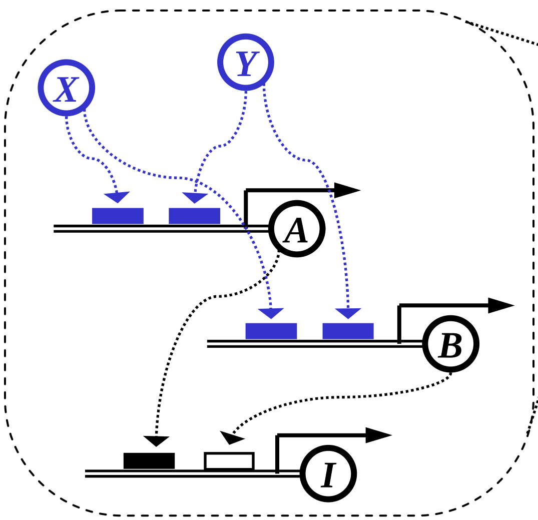


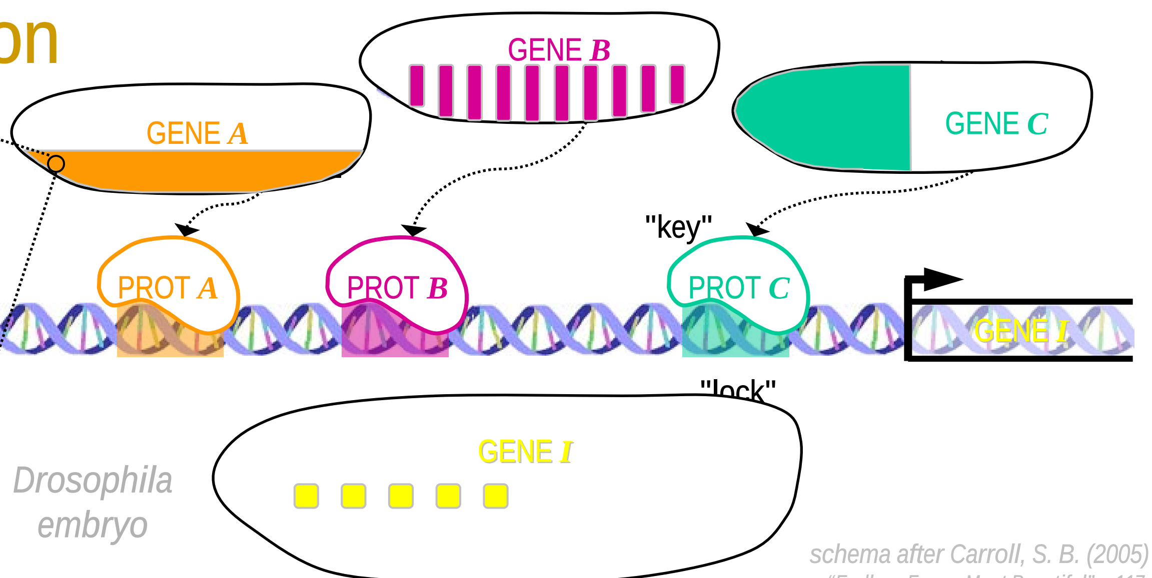
Cellular Potts model
Graner, Glazier, Hogeweg
http://www.compucell3d.org



Spring-mass model
Doursat (2009) ALIFE XI

➢ Genetic regulation



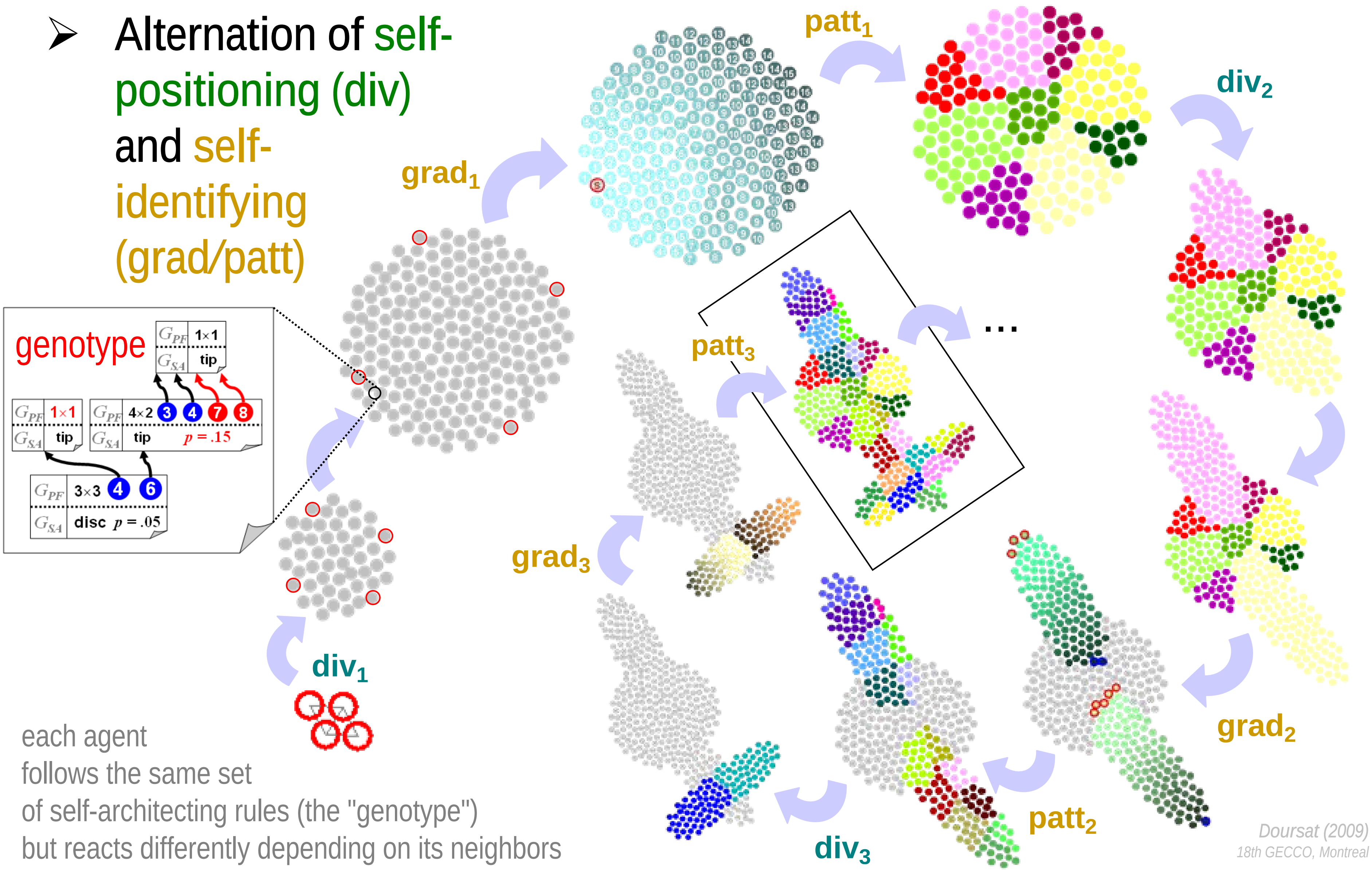


schema after Carroll, S. B. (2005) "Endless Forms Most Beautiful", p117

4. Morphogenetic Engineering

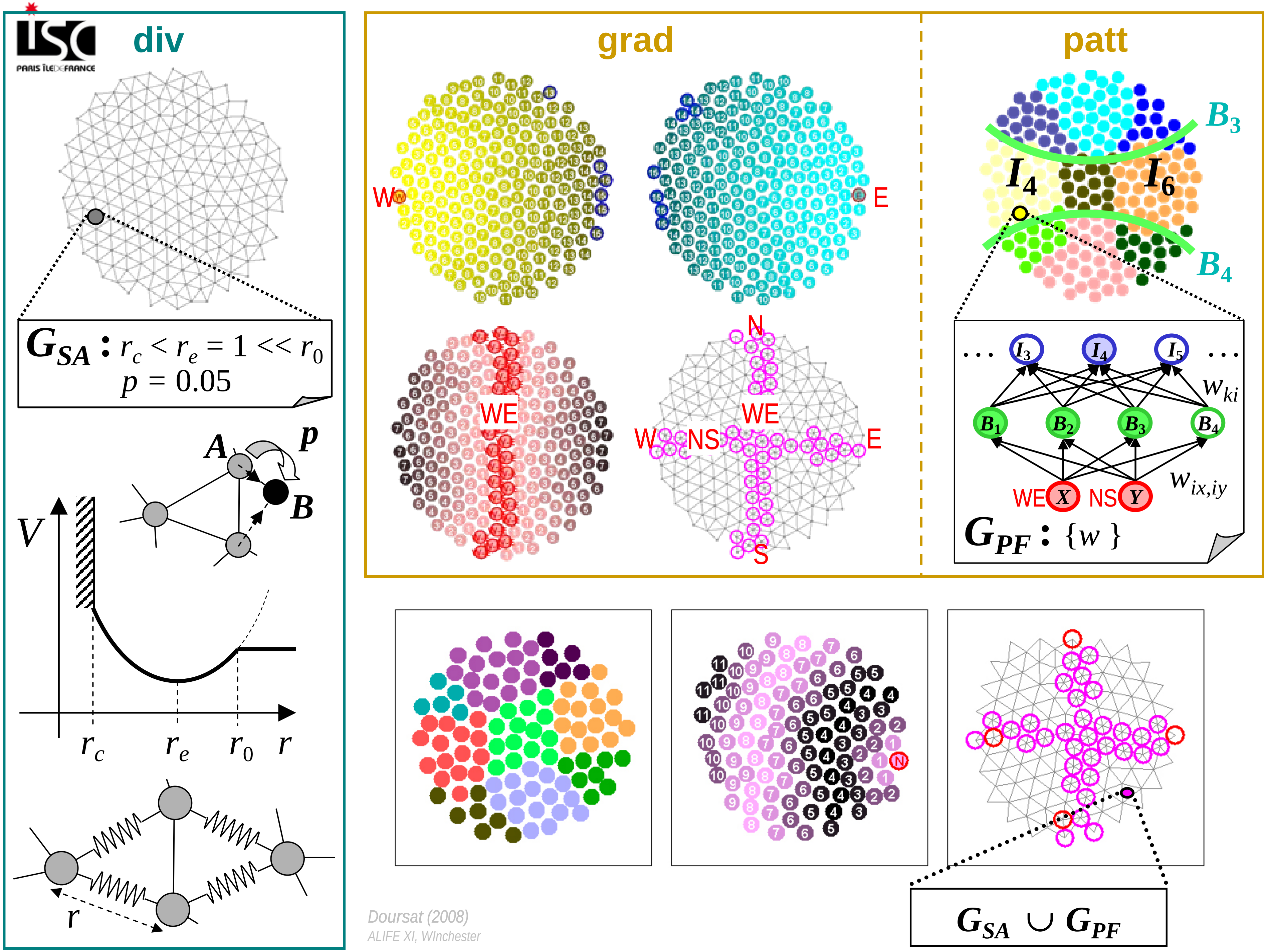
Capturing the essence of morphogenesis in an Artificial Life agent model

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

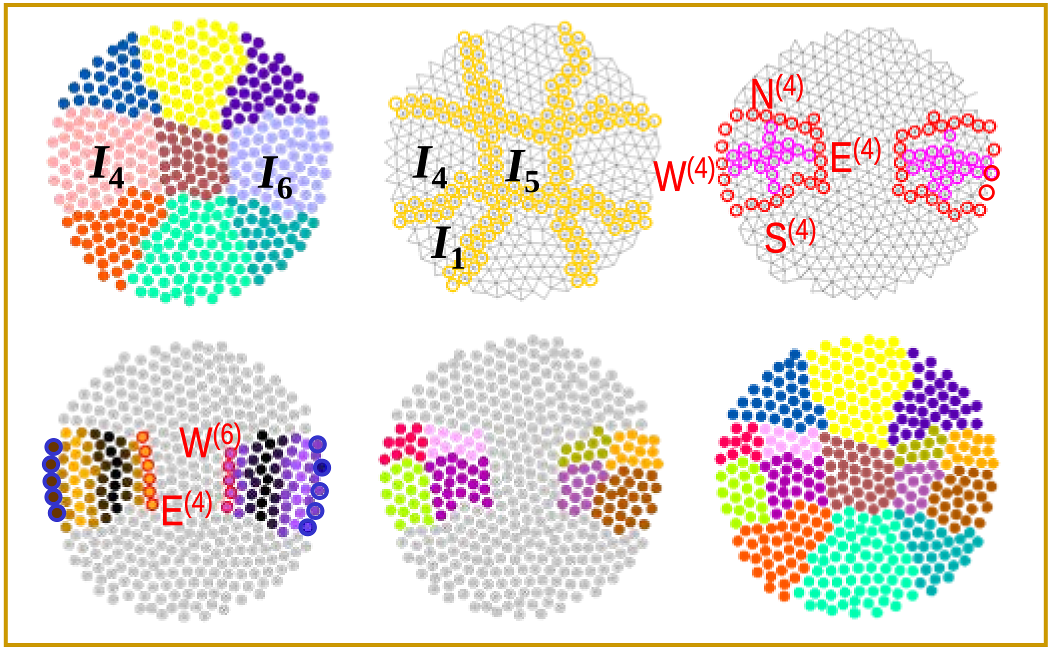


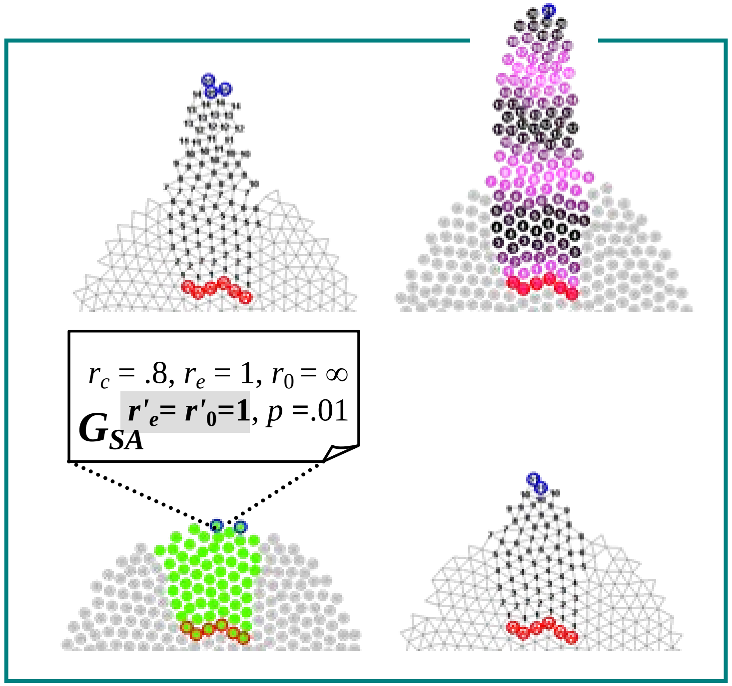
each agent
follows the same set
of self-architecting rules (the "genotype")
but reacts differently depending on its neighbors

Doursat (2009)
18th GECCO, Montreal

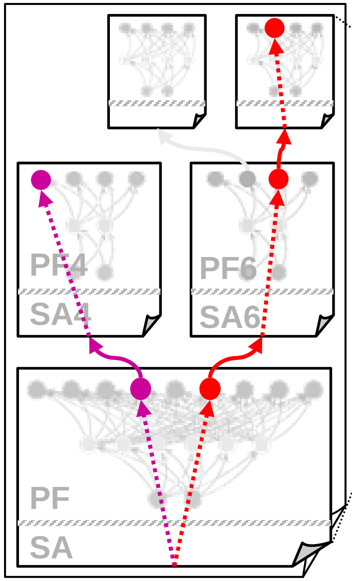

div
grad
patt
G_{SA} : $r_c < r_e = 1 << r_0$
$p = 0.05$
A
B
p
V
r_c
r_e
r_0
r
W
E
WE
N
NS
S
B_3
B_4
I_4
I_6
I_3
I_5
B_1
B_2
w_{ki}
$w_{ix,iy}$
X
Y
G_{PF} : {w}
$G_{SA} \cup G_{PF}$
Doursat (2008)
ALIFE XI, Winchester

4. Morphogenetic Engineering

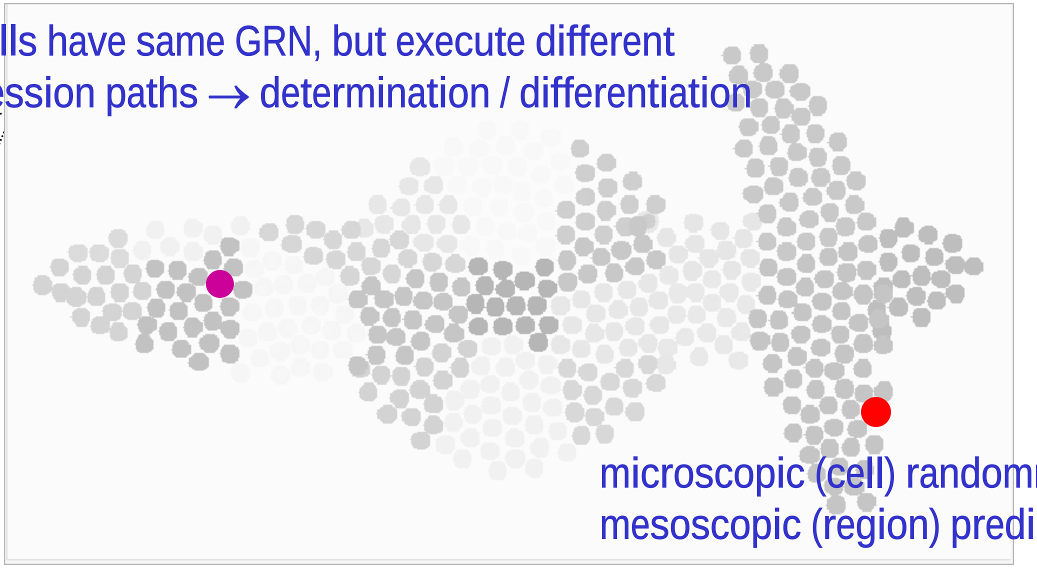




Doursat (2008)
ALIFE XI, Winchester



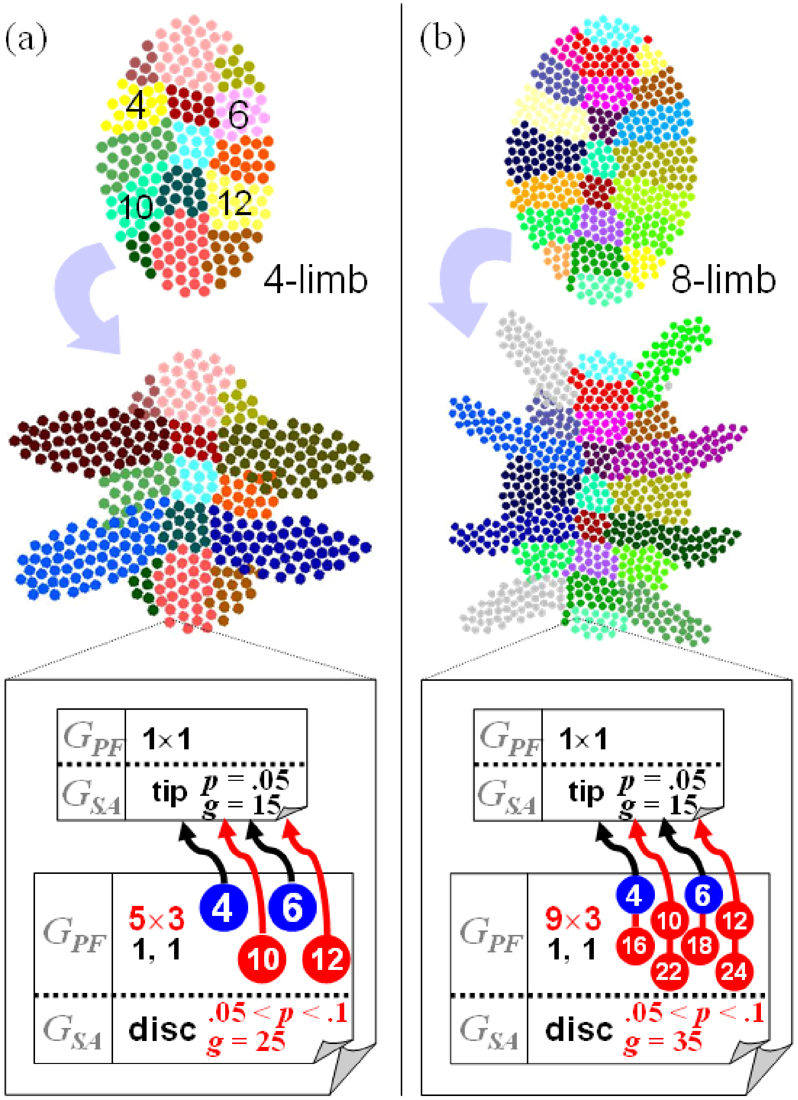
all cells have same GRN, but execute different expression paths → determination / differentiation

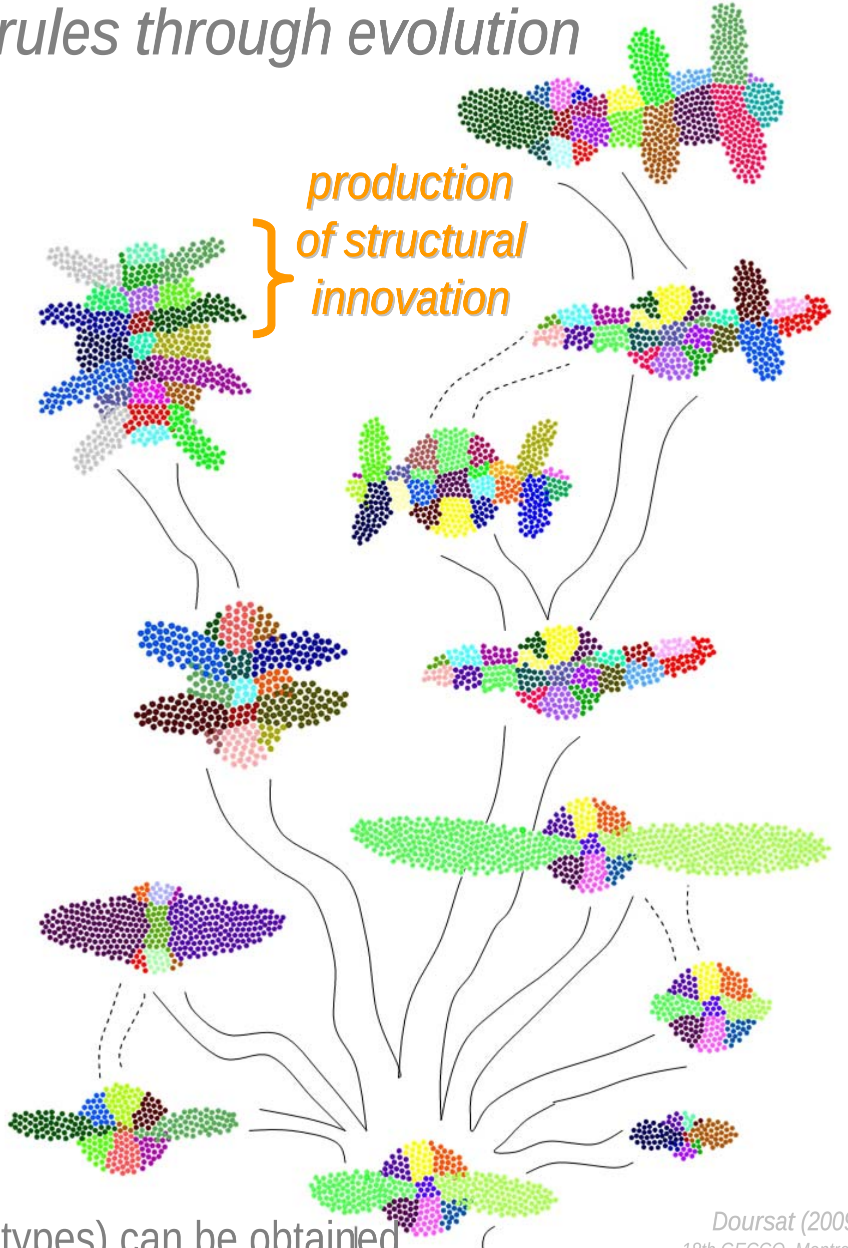


microscopic (cell) randomness, but mesoscopic (region) predictability

4. Morphogenetic Engineering

Changing the agents' self-architecting rules through evolution



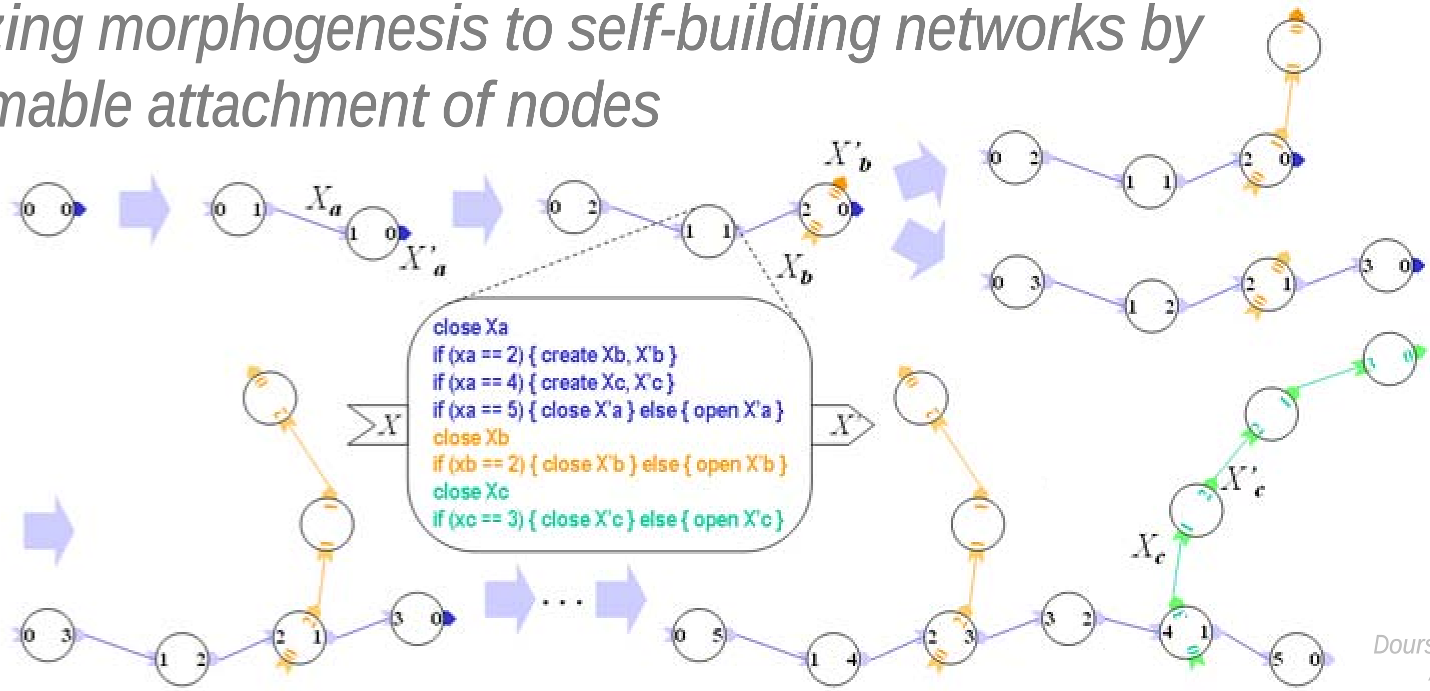


by tinkering with the genotype, new architectures (phenotypes) can be obtained

Doursat (2009)
18th GECCO, Montreal

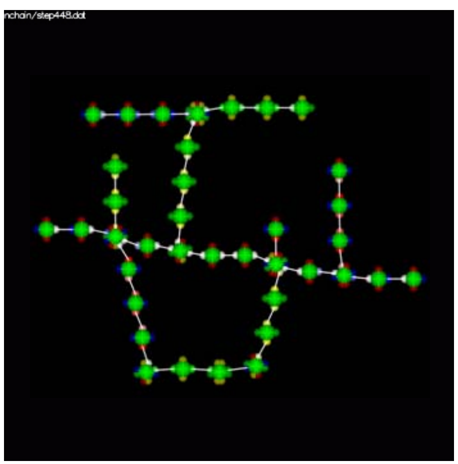
4. Morphogenetic Engineering

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

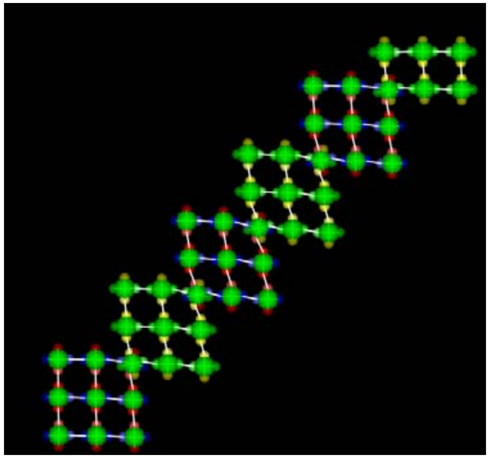


Doursat & Ulieru (2008)
Autonomics 2008, Turin

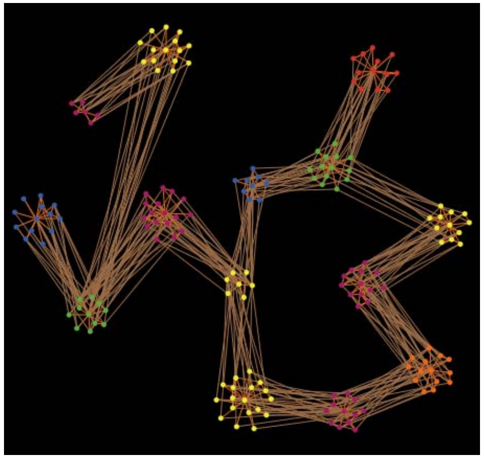
simulations by Adam MacDonald, U of New Brunswick



single-node
composite branching

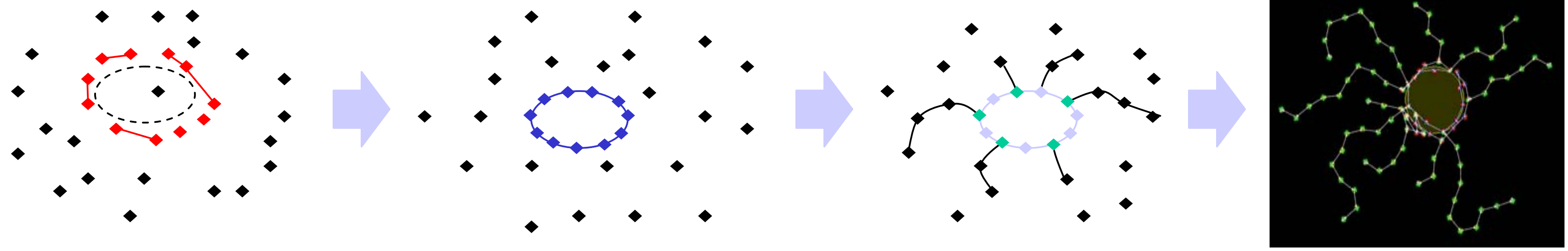


iterative lattice pile-up



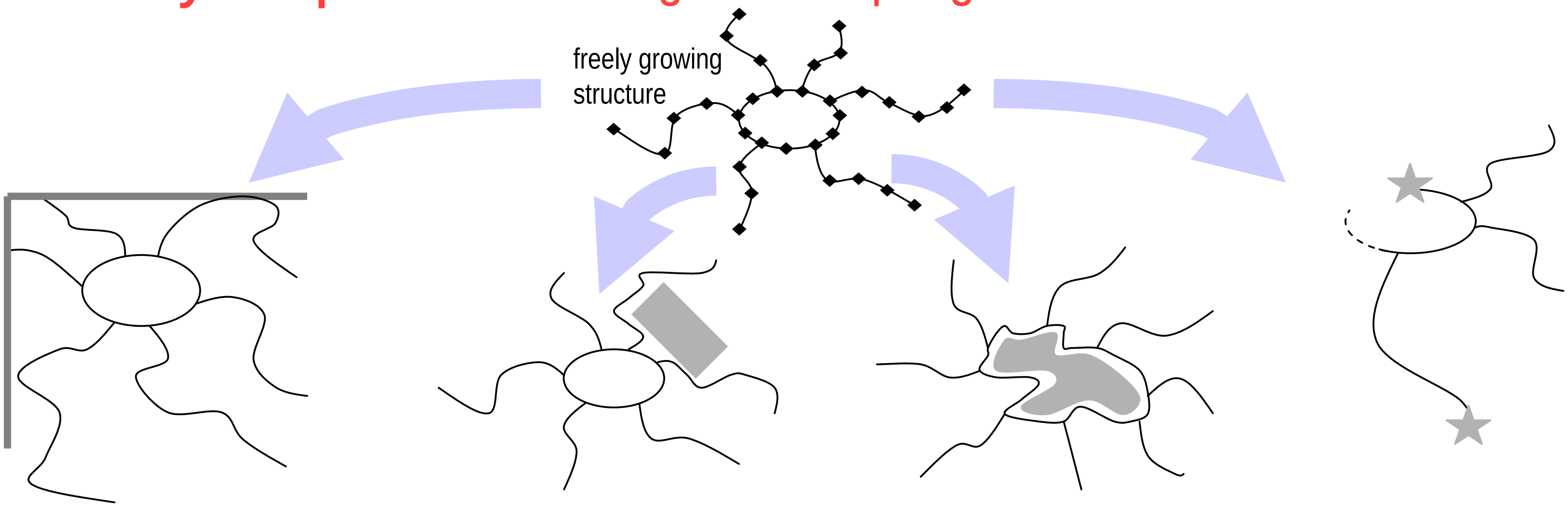
clustered
composite branching

Development: growing an intrinsic architecture

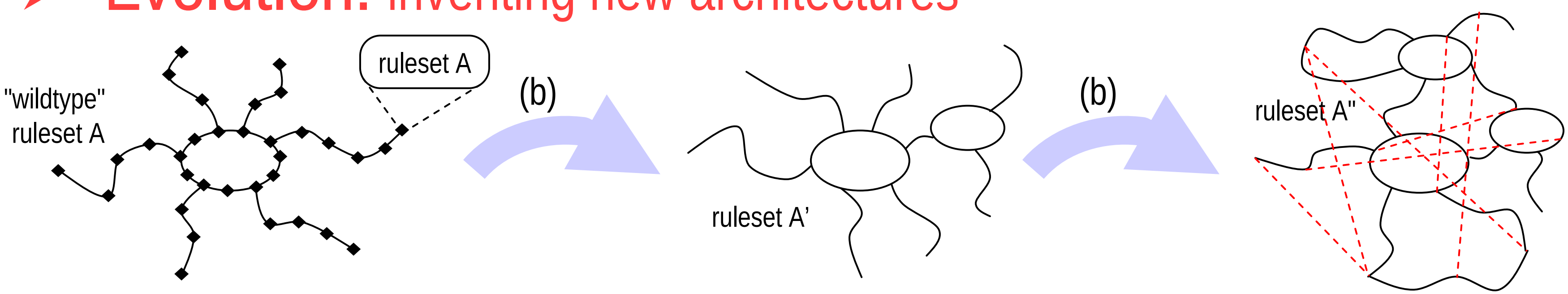


Ulieru & Doursat (2010) ACM TAAS
simulation by Adam MacDonald, UNB

Polymorphism: reacting and adapting to the environment



Evolution: inventing new architectures



4. Morphogenetic Engineering (ME)

TAKEAWAY ME is about programming the agents of emergence

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

b) ME brings a new focus on "complex systems engineering"
   - ✓ exploring the artificial design and implementation of **autonomous systems capable of developing sophisticated, heterogeneous morphologies** or architectures without central planning or external lead

c) Related *emerging ICT disciplines* and application domains
   - ✓ *amorphous/spatial computing* (MIT)
   - ✓ *organic computing* (DFG, Germany)
   - ✓ *pervasive adaptation* (FET, EU)
   - ✓ *ubiquitous computing* (PARC)
   - ✓ *programmable matter* (CMU)
   - ✓ swarm robotics, modular/reconfigurable robotics
   - ✓ mobile ad hoc networks, sensor-actuator networks
   - ✓ synthetic biology, etc.

ARCHITECTURE AND SELF-ORGANIZATION

1. What are Complex Systems?

- Decentralization
- Emergence
- Self-organization

2. Architects Overtaken by their Architecture

Designed systems that became suddenly complex

3. Architecture Without Architects

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

but were not

4. Morphogenetic Engineering

From cells and insects to robots and networks

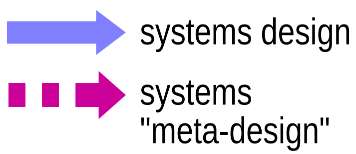
5. The New Challenge of "Meta-Design"

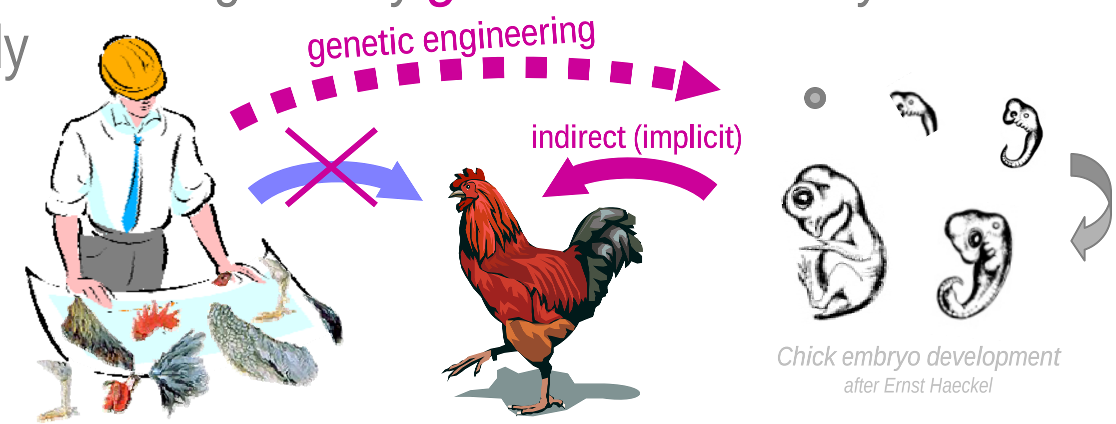
Or how to organize spontaneity

5. The New Challenge of "Meta-Design"

➢ ME and other emerging ICT fields are all proponents of the shift from design to "meta-design"

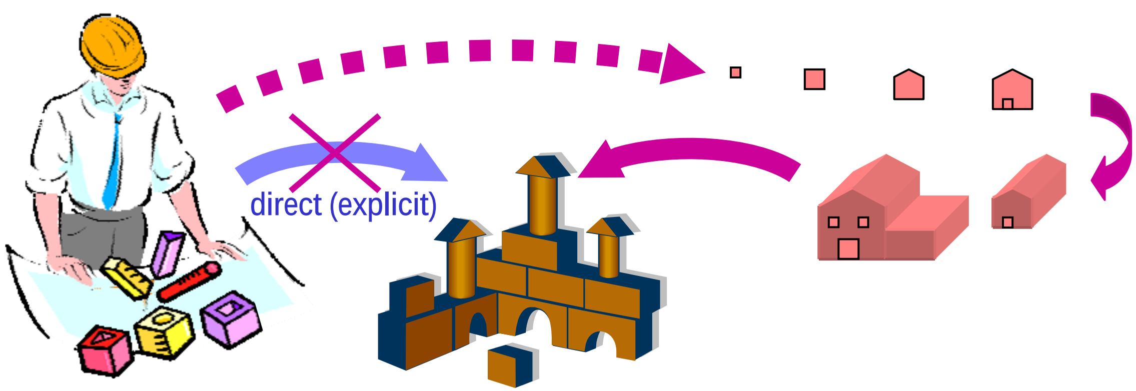
- ✓ <u>fact</u>: organisms endogenously ***grow*** but artificial systems ***are built*** exogenously





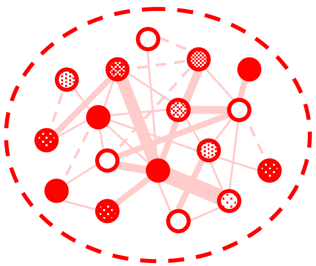
- ✓ <u>challenge</u>: can architects "step back" from their creation and only *set the generic conditions* for systems to self-assemble?

instead of building the system from the top ("phenotype"),
<u>program the components</u> from the bottom ("genotype")



5. The New Challenge of "Meta-Design"

- Between natural and engineered emergence

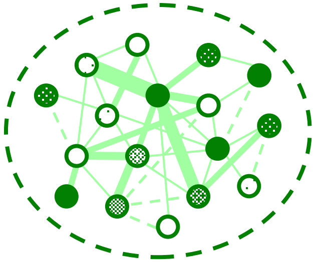


CS science: observing and understanding "natural", spontaneous emergence (including human-caused)
→ *Agent-Based Modeling (ABM)*

But CS meta-design is not without its paradoxes...

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

CS meta-design: *fostering and guiding complex systems (e.g. techno-social)*



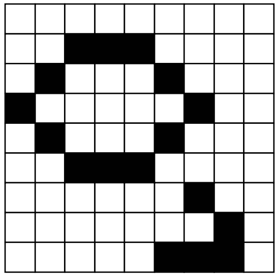
CS engineering: creating and programming a new "artificial" emergence
→ *Multi-Agent Systems (MAS)*

5. The New Challenge of "Meta-Design"

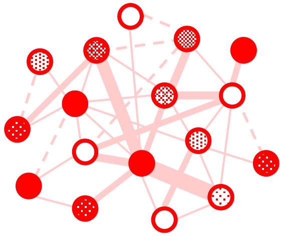
➢ People: the ABM modeling perspective of the social sciences

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

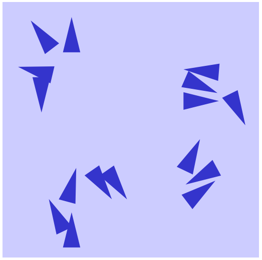
- ✓ main origin: cellular automata (CA)
  - von Neumann self-replicating machines → Ulam's "paper" abstraction into CAs → Conway's *Game of Life*
  - based on ***grid*** topology



- ✓ 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*

5. The New Challenge of "Meta-Design"

- 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

5. The New Challenge of "Meta-Design"

TAKEAWAY **Getting ready to organize spontaneity**

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

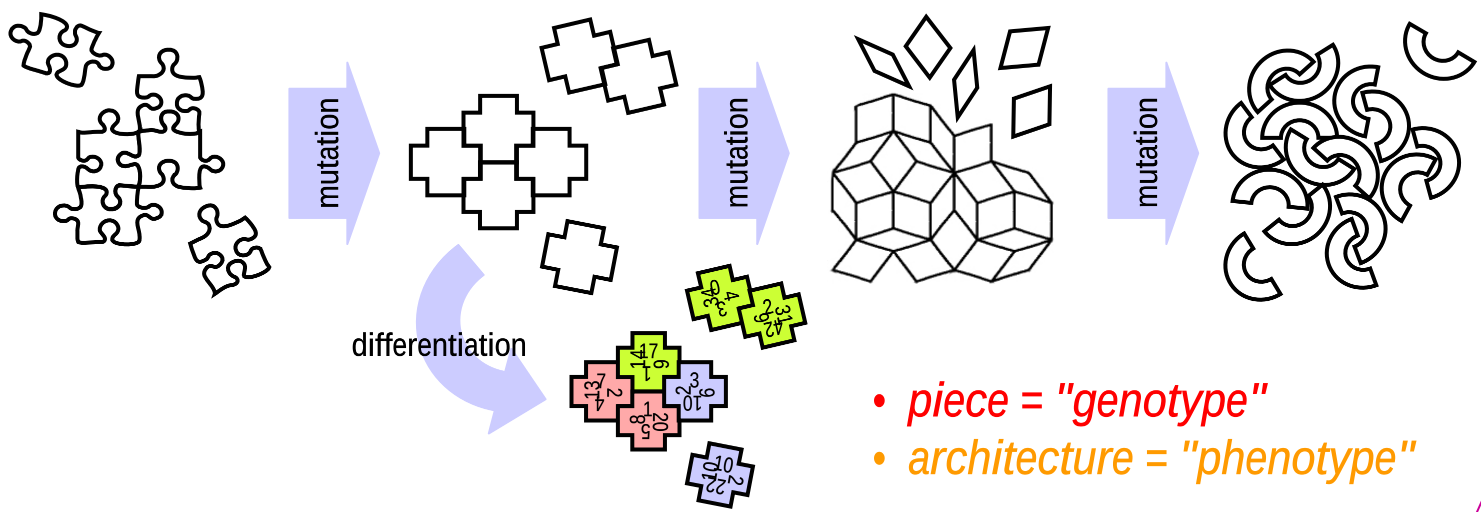
- ✓ Instead of assembling a construction yourself, shape its building blocks in a way that they self-assemble for you—and come up with new solutions

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"*

Architecture And Self-Organization

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Toward Self-Organized Enterprise Architecture?

Architecture Without Architects

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