Embryomorphic Engineering: From biological development to self-organized computational architectures

René Doursat
http://www.iscpif.fr/~doursat
Systems that are **self-organized and architectured**

- Free self-organization
- Meta-design the agents
- Decompose the system
- Self-organized architecture / architectured 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?
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. Embryomorphic Engineering
   From biological cells 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) decentralized: 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
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

- **Ex: Swarm intelligence – Insect colonies**
  - trails form by ants that follow and reinforce each other’s pheromone path
1. What are Complex Systems?

- **Ex: Collective motion – Flocking, schooling, herding**
  - Fish school (Eric T. Schultz, University of Connecticut)
  - Bison herd (Montana State University, Bozeman)
  - Separation, alignment and cohesion (*Boids* model, Craig Reynolds)
- Thousands of animals that adjust their position, orientation and speed wrt to their nearest neighbors
- NetLogo Flocking simulation

- **Ex: Diffusion and networks – Cities and social links**
  - Clusters and cliques of people who aggregate in geographical or social space
  - NetLogo urban sprawl simulation
  - "scale-free" network model
  - Cellular automata model
1. What are Complex Systems?

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

- The brain
- Organisms
- Ant trails
- Termite mounds
- Animal flocks
- Cities, populations
- Markets, economy
- Social networks
- Internet, Web
- Living cell
- Physical patterns
- Biological patterns
1. What are Complex Systems?

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?

3 main differences with traditional architecting

c) Self-organization: the system operates and changes 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 and let go"?
1. What are Complex Systems?

Paris Ile-de-France

National

Lyon Rhône-Alpes

4th French Complex Systems Summer School, 2010
1. What are Complex Systems?

A vast archipelago of precursor and neighboring disciplines

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

- Dynamics: behavior and activity of a system over time
  - Nonlinear dynamics & chaos
  - Stochastic processes
  - Systems dynamics (macro variables)

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)

multitude, statistics: large-scale properties of systems
  - Graph theory & networks
  - Statistical physics
  - Agent-based modeling
  - Distributed AI systems
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Complex systems seem so different from architected systems, and yet...

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At large scales, human superstructures are "natural" CS by their unplanned, spontaneous emergence and adaptivity... 

- geography: cities, populations
- people: social networks
- wealth: markets, economy
- technology: Internet, Web

... arising from a multitude of traditionally designed artifacts
- houses, buildings
- address books
- companies, institutions
- computers, routers
2. Architects Overtaken by their Architecture

- At mid-scales, human artifacts are classically architected

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

- 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
2. Architects Overtaken by their Architecture

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

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

→ 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  energy & environment
  - education  defense & security
  - business  finance
- from a centralized oligarchy of providers of *data, knowledge, management, information, energy*
- to a dense heterarchy of *proactive participants:*
  - patients, students, employees, users, consumers, etc.

→ in this context, impossible to assign every single participant a predetermined role
2. Architects Overtaken by their Architecture

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**

b) 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. Embryomorphic Engineering → 5. "Meta-Design"
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Morphological (self-dissimilar) systems:

pattern formation $\neq$ morphogenesis

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

—attributed to A. Turing, after his 1952 paper on morphogenesis
3. Architecture Without Architects

"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**

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

**Ex: Swarm intelligence – Termite mounds**

- Termites exhibit stigmergy, a form of indirect communication, as they construct termite mounds.

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*Termite mound* (J. McLaughlin, Penn State University)

*Termite stigmergy* (after Paul Grassé; from Solé and Goodwin, "Signs of Life", Perseus Books)
3. Architecture Without Architects

From "statistical" to "morphological" CS in inert matter / insect constructions / multicellular organisms

physical pattern formation

more intrinsic, sophisticated architecture

graains of sand + air

social insect constructions

biological morphogenesis

new inspiration

insects

network of ant trails
3. Architecture Without Architects

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

→ cells and social insects have successfully "aligned business and infrastructure" for millions of years without any architect telling them how to...
Many self-organized systems exhibit random patterns...

(a) "simple"/random self-organization

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

(d) direct design (top-down)
3. Architecture Without Architects

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

(b) natural self-organized architecture

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

- 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: 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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4. Embryomorphistic 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 ...

... toward possible outcomes in distributed, decentralized engineering systems
4. Embryomorphic Engineering

A closer look at morphogenesis: it couples assembly and patterning

- **Sculpture → forms**
  - "shape from patterning"
  - the forms are "sculpted" by the self-assembly of the elements, whose behavior is triggered by the colors

- **Painting → colors**
  - "patterns from shaping"
  - new color regions appear (domains of genetic expression) triggered by deformations

Adám Szabó, *The chicken or the egg* (2005)

Niki de Saint Phalle

http://www.szaboadam.hu
4. Embryomorphic Engineering

A closer look at morphogenesis: ↔ it couples *mechanics* and *genetics*

- **Cellular mechanics**
  - adhesion
  - deformation / reformation
  - migration (motility)
  - division / death

- **Genetic regulation**

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*after Carroll, S. B. (2005) Endless Forms Most Beautiful, p117*
4. Embryomorphic Engineering

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

Cellular mechanics
- modification of cell size and shape
- mechanical stress, mechano-sensitivity
- growth, division, apoptosis
- change of cell-to-cell contacts
- change of signals, chemical messengers

Genetic regulation
- gene regulation
- diffusion gradients ("morphogens")

∃ Cellular mechanics
∃ Genetic regulation
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.
$G_{SA}: \ r_c < r_e = 1 \ll r_0$

$p = 0.05$
grad

[Diagram with various symbols and numbers indicating directions like NE, NW, SE, and SW]
patt

\[ G_{PF}: \{w \} \]
4. Embryomorphitic Engineering

Programmed patterning (patt): the hidden embryo atlas

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

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

c) gene regulatory network used by each agent to calculate its expression levels, here: $B_1 = \sigma(1/3 - X)$, $B_3 = \sigma(2/3 - Y)$, $I_4 = B_1B_3(1 - B_4)$, etc.
The image contains a complex diagram with various components labeled as `div`, `grad`, and `patt`. The text includes mathematical expressions and symbols, such as:

- $G_{SA}: r_c < r_e < 1 << r_0$
- $p = 0.05$
- $G_{PF}: \{w\}$

The diagram also includes references to the work of Doursat (2008) and contains a symbol for `GSA ∪ GPF`.

The content suggests a study or analysis related to some form of graph theory or network analysis, possibly within the field of artificial life or computational neuroscience.
4. Embryomorphic Engineering

Morphological refinement by iterative growth

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

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

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

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

microscopic (cell) randomness, but mesoscopic (region) predictability
Quantitative mutations: limb thickness

(a) (b) (c)

wild type

thin-limb

thick-limb

4. Embryomorphomorphic Engineering

Embryomorphomorphic Engineering
Quantitative mutations: body size and limb length

(a) small
(b) long-limb
(c) short-limb

![Diagram showing quantitative mutations affecting body size and limb length.](image-url)
Qualitative mutations: limb position and differentiation

antennapedia homology by duplication divergence of the homology

(a) antennapedia
(b) duplication (three-limb)
(c) divergence (short & long-limb)
4. Embryomorphistic Engineering

➤ Qualitative mutations: 3rd-level digits

(a) (b) (c)
4. Embryomorphemic Engineering

Changing the agents’ self-architecting rules through evolution

by tinkering with the genotype, new architectures (phenotypes) can be obtained
4. Embryomorphomic Engineering

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

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

4. Embryomorphie Engineering

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

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

Doursat & Ulieru (2008)
**Development:** growing an intrinsic architecture

**Polymorphism:** reacting and adapting to the environment

**Evolution:** inventing new architectures
4. Embryomorphics Engineering (ME)

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

- **Fact**: organisms endogenously grow but artificial systems are built exogenously.

- **Challenge**: 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"), program the components 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)
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.
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"
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