Causing and influencing patterns by designing the agents:
Complex systems made simpler?

René Doursat
http://www.iscpif.fr/~doursat
INSTITUT DES SYSTEMES COMPLEXES
Paris Ile-de-France
SISC'09
25-27 novembre 2009
Auditorium du CNRS
3, rue Michel-Ange
75016 Paris

3e Colloque National
RNSC / ISC-PiF / iXXi

Le Réseau National des Systèmes Complexes (RNSC), l'Institut des Systèmes Complexes Paris Île-de-France (ISC-PiF) et l'Institut des Systèmes Complexes Rhône-Alpes (iXXI) s'associent pour présenter la troisième édition du Colloque national des systèmes complexes.

Vers une science et ingénierie des systèmes complexes

île de France
From natural CS to designed CS (and back)

The challenges of complex systems (CS) research

CS science: understanding "natural" CS
(spontaneously emergent, including human activity)

Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

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

CS engineering: designing a new generation of "artificial" CS (harnessed & tamed, including nature)
(a) Genotypical / generative level
Designing (evolving) the agents, not the system:
Lessons from morphogenesis

→ Causality from micro to macro level

(b) Phenotypical / phenomenological level
Describing the system, not the agents:
Lessons from neural networks

→ Causality within the mesocopic level
(a) Genotypical / generative level
Designing (evolving) the agents, not the system: Lessons from morphogenesis

→ Causality from micro to macro levels
Systems that are **self-organized** and **architectured**

- **Free self-organization**
- **Deliberate design**

**Designed self-organization / self-organized design**

**The challenge for complex systems:** integrate a true **architecture**

**The challenge for complicated systems:** integrate **self-organization**
Toward programmable self-organization

- **Self-organized systems**
  - a myriad of self-positioning agents
  - collective order is not imposed from outside (only influenced)
  - comes from purely *local* information & interaction around each agent
  - no agent possesses the global map or goal of the system
  - but every agent may contain all the *rules* that contribute to it

- **Structured systems**
  - true *architecture*: non-trivial, complicated morphology
    - *hierarchical*, multi-scale: regions, parts, details, agents
    - *modular*: reuse, quasi-repetition
    - *heterogeneous*: differentiation & divergence in the repetition
  - *random* at the microscopic level, *but reproducible* (quasi deterministic) at the mesoscopic and macroscopic levels
Exemple of hybrid mesoscopic model

Recursive morphogenesis

genotype

grad₁

div₁

patt₁

div₂

patt₂

div₃

patt₃

grad₂

grad₃
\( G_{SA}: r_c < r_e = 1 << r_0 \)
\( p = 0.05 \)

\( G_{PF}: \{ w \} \)
Hierarchical morphogenesis

\( r_c = .8, r_c = 1, r_0 = \infty \)

\( G_{SA} \)

\( r'_c = r'_0 = 1, p = .01 \)
Multi-agent evolutionary development (evo-devo)

- Genotype mutations → phenotype variations (qualitative)

Genotype mutations: antennapedia

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

- duplication (three-limb)
  - PF × SA 1×1 tip p = .05
  - PF × SA 3×3 disc p = .05

- divergence (short & long-limb)
  - PF × SA 1×1 tip p = .05
  - PF × SA 3×3 disc p = .05
  - PF × SA 1×1 tip p = .03
  - PF × SA 1×1 tip p = .1
  - PF × SA 3×3 disc p = .05
Multi-agent evolutionary development (evo-devo)

- Genotype mutations → phenotype variations (qualitative)
Multi-agent evolutionary development (evo-devo)

Artificial phylogenetic tree

future directions:
• better biomechanics (3D): cytoskeleton, migration
• better gene regulation

optimization & validation of parameters
The self-made puzzle of “evo-devo” engineering

Development: the missing link of the Modern Synthesis...

Genotype \[\approx ( ) \approx\] Phenotype

- **Genotype**
  - More or less direct representation
  - Generic elementary rules of self-assembly

- **Phenotype**
  - Macroscopic, emergent level
  - Microscopic, componential level

- **Transformation**
  - More or less direct representation
  - ≈ ( ) ≈
Toward “evo-devo” engineering

... and of Evolutionary Computation: toward “meta-design”

- organisms endogenously grow but artificial systems are built exogenously

- could engineers “step back” from their creation and only set generic conditions for systems to self-assemble?

instead of building the system from the top (phenotype), program the components from the bottom (genotype)
Morphogenetic Engineering Workshop

ISC, Paris, June 2009
ANTS Conference, Brussels, Sept 2010
Springer book, end 2010

Exploring various engineering approaches to the artificial design and implementation of autonomous systems capable of developing complex, heterogeneous morphologies
The evolutionary “self-made puzzle” paradigm

- Construe systems as **self-assembling** (developing) **puzzles**
- Design and **program their pieces** (the “genotype”) 
- Let them evolve by **variation of the pieces** and **selection** of the architecture (the “phenotype”)

**Genotype: rules at the **micro** level of agents**
- ability to **search** and **connect** to other agents
- ability to **interact** with them over those connections
- ability to **modify** one’s internal state (differentiate) and rules (evolve)
- ability to provide a specialized local **function**

**Phenotype: collective behavior, visible at the **macro** level**
The evolutionary “self-made puzzle” paradigm

a. Construe systems as self-assembling (developing) puzzles

b. Design and program their pieces (the “genotype”)

c. Let them evolve by variation of the pieces and selection of the architecture (the “phenotype”)
Beyond statistics: heterogeneity, modularity, reproducibility

- Complex systems can be much more than a "soup"
  - "complex" doesn’t necessarily imply "homogeneous"...
    → heterogeneous agents and diverse patterns, via positions
  - "complex" doesn’t necessarily imply "flat" (or "scale-free")...
    → modular, hierarchical, detailed architecture (at specific scales)
  - "complex" doesn’t necessarily imply "random"...
    → reproducible patterns relying on programmable agents
Paradoxes in approaching complexity

- The paradoxes of complex systems engineering
  - can autonomy be planned?
  - can decentralization be controlled?
  - can evolution be designed?

- Can we expect specific characteristics from systems that we otherwise let free to assemble and invent themselves?

- Ultimate goal: "design-by-emergence" of pervasive computing and communication environments able to address and harness complexity
From "scale-free" to structured networks

single-node composite branching

iterative lattice pile-up

clustered composite branching
Self-knitting networks

- Not random, but **programmable** attachment

- a generalisation of morphogenesis in \( n \) dimensions

- the node routines are the *"genotype"* of the network
Order influenced (not imposed) by the environment

- Collaboration with Prof. Mihaela Ulieru, Canada Research Chair (UNB)
- Some simulations by Adam MacDonald (MS student at UNB), based on his software “Fluidix” (http://www.onezero.ca)
Toward concrete applications

Possible example: self-organized security (SOS) scenario

(mockup screens: not a simulation ... yet)
(b) Phenotypical / phenomenological level
Describing the system, not the agents:
Lessons from neural networks

→ Causality within the mesocopic level
It is not because the brain is an intricate network of microscopic causal transmissions (neurons activating or inhibiting other neurons) that the appropriate description at the mesoscopic functional level should be “signal / information processing”.

This denotes a confusion of levels: mesoscopic dynamics is emergent, i.e., it creates mesoscopic objects that obey mesoscopic laws of interaction and assembly, qualitatively different from microscopic signal transmission.
The literal informational paradigm
Old, unfit engineering metaphor: “signal processing”

- **feed-forward** structure – activity literally “moves” from one corner to another, from the input (problem) to the output (solution)
- **activation** paradigm – neural layers are initially silent and are literally “activated” by potentials transmitted from external stimuli
- **coarse-grain** scale – a few units in a few layers are already capable of performing complex “functions”
The emergent dynamical paradigm

- New dynamical metaphor: mesoscopic excitable media

  - **recurrent** structure – activity can “flow” everywhere on a fast time scale, continuously forming new patterns; output is in the patterns

  - **perturbation** paradigm – dynamical assemblies are already active and only “influenced” by external stimuli and by each other

  - **fine-grain** scale – myriads of neurons form quasi-continuous media supporting structured pattern formation at multiple scales
Natural sciences in the 19th century

**macrolevel:**
*laws of genetics*

\[ TT \times Tt \rightarrow Tt \times Tt \rightarrow TT, Tt, tT, tt \]

**microlevel:**
*atoms*
Natural sciences in the 20th century

macrolevel: laws of genetics

mesolevel: molec. biology

microlevel: atoms

→ multiscale complex system
Cognitive science in the 20th century

**macrolevel:** symbols

“John gives a book to Mary”  →  “Mary is the owner of the book”

**microlevel:** neurons
Cognitive science in the 21st century?

macrolevel: symbols
“John gives a book to Mary” → “Mary is the owner of the book”

mesolevel: “molec. cognition”

microlevel: neurons

→ multiscale complex system

Mesoscopic Cognition

- **AI: symbols, syntax → production rules**
  - logical systems define high-level symbols that can be composed together in a generative way
  - they are lacking a “microstructure” needed to explain the fuzzy complexity of perception, categorization, motor control, learning

- **Missing link: “mesoscopic” level of description**
  - cognitive phenomena emerge from the underlying complex systems neurodynamics, via intermediate spatiotemporal patterns

- **Neural networks: neurons, links → activation rules**
  - in neurally inspired dynamical systems, the nodes of a network activate each other by association
  - they are lacking a “macrostructure” needed to explain the systematic compositionality of language, reasoning, cognition
Toward a fine-grain mesoscopic neurodynamics

- The dynamic richness of spatiotemporal patterns (STPs)
  - large-scale, localized dynamic cell assemblies that display complex, **reproducible** digital-analog regimes of neuronal activity
  - these regimes of activity are supported by specific, **ordered** patterns of recurrent synaptic connectivity

- mesoscopic neurodynamics: construing the brain as a (spatio-temporal) **pattern formation machine**
Mesoscopic Cognition

- Hypothesis 1: mesoscopic neural pattern formation is of a fine spatiotemporal nature

- Hypothesis 2: mesoscopic STPs are individuated entities that are
  
a) endogenously produced by the neuronal substrate,

b) exogenously evoked & perturbed under the influence of stimuli,

c) interactively binding to each other in competitive or cooperative ways.
a) Mesoscopic patterns are endogenously produced

- given a certain connectivity pattern, cell assemblies exhibit various possible *dynamical regimes*, modes, patterns of ongoing activity
- the underlying connectivity is itself the product of *epigenetic* development and *Hebbian* learning, from activity

→ the identity, specificity or stimulus-selectiveness of a mesoscopic entity is largely determined by its internal pattern of connections
Mesoscopic Cognition

b) Mesoscopic patterns are exogenously influenced

✓ external stimuli (via other patterns) may *evoke & influence* the pre-existing dynamical patterns of a mesoscopic assembly

✓ it is an indirect, *perturbation* mechanism; not a direct, activation mechanism

✓ mesoscopic entities may have stimulus-specific *recognition or “representation”* abilities, without being “templates” or “attractors” (no resemblance to stimulus)
Mesoscopic Cognition

c) Mesoscopic patterns interact with each other

- populations of mesoscopic entities can **compete & differentiate** from each other to create specialized recognition units
- and/or they can **bind** to each other to create composed objects, via some form of temporal coherency (sync, fast plasticity, etc.)