Architectures That Are Self-Organized and Complex: From Morphogenesis to Engineering

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Computer Science at Victoria

✓ “Computer Science is the study of computing.”
✓ “This includes the engineering aspects of the design of complex systems, fundamental theories of computer science, and techniques and tools used in a range of applications.”
✓ “As society’s dependence on the reliability and correctness of computer-based systems increases, so does the need for experts to design and build the systems.”
Information Science at Otago

- distributed systems
- multi-agent systems
- spatial information systems
- CA software engineering systems
- intelligent information systems
- etc.

→ “the scope in which computers operate is growing relentlessly: increasing demand for computation in all fields”

“infoware” = complex systems (components in a network)
Designing Complexity

- Rapid growth in size & complexity of computer systems, whether hardware, software, or (info) networks, ...

- Number of transistors/year
- Number of O/S lines of code/year
- Number of network hosts/year

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Doursat, R. - From morphogenesis to engineering
Designing Complexity

... leads us to rethink engineering as complex systems

- large number of elements interacting locally
- simple individual behaviors creating a complex emergent behavior
- decentralized dynamics: no master blueprint or grand architect

✓ in particular, seek inspiration from biological and social systems

- physical pattern formation
- organism development
- insect colonies
- neurons & cognition
- Internet & Web
- social networks
How can we make agents get together and do something, without placing them by hand?
Designing Complexity

Complex systems engineering

Transfers among systems

Understanding “natural” complex systems
(i.e., spontaneously emergent, including human activity)

Exports
- decentralization
- autonomy, homeostasis
- learning, evolution

Imports
- modeling
- controlling
- utilizing

Design a new generation of “artificial” complex systems
(i.e., harnessed, including nature)
Bio-Inspired Engineering

- **Natural adaptive systems as a new paradigm for ICT**

  - natural complex adaptive systems, biological or social, can become a new and powerful source of inspiration for future IT in its transition toward autonomy

  - “emergent engineering” will be less about direct design and more about developmental and evolutionary meta-design

  - it will also stress the importance of constituting fundamental laws of *development* and developmental *variations* before these variations can even be selected upon in the evolutionary stage

  - it is conjectured that fine-grain, *hyperdistributed* systems will be uniquely able to provide the required “solution-rich” space for successful evolution by selection
Toward programmable, emergent complex formations

- self-organized physical systems generally form simple, repetitive, random patterns...

- ... while complicated, controlled architectures are generally designed by humans

- thus far, the only emergent and complex forms come from biological and social development

→ can we reproduce them in artificial systems: morphogenesis-inspired engineering?
Designing Complexity

- From centralized heteromy to decentralized autonomy

- artificial systems are built exogenously, organisms endogenously grow

- future engineers should “step back” from their creation and only set generic conditions for systems to self-assemble and evolve
Evolutionary Meta-Design

Pushing engineering toward evolutionary biology

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**intelligent design**
- heteronomous order
- centralized control
- manual, extensional design
- engineer as a micromanager
- rigidly placing components
- tightly optimized systems
- sensitive to part failures
- need to control
- need to redesign

*complicated systems: planes, computers*

**intelligent & evolutionary “meta-design”**
- autonomous order
- decentralized control
- automated, intentional design
- engineer as a lawmaker
- allowing fuzzy self-placement
- hyperdistributed & redundant systems
- insensitive to part failures
- prepare to adapt & self-regulate
- prepare to learn & evolve
- *complex systems: Web, market*

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... computers?
**Embryomorphic Engineering**

- **Observing, modeling → exporting biological development**
  - automating the *observation* and description of developing organisms with image processing, statistical and machine learning techniques
  - designing mathematical/computational *models* of embryonic growth
  - *implementing* biological development in engineering systems: distributed architectures as a prerequisite for evolutionary innovation

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European projects “Embryomics” & “BioEmergences”
The Self-Made Puzzle

- Complex morphogenesis: Integrating *self-assembly* and *pattern formation* under non-random *genetic regulation*

  - **self-assembly (SA)**
    - usually focuses on pre-existing components endowed with fixed shapes
    - . . . but cells *dynamically divide and differentiate* toward selective adhesion

  - **pattern formation (PF)**
    - generally orderly states of activity on top of continuous 2-D or 3-D substrate
    - . . . but gene expression patterning arises in *perpetually reshaping* organism

  - **non-random genetic regulation (GRN)**
    - both phenomena often thought stochastic: mixed components that randomly collide in SA; spots and stripes that pop up from instabilities in PF
    - . . . but cells are *pre-positioned* where they divide, and genetic identity domains are *highly regulated* in number and position

→ *integrate these 3 aspects in artificial “embryomorphic” systems*
The Self-Made Puzzle

1. Self-Assembly of Pre-Patterned Components

+ 2. Pattern Formation in Pre-Assembled Media

= 3. Integrating Self-Assembly and Pattern Formation Under Genetic Regulation
   a. The self-painting canvas
   b. The modular canvas
   c. The deformable canvas

4. Bio-Inspired Evolutionary Meta-Design

A simple model of swarm behavior

- illustrating “existence of components” and “binding fate”
  - in 2-D space, two types of particles ($\alpha$ and $\beta$)
  - attractive and repulsive interactions, modeled as potentials $V(r)$ around each particle
  - $V$ is the equivalent of a geometrical “shape”, i.e., specific binding affinities

![Diagram of swarm behavior](image)

Molecular-style SA: structuration from a random mix

✓ “shaking the puzzle box”
  - $\alpha$ particles randomly collide and cluster together within a sea of $\beta$ particles
  - like molecules, dissociated cells can also spontaneously sort again
  - however, mostly artificial experiments; not a major natural mechanism

→ the complex architecture of an organism does not emerge out of a giant swarm of trillions of disaggregated cells reassembling in parallel

**Multicellular-style SA: structuration from development**

- "growing the embryo"
  - starting with only a few particles of each type
  - particles *divide* into same-type particles, under uniform probability
  - new particles pop up *pre-positioned* near the type that produced them
  - particles only briefly rearrange within their local neighborhood

- **Molecular-style SA: colliding pre-shaped particles**
  - 15 particles of type \( \gamma \) interacting via polar potential \( V_\gamma(r) \)
    - drawn as small rectangles (straight or bent) instead of discs
    - colliding SA: identical particles with vertical poles \((\theta_1, \theta_2) = (\pi/2, -\pi/2)\)
      snap into place, forming a straight chain
    - pre-shaped SA: uniquely shaped particles, with various \((\theta_1, \theta_2)\), are unable to coordinate: they only explore suboptimal and unstable states

- **Multicellular-style SA: growing and reshaping particles**
  - 15 particles of type $\gamma$ interacting via polar potential $V_\gamma(r)$
    - drawn as small rectangles (straight or bent) instead of discs
    - growing SA: the same string can be formed by dividing vertical particles
    - reshaping SA: then, each particle dynamically bends its shape in specific ways, making the string invaginate (final angles same as pre-shaped particles)

➢ Biological cells use mechanisms that greatly facilitate SA

✓ future artificial systems design could follow a similar approach
  ▪ instead of letting components haphazardly try to match each other's pre-existing constraints, like molecules in a solution... 
  ▪ ...let components dynamically create and reshape themselves “on the spot,” as cells do

✓ from stochastic (molecular-style) self-assembly to programmable (multicellular-style) self-assembly
  ▪ components must be able to dynamically modify their behavior (divide, differentiate, migrate) through communication
  ▪ cells do not just snap into place; they send molecular signals to each other

→ cells form patterns of differentiation at the same time that they are self-assembling
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Pattern formation vs. morphogenesis

- since Turing (1952), “morphogenesis” is often confused with “pattern formation”
  - yet they do not emphasize the same aspect of emerging order
- “pattern formation” = emergence of statistically regular motifs
  - in quasi-continuous and initially homogeneous 2-D or 3-D media
  - shimmering landscapes of activity on a more or less fixed backdrop
  - pattern formation “paints” a pre-existing space
- “morphogenesis” = generation of complex, heterogeneous form
  - originally, biological development of organs and structures of an organism
  - by extension: physical (geomorphogenesis), social (urban morphogenesis)...
  - creation of intricate, heterogeneous architectures and structures
  - morphogenesis “sculpts” its own space

- Classical PF is free (random), biological PF is guided

- Stochasticity at micro-level (elts) and meso-level (patterns)
- PF studies focus on instabilities and amplification of fluctuations
- Outcome generally unpredictable in number and position of domains
- Conversely, macroscopic formation fairly regular: repeated motifs, statistical uniformity like textures
- Mesoscopic organs and limbs have intricate, non-random morphologies
- Reaction-diffusion based(?) animal coats are only a marginal aspect
- Development is reproducible in number and position of body parts
- Most of organism development is under deterministic genetic control: heterogeneous, rich in information

Convection cells
www.chabotspace.org

Reaction-diffusion
texturegarden.com/java/rd

Fruit fly embryo
Sean Carroll, U of Wisconsin

Larval axolotl limb
Gerd B. Müller

- **Biological PF relies on highly informed agents**
  - non-biological, physical-chemical pattern formation
    - elements are molecules, simple bodies or elementary volumes of homogeneous solution
    - each element contains very little information, creating simple constraints (activation vs. inhibition)
  - biological, multicellular morphogenesis
    - unique characteristic: each one of its self-organizing elements, the cell, contains a rich source of information stored in the DNA
    - this information endows it with a vast repertoire of highly non-trivial behaviors
    - even admitting that DNA is less than a “program,” it is still at least, a repository of stimuli-response rules, vastly superior in quantity of functional information to purely physical-chemical elements

Embyrogenesis combines PF and morphogenetic SA

- shapes from patterning; patterns from shaping
  - structures are “sculpted” from the self-assembly of elements, prompted by the “painting” of their genetic identity
  - conversely, newly formed shapes are able to support, and trigger, new domains of genetic expression

- tightly integrated loop under non-random genetic regulation
  - DNA is “consulted” at every step of this exchange, in every cell
  - it produces the proteins that guide the cell’s highly specific biomechanic behavior (shaping) and signalling behavior (patterning)
"Shape from patterning" examples

- deriving morphogenetic SA (bottom frames) from PF (top frames)
  - slime mold amoebae first generate waves of chemical signalling (top), then follow concentration gradients and aggregate (bottom)
  - type-$\alpha$ particles differentiating from a prepatter before assembling
  - bending angle of each $\gamma$ particle also determined by a prepatter of identity

http://zool33.uni-graz.at/schmickl
Preview: embryomorphic architectures

- functional dependency between cell identities and mechanical cell behaviors
- alternation of PF-induced differentiation and heterogeneous-type SA at all scales of detail
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Developmental genes are expressed in spatial domains

thus combinations of switches can create patterns by union and intersection, for example: $I = (\text{not } A) \text{ and } B \text{ and } C$

Three-tier GRN model: integrating positional gradients

- $A$ and $B$ are themselves triggered by proteins $X$ and $Y$

- $X$ and $Y$ diffuse along two axes and form concentration gradients

- Different thresholds of lock-key sensitivity create different territories of gene expression in the geography of the embryo
A lattice of Positional-Boundary-Identity (PBI) GRNs

- network of networks: each GRN is contained in a cell, coupled to neighboring cells via the positional nodes (for diffusion)
- a pattern of gene expression is created on the lattice

- The hidden geography of the embryo
  - self-patterning obtained from a 3B-6I gene regulatory network $G$ in a 200-cell oval-shaped embryo
  - each view is “dyed” for the expression map of one of the 11 genes, e.g.: $B_1 = \sigma(Y - 1/2)$, $B_2 = \sigma(X - 1/3)$, $I_6 = B_1 B_3$ ...

\[ I_1(x, y) \quad I_2(x, y) \quad I_3(x, y) \quad I_4(x, y) \quad I_5(x, y) \quad I_6(x, y) \]

\[ B_1(x, y) \quad B_2(x, y) \quad B_3(x, y) \]

\[ G \quad X(x, y) \quad Y(x, y) \]

\[ I_1 \ldots I_6 \quad B_2 \quad B_3 \quad X, Y \]
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4. Bio-Inspired Evolutionary Meta-Design

b. modular canvas

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

- **Multiscale refinement using a hierarchical GRN**
  - Instead of one flat tier of $B$ nodes, use a pyramid of PBI modules
  - The activation of an $I$ node controls the onset of a new $P$ layer
  - In the first stage, a base PBI network creates broad domains
    - In the next stage, another set of PBI networks subdivide these domains into compartments at a finer scale, etc.

b. modular canvas

Static vs. growing multiscale canvas

- 32x32 hexagonal lattice of cells, two-level gene network $\Gamma$: base subnet $G_0$, then 2 subnets $G_1$, $G_2$ triggered by $I_1$ and $I_2$

$\Gamma$

2 domains are further subdivided

Equivalent pattern obtained by uniform expansion from 8x8 cells
The inherent modularity of hierarchical GRNs

- organisms contain “homologous” parts (arthropod segments, vertebrate teeth and vertebrae, etc.)
- homology also exists between species (tetrapod limbs)
- similarities in DNA sequences reveal that homology is the evolutionary result of duplication followed by divergence
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Cell adhesion, division and migration

- the previous canvas was only growing uniformly; the model is now augmented with elements of cellular biomechanics and morphodynamics that can create nontrivial shapes
- cell coordinates vary according to three mechanistic principles:
  1. elastic cell rearrangement under differential adhesion
  2. inhomogeneous cell division
  3. tropic cell migration
- these principles will be linked to the self-patterning process through a functional dependency between cell identities and mechanical cell behaviors
Simple mesh model of cell adhesion and elasticity

a) isotropic “blob” of identical cells dividing at 1% rate, in which nearby daughter cells rearrange under elastic forces

b) anisotropic “limb” growth: only center domain $I_2$ divides (upward stretch due to $2x:y$ anisotropic rescaling); lateral cells have different identity $I_1$ and no adhesion to $I_2$ lineage
Inhomogeneous cell division (cont’d)

✓ using differential adhesion, anisotropic cleavage planes and rescaling, this model can also generate directional offshoot akin to limb development

✓ here, different weights in base module $G'_{0}$ make a thicker central row, and place $I'_{1}$ and $I'_{2}$ dorsally and ventrally

✓ different adhesion coefficients also make $I'_{1}$ and $I'_{2}$ grow “limbs”, sub-patterned by $G'_{1}$ and $G'_{2}$
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4. Bio-Inspired Evolutionary Meta-Design
4. Evolutionary Meta-Design

The paradoxical goals of complex systems engineering

- how can we expect specific characteristics from systems that are otherwise free to invent themselves?
  - how to plan self-organization?
  - how to control decentralization?
  - how to design evolution?

- the challenge is not so much to allow self-organization and emergence but, more importantly, to guide them

- ex: embryomorphic engineering:
  - given a desired phenotype, what genotype should produce it?
4. Evolutionary Meta-Design

3 challenges of CS engineers: growth, function, evolution

1. **how does the system grow?** (task of the developmental IMD engineer)
   - development results from a combination of elementary mechanisms: elements change internal state, communicate, travel, divide, die, etc.
   - starting from a single element, a complex and organized architecture develops by repeatedly applying these rules inside each element
   → *task 1 consists of combining these principles and designing their dynamics*

2. **how does the system function?** (task of the functional IMD engineer)
   - this task is about defining the nature of the elements their functionality: nano/bio components? software modules? robot parts? swarm robots?
   - are they computing? physically moving? or both? etc.

3. **how does the system evolve?** (task of the EMD engineer)...
   - how the system varies (randomly)
   - how it is selected (nonrandomly)
4. Evolutionary Meta-Design

➢ Selecting without expectations?

✓ different degrees of fitness constraints

a) selecting for a specific organism (shape, pattern)
   - reverse problem: given the phenotype, what should be the genotype?
   - direct recipe; ex: Nagpal’s macro-to-microprogram Origami compilation
   - otherwise: learn or evolve under strict fitness → difficult to achieve!

b) selecting for a specific function, leaving freedom of architecture
   - given a task, optimize performance (computing, locomotion, etc.)
   - be surprised by pattern creativity; ex: Avida, GOLEM, Framsticks

c) selecting the unexpected
   - create a “solution-rich” space by (a) combinatorial tinkering on redundant parts and (b) relaxing/diversifying the requirements
   - harvest interesting or surprising organisms from a free-range menagerie
The Self-Made Puzzle

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