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

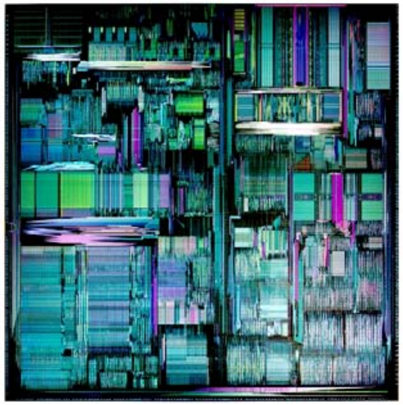
- ✓ distributed systems
- ✓ multi-agent systems
- ✓ spatial information systems
- ✓ CA software engineering systems
- ✓ intelligent information systems
- ✓ etc.

} "infoware" = complex systems (components in a network)

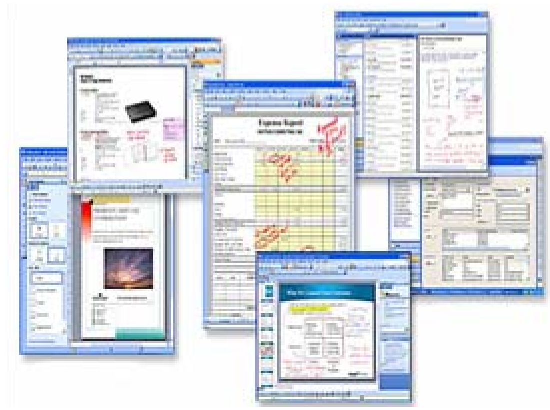
→ *"the scope in which computers operate is* ***growing*** *relentlessly: increasing demand for computation in all fields"*

Designing Complexity

- Rapid growth in size & complexity of computer systems,

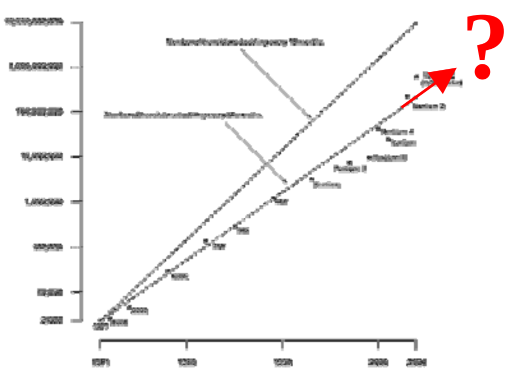


whether hardware,

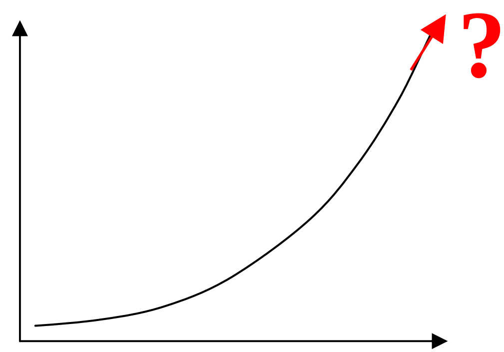


software,

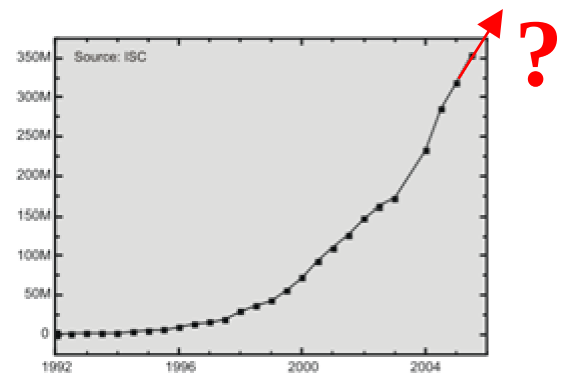
or (info) networks, ...



number of transistors/year



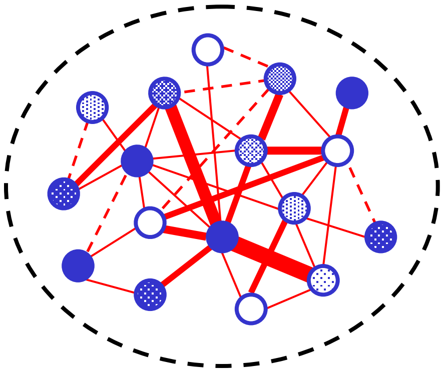
number of O/S lines of code/year



number of network hosts/year

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

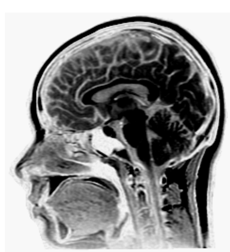
✓ in particular, seek inspiration from biological and social systems

physical pattern formation

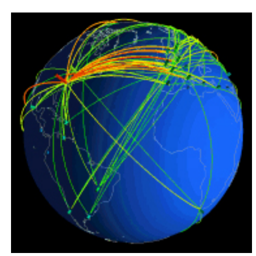
organism development

insect colonies

neurons & cognition



Internet & Web



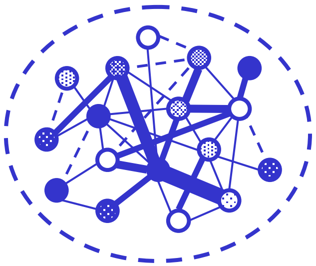
social networks

How can we make agents get together and do something, without placing them by hand?

Designing Complexity

- **Complex systems engineering**

Transfers
- among systems

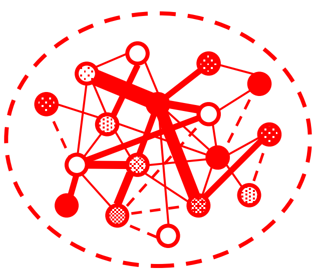


Understanding "natural" complex systems

(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

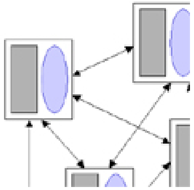
Complex Morphogenesis

➢ Toward programmable, emergent complex formations

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

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

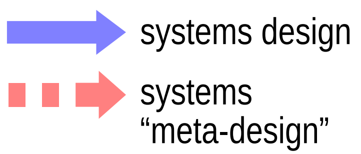
- ✓ thus far, the only **emergent** and **complex** forms come from biological and social development

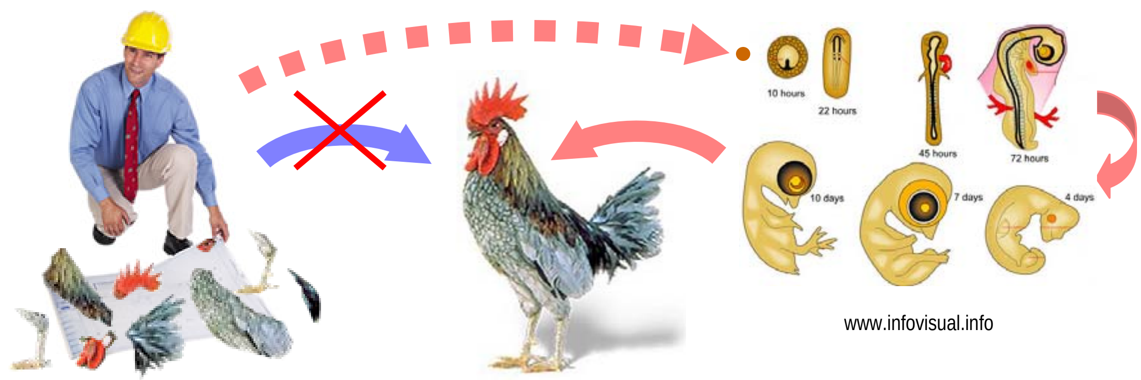
   

→ *can we reproduce them in artificial systems: morphogenesis-inspired engineering?*

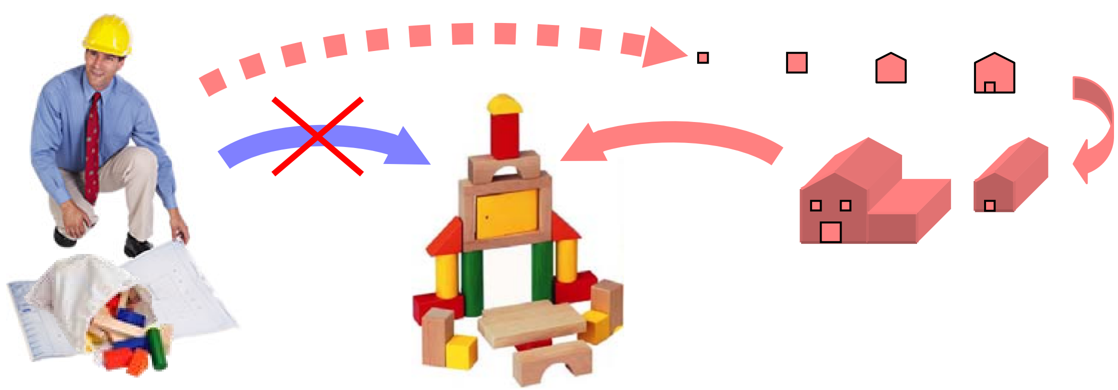
Designing Complexity

- From centralized heteromy to decentralized autonomy
  - ✓ artificial systems *are built* exogenously, organisms endogenously *grow*



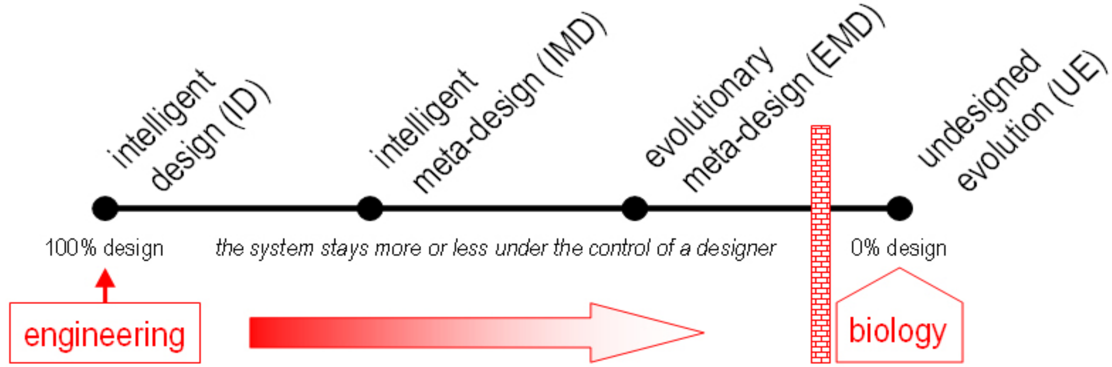


  - ✓ future engineers should “step back” from their creation and only set *generic* conditions for systems to self-assemble and evolve



Evolutionary Meta-Design

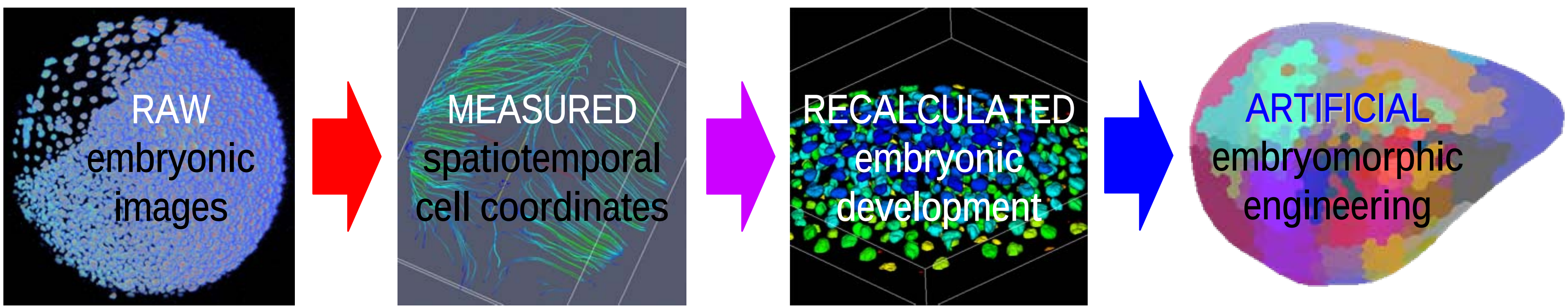
➢ Pushing engineering toward evolutionary biology



intelligent design		intelligent & evolutionary "meta-design"
heteronomous order	▪	autonomous order
centralized control	▪	decentralized control
manual, extensional design	▪	automated, intentional design
engineer as a micromanager	▪	engineer as a lawmaker
rigidly placing components	▪	allowing fuzzy self-placement
tightly optimized systems	▪	hyperdistributed & redundant systems
sensitive to part failures	▪	insensitive to part failures
need to control	▪	prepare to adapt & self-regulate
need to redesign	▪	prepare to learn & evolve
complicated systems: planes, ~~computers~~	▪	*complex* systems: Web, market ... 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*

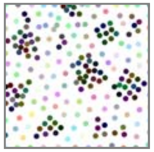


European projects “Embryomics” & “BioEmergences”

The Self-Made Puzzle

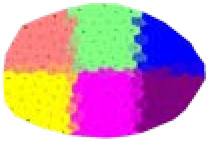
➢ Complex morphogenesis: Integrating *self-assembly* and *pattern formation* under non-random *genetic regulation*

✓ self-assembly (SA)



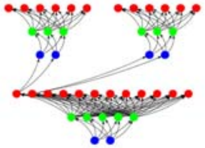
- usually focuses on pre-existing components endowed with fixed shapes
- . . . but cells *dynamically divide and differentiate* toward selective adhesion

✓ pattern formation (PF)

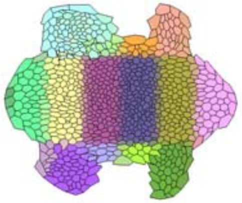


- generally orderly states of activity on top of continuous 2-D or 3-D substrate
- . . . but gene expression patterning arises in *perpetually reshaping* organism

✓ 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

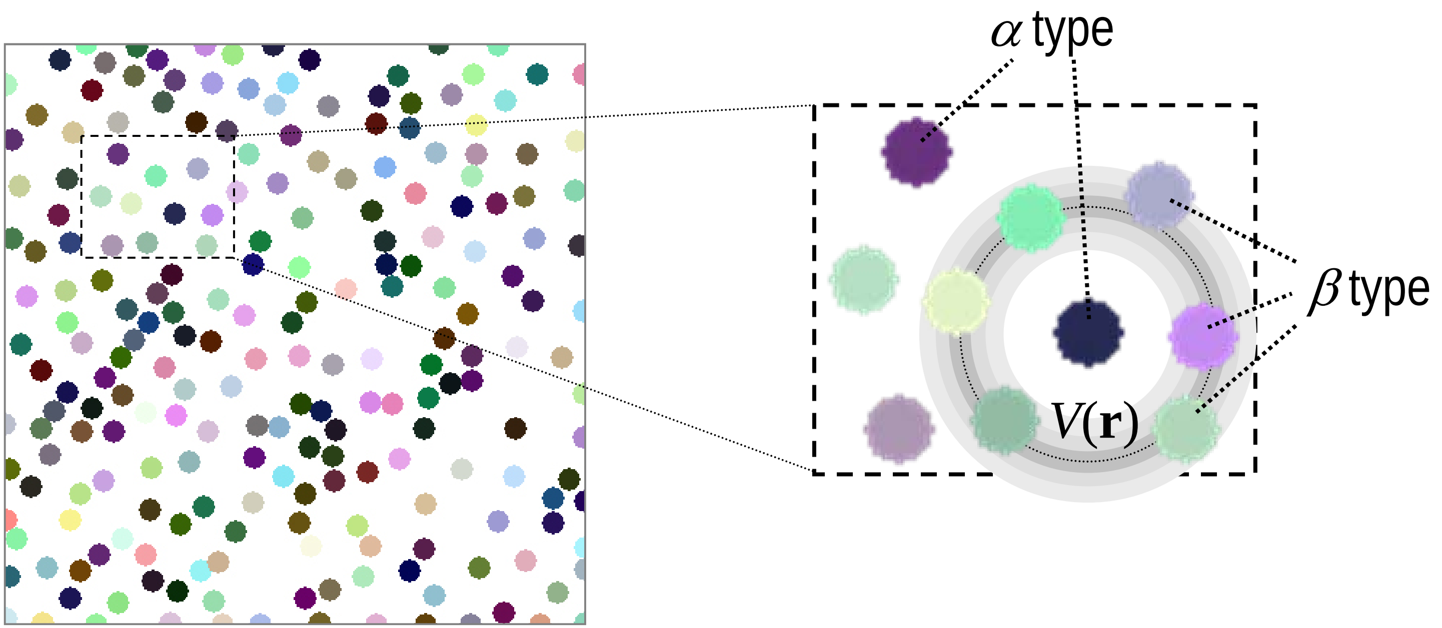
= 3. Integrating Self-Assembly and Pattern Formation Under Genetic Regulation
    a. The self-painting canvas
    b. The modular canvas
    c. The deformable canvas

4. Bio-Inspired Evolutionary Meta-Design

1. Self-Assembly + 2. Pattern Formation = 3. Morphogenesis

➢ A simple model of swarm behavior

- ✓ illustrating "existence of components" and "binding fate"
  - in 2-D space, two types of particles (α and β)
  - attractive and repulsive interactions, modeled as potentials $V(\mathbf{r})$ around each particle
  - V is the equivalent of a geometrical "shape", i.e., specific binding affinities

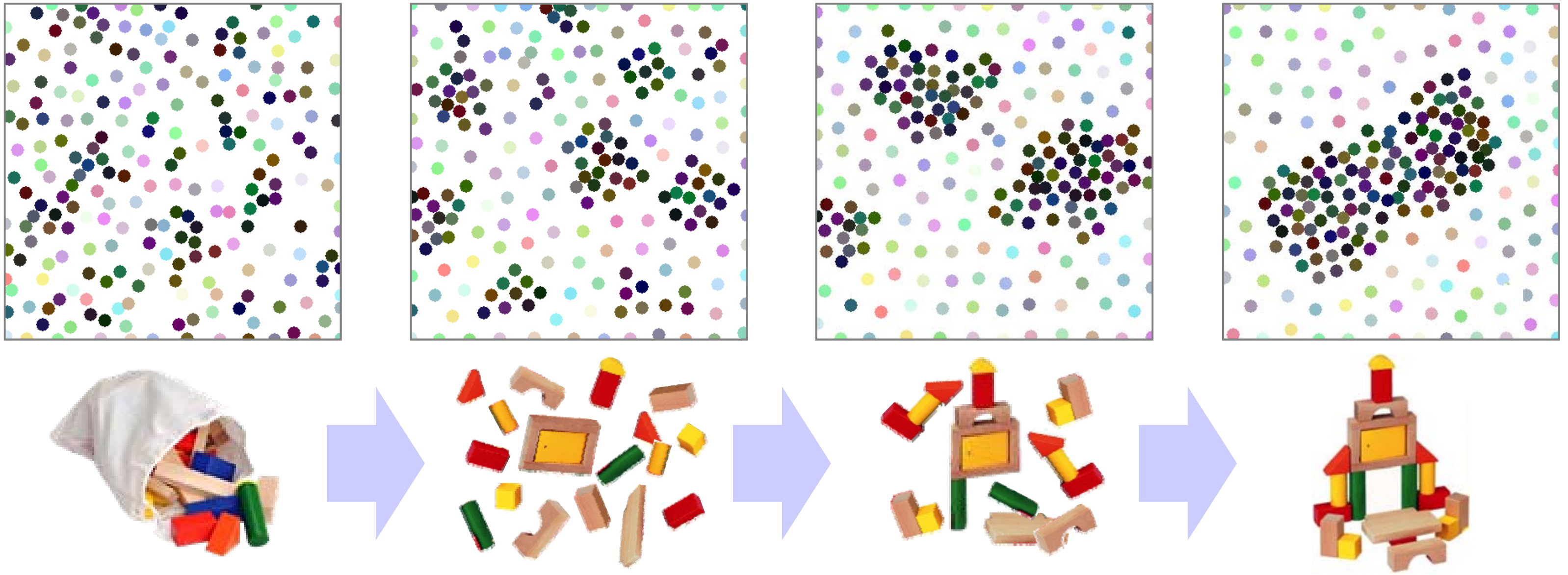


1. Self-Assembly + 2. Pattern Formation = 3. Morphogenesis

➢ *Molecular*-style SA: structuration from a random mix

- ✓ "shaking the puzzle box"
  - α particles randomly collide and cluster together within a sea of β particles
  - like molecules, dissociated cells can also spontaneously sort again
  - however, mostly artificial experiments; not a major natural mechanism

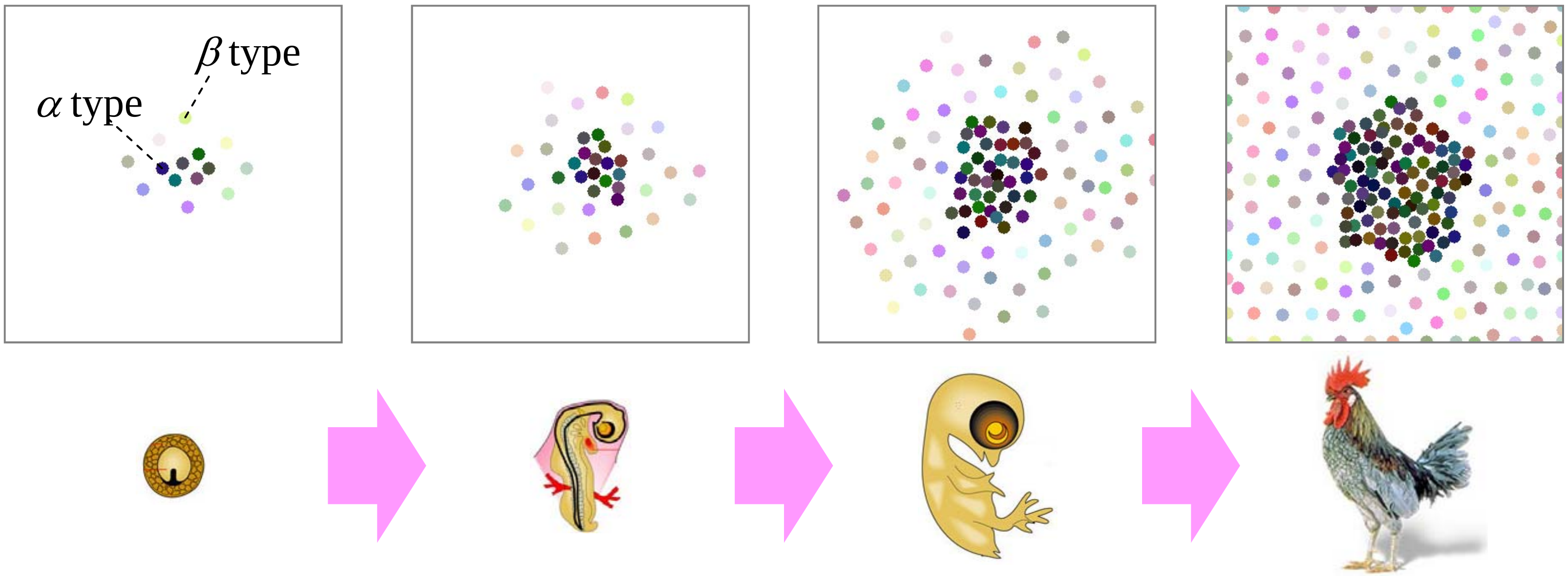
  $\rightarrow$ *the complex architecture of an organism does not emerge out of a giant swarm of trillions of disaggregated cells reassembling in parallel*



1. Self-Assembly + 2. Pattern Formation = 3. Morphogenesis

➢ *Multicellular*-style SA: structuration from development

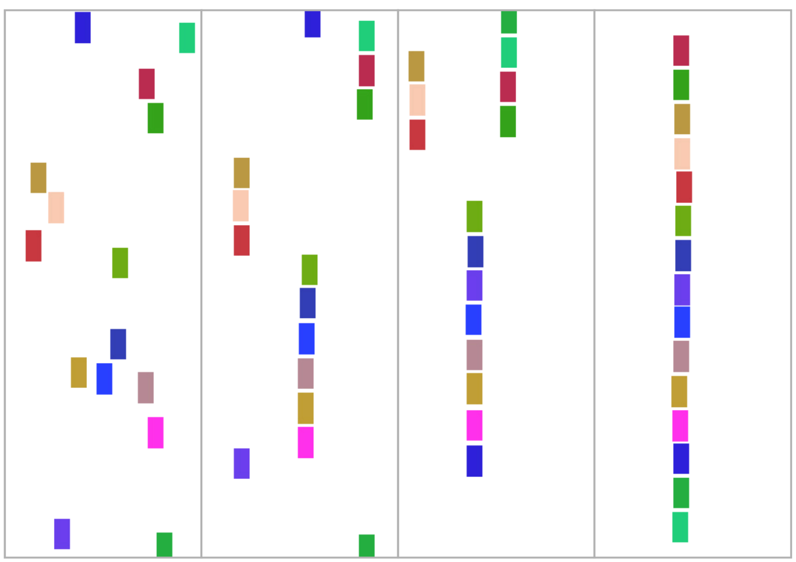
- ✓ "growing the embryo"
  - starting with only a few particles of each type
  - particles *divide* into same-type particles, under uniform probability
  - new particles pop up *pre-positioned* near the type that produced them
  - particles only briefly rearrange within their local neighborhood

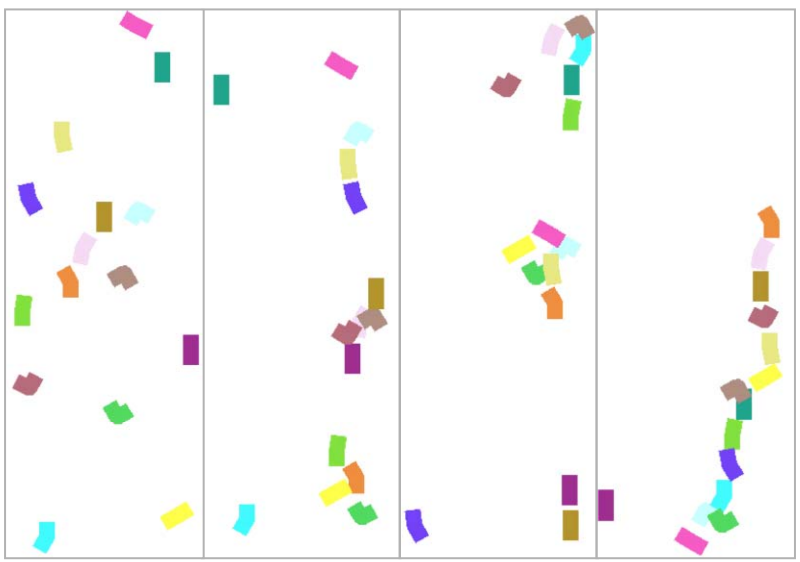


1. Self-Assembly + 2. Pattern Formation = 3. Morphogenesis

➢ *Molecular*-style SA: colliding pre-shaped particles

- ✓ 15 particles of type γ interacting via polar potential $V_\gamma(\mathbf{r})$
  - 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 (θ_1, θ_2), are unable to coordinate: they only explore suboptimal and unstable states

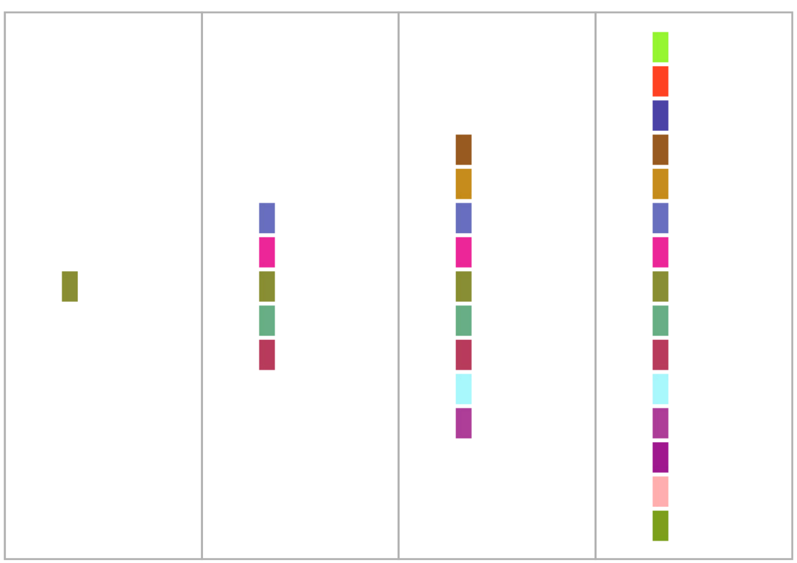


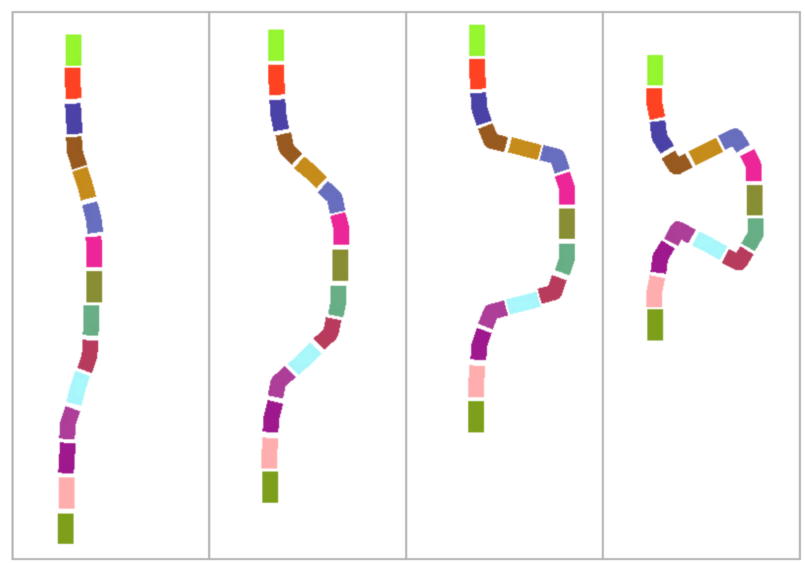


1. Self-Assembly + 2. Pattern Formation = 3. Morphogenesis

➢ *Multicellular*-style SA: growing and reshaping particles

- ✓ 15 particles of type γ interacting via polar potential $V_\gamma(\mathbf{r})$
  - 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)





1. Self-Assembly + 2. Pattern Formation = 3. Morphogenesis

- ➢ 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*

The Self-Made Puzzle

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4. Bio-Inspired Evolutionary Meta-Design

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*

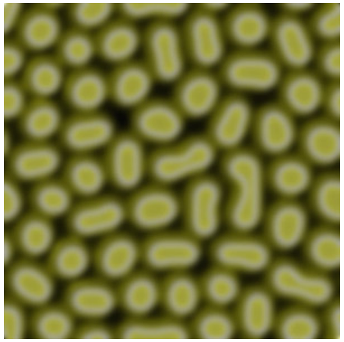
1. Self-Assembly + 2. Pattern Formation = 3. Morphogenesis

➢ Classical PF is *free* (random), biological PF is *guided*

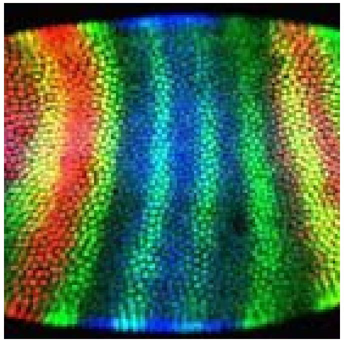
- stochasticity at micro-level (elts) and meso-level (patterns)
- PF studies focus on *instabilities* and amplification of fluctuations
- outcome generally *unpredictable* in number and position of domains
- conversely, macroscopic formation fairly regular: repeated motifs, statistical *uniformity* like 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

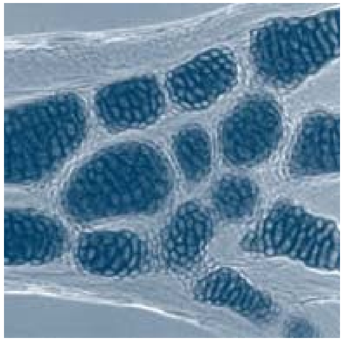
convection cells
www.chabotspace.org



reaction-diffusion
texturegarden.com/java/rd



fruit fly embryo
Sean Caroll, 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

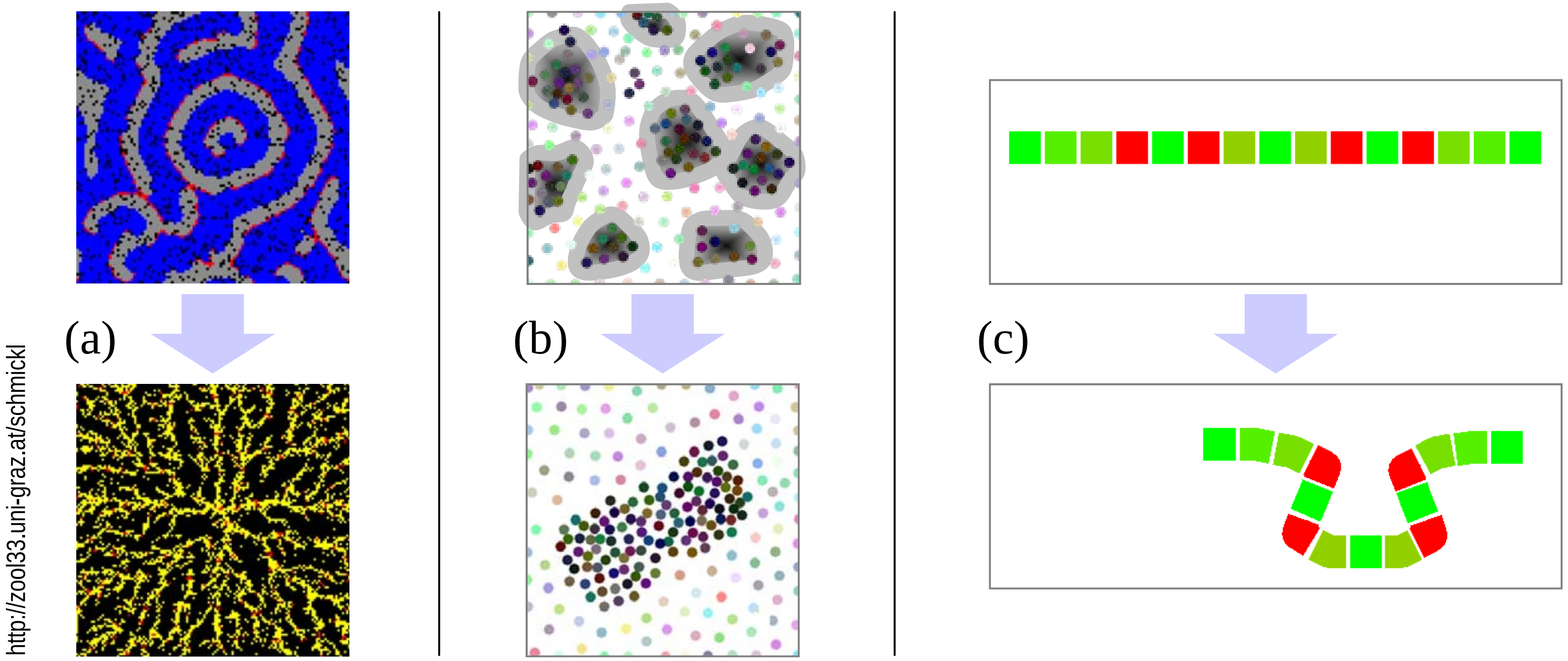
1. Self-Assembly + 2. Pattern Formation = 3. Morphogenesis

➢ Embryogenesis 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)

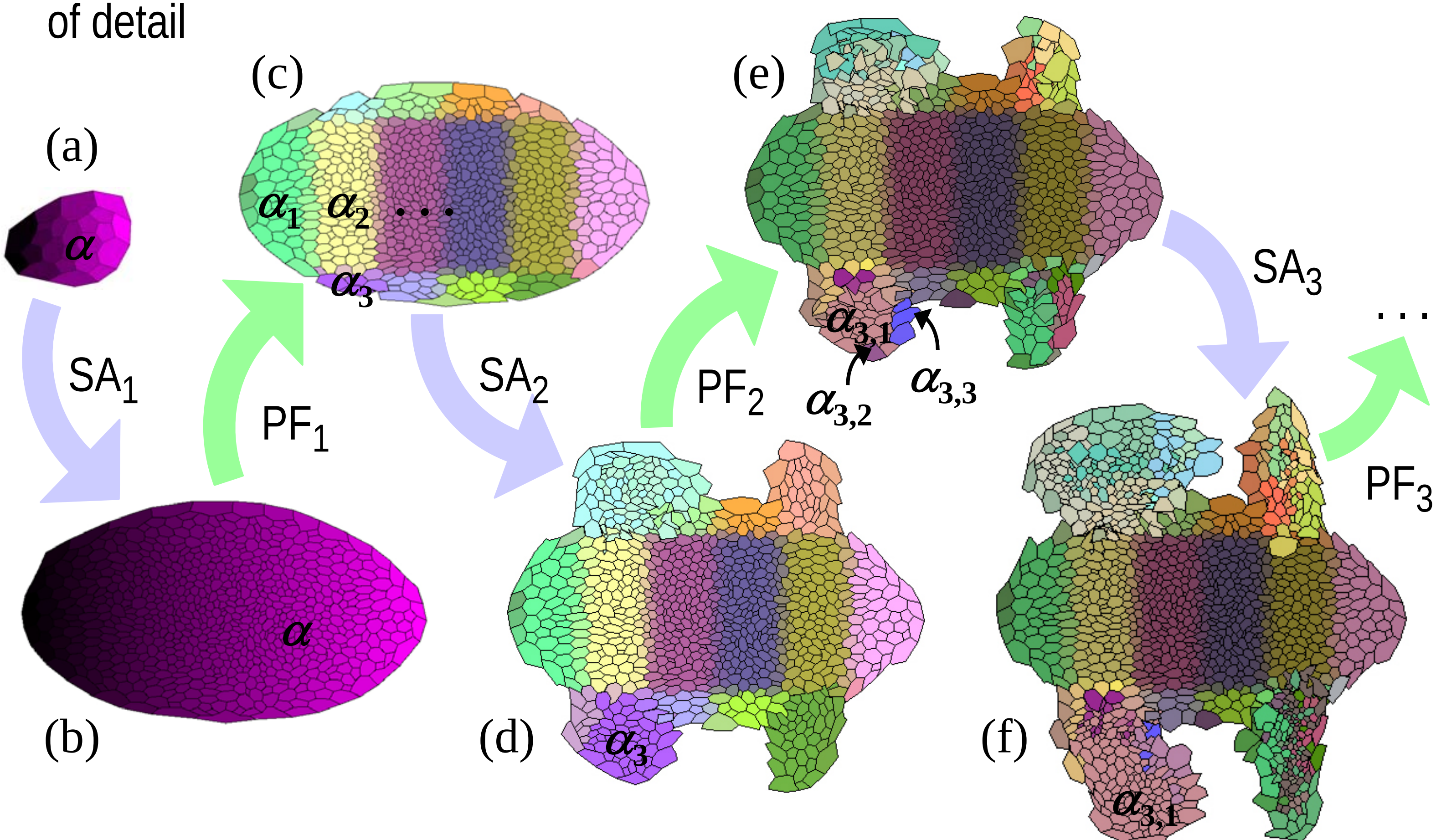
“Shape from patterning” examples

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



➢ 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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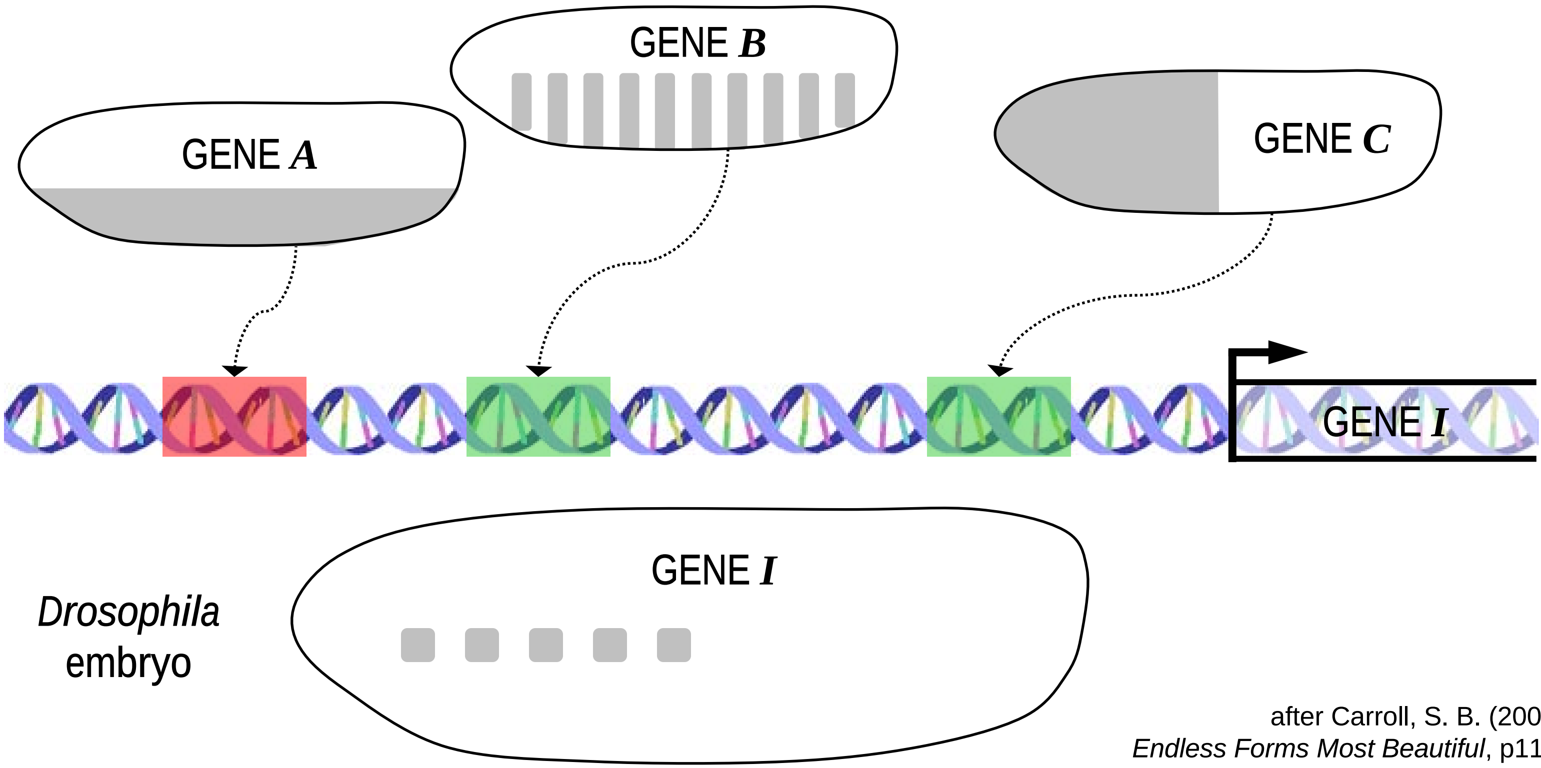
4. Bio-Inspired Evolutionary Meta-Design

➢ Developmental genes are expressed in spatial domains

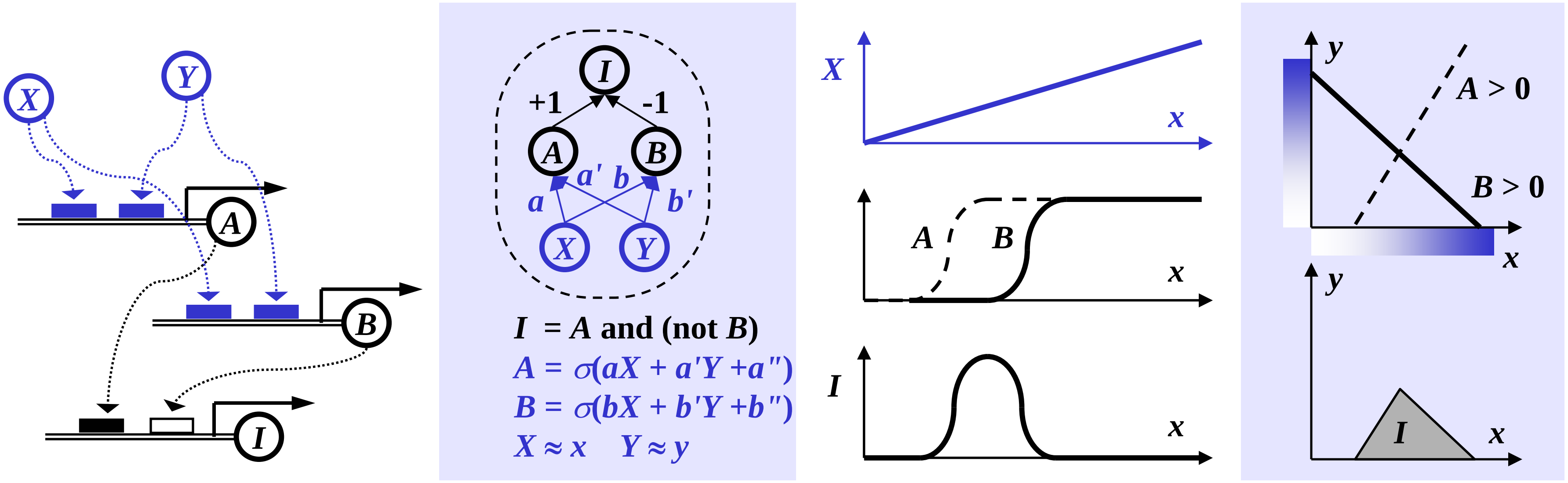
- ✓ thus combinations of switches can create patterns by union and intersection, for example: $I = (\text{not } A) \text{ and } B \text{ and } C$



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

➢ Three-tier GRN model: integrating positional gradients

✓ A and B are themselves triggered by proteins X and Y

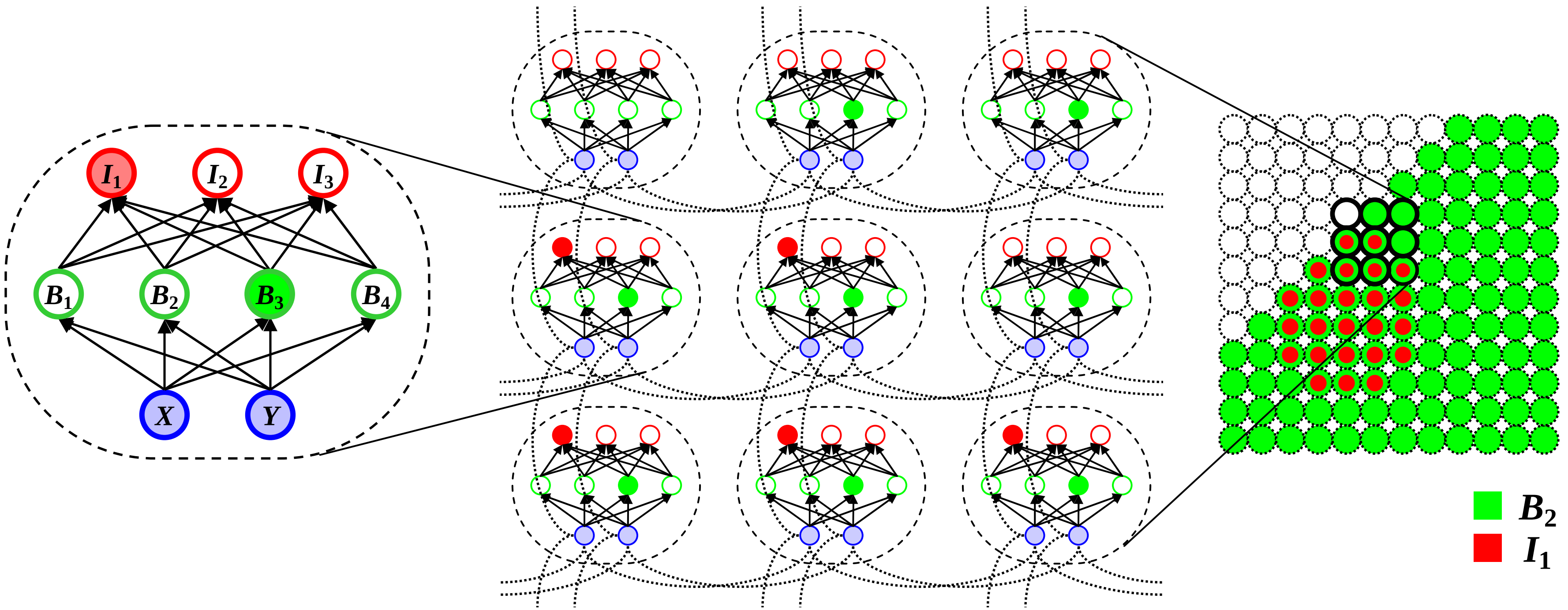


✓ X and Y diffuse along two axes and form concentration gradients

→ *different thresholds of lock-key sensitivity create different territories of gene expression in the geography of the embryo*

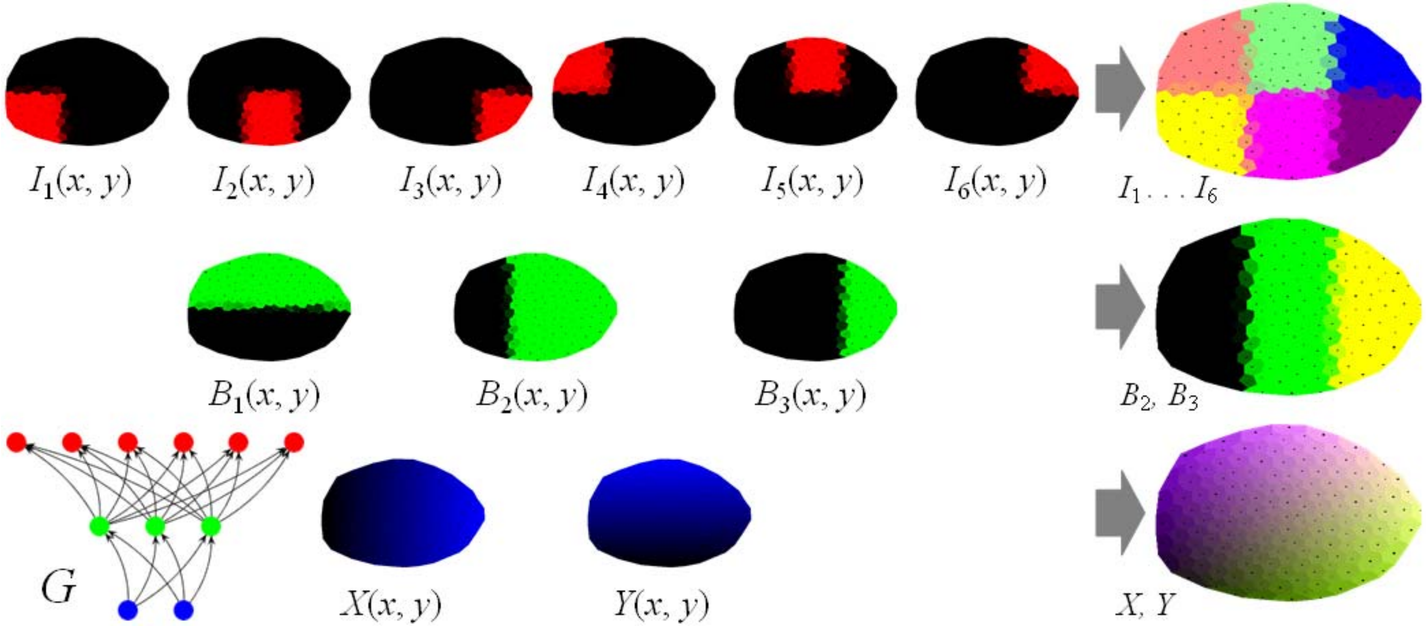
➢ A lattice of Positional-Boundary-Identity (PBI) GRNs

- ✓ 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.: $B_1 = \sigma(Y - 1/2)$, $B_2 = \sigma(X - 1/3)$, $I_6 = B_1 B_3$ ...



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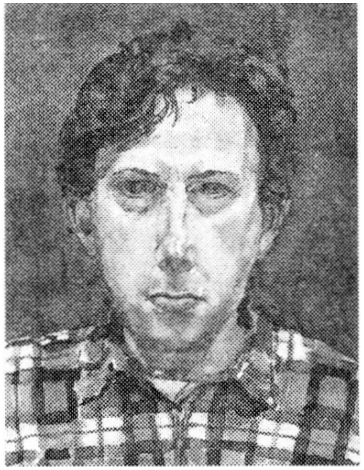
➢ Morphological refinement by iterative growth

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

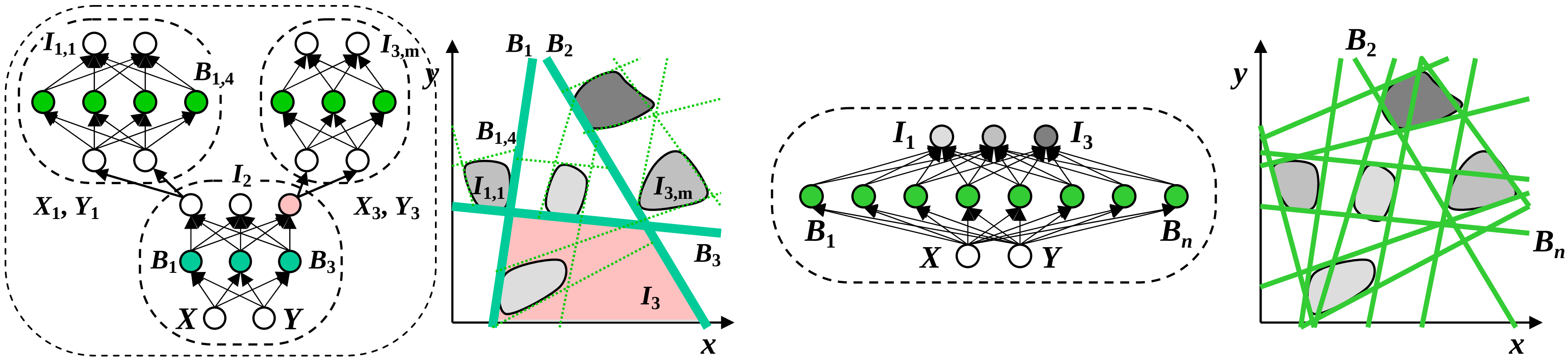
✓ . . . while, at the same time, the canvas grows



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

➢ Multiscale refinement using a hierarchical GRN

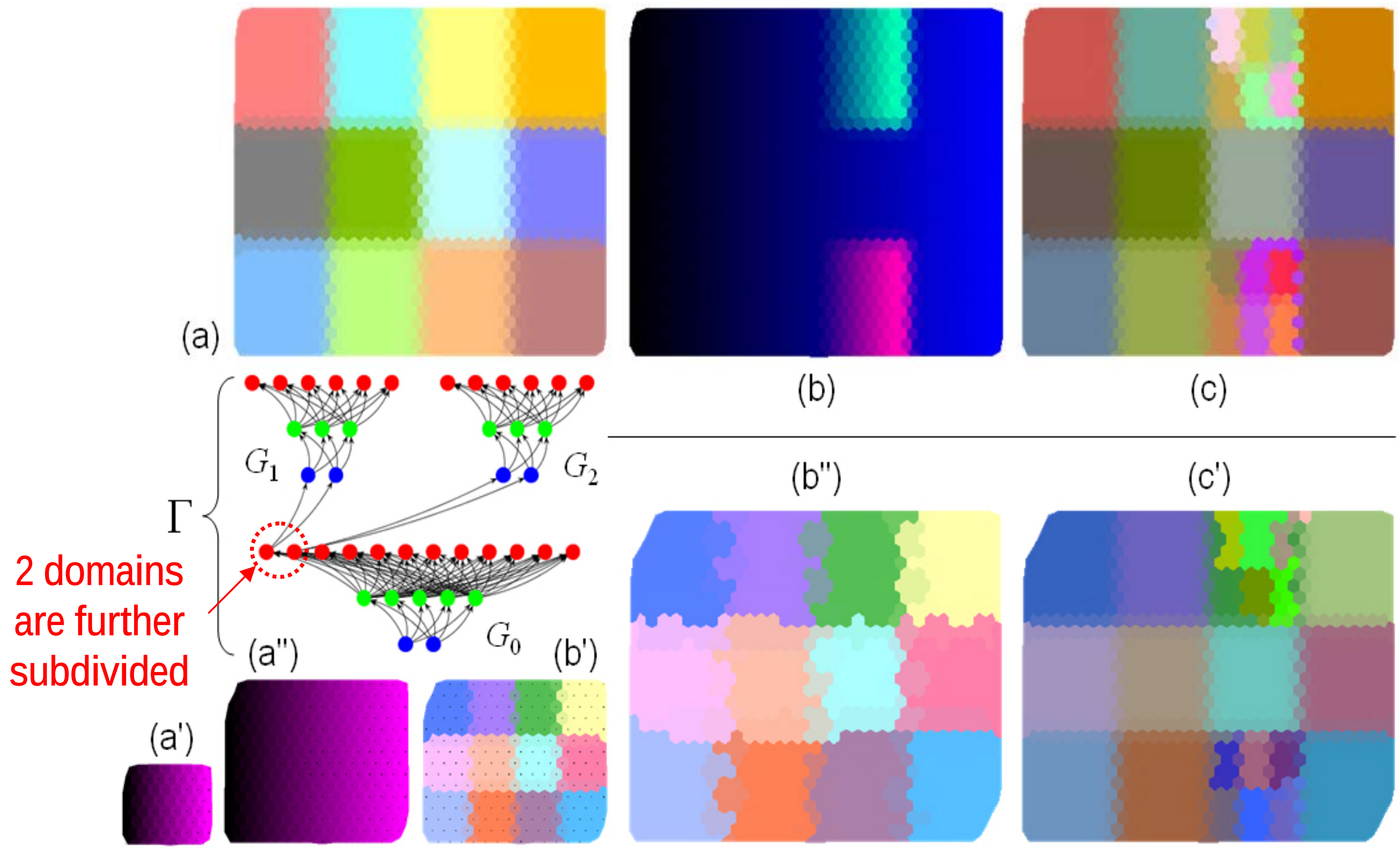
- ✓ instead of one flat tier of B nodes, use a pyramid of PBI modules
- ✓ the activation of an I node controls the onset of a new P layer
- ✓ in the first stage, a base PBI network creates broad domains



- ✓ in the next stage, another set of PBI networks subdivide these domains into compartments at a finer scale, etc.

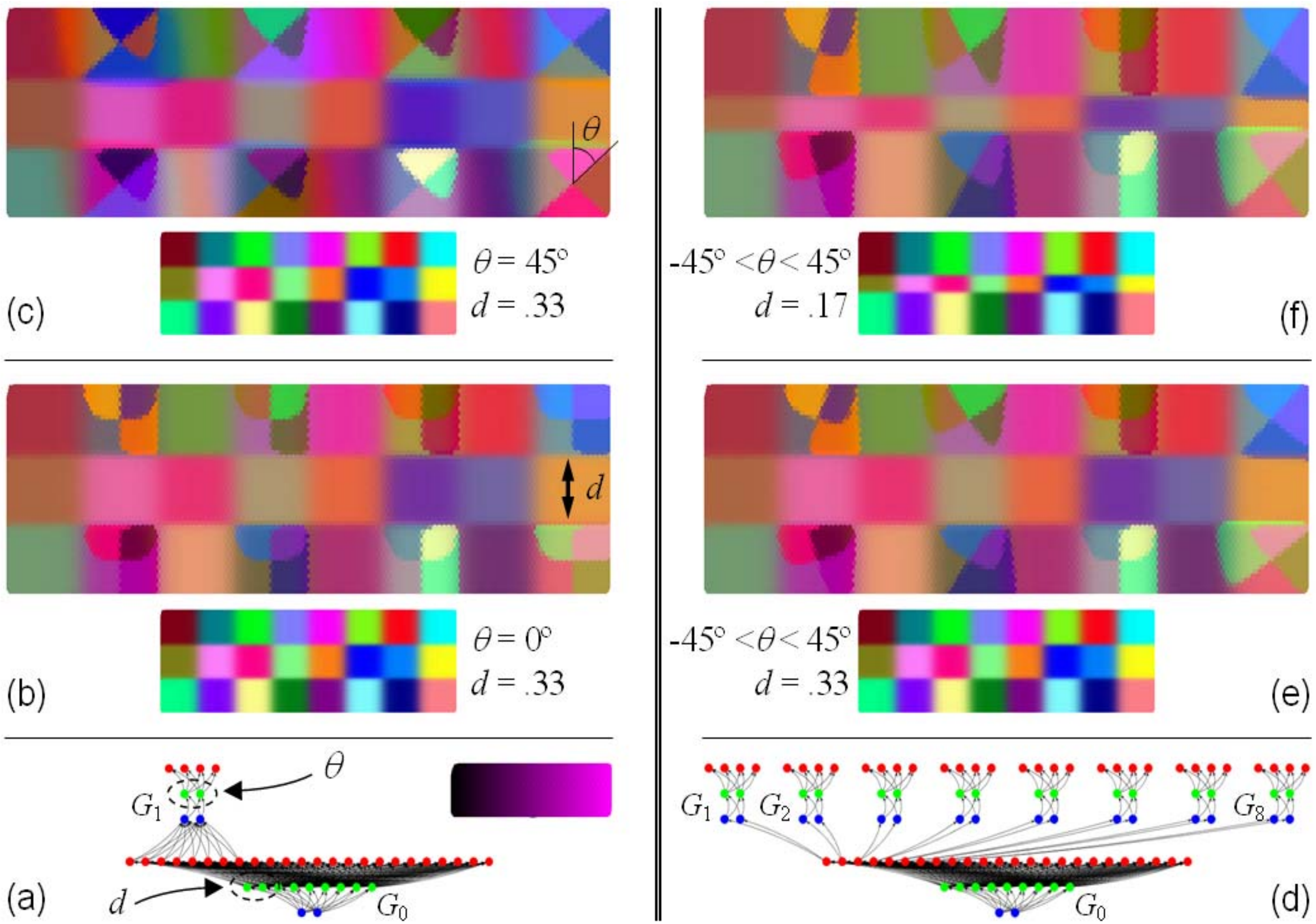
➢ Static vs. growing multiscale canvas

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



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*

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

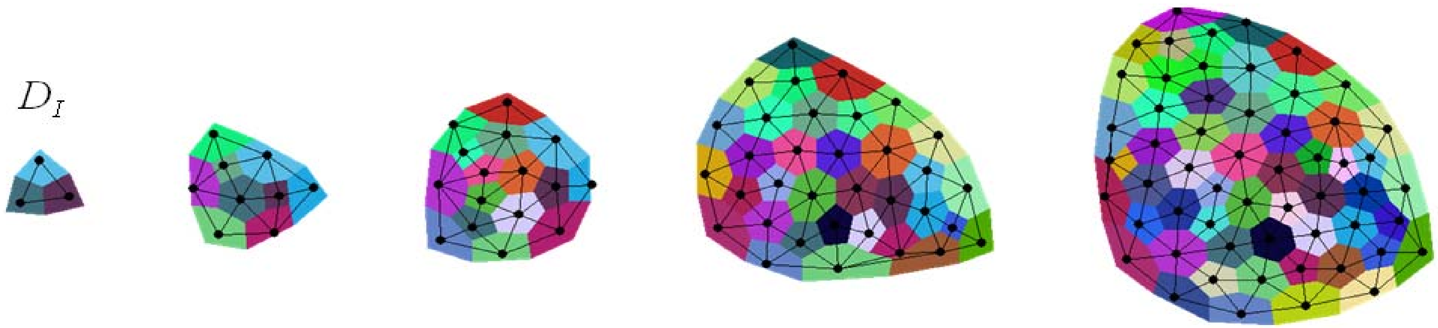
4. Bio-Inspired Evolutionary Meta-Design

Cell adhesion, division and migration

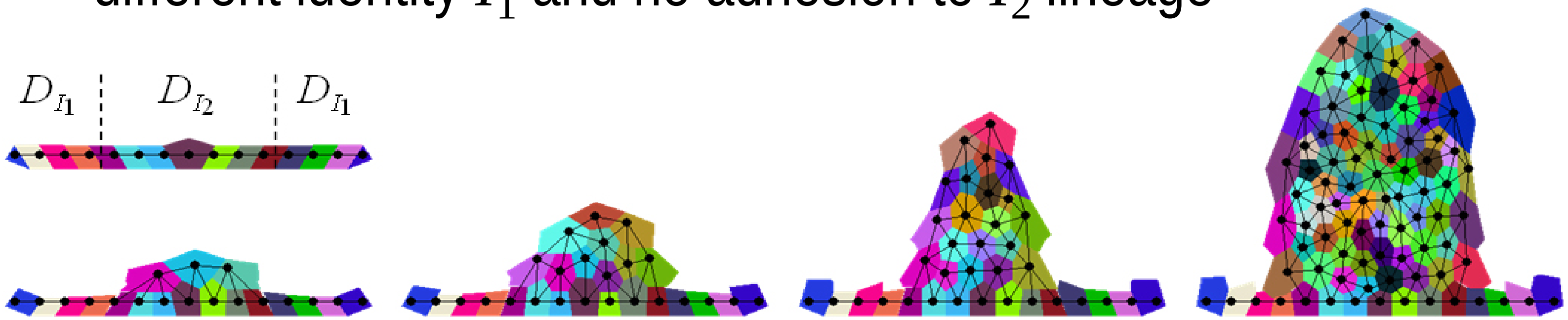
- ✓ the previous canvas was only growing uniformly; the model is now augmented with elements of cellular biomechanics and morphodynamics that can create nontrivial shapes
- ✓ cell coordinates vary according to three mechanistic principles:
  1. elastic cell rearrangement under differential adhesion
  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

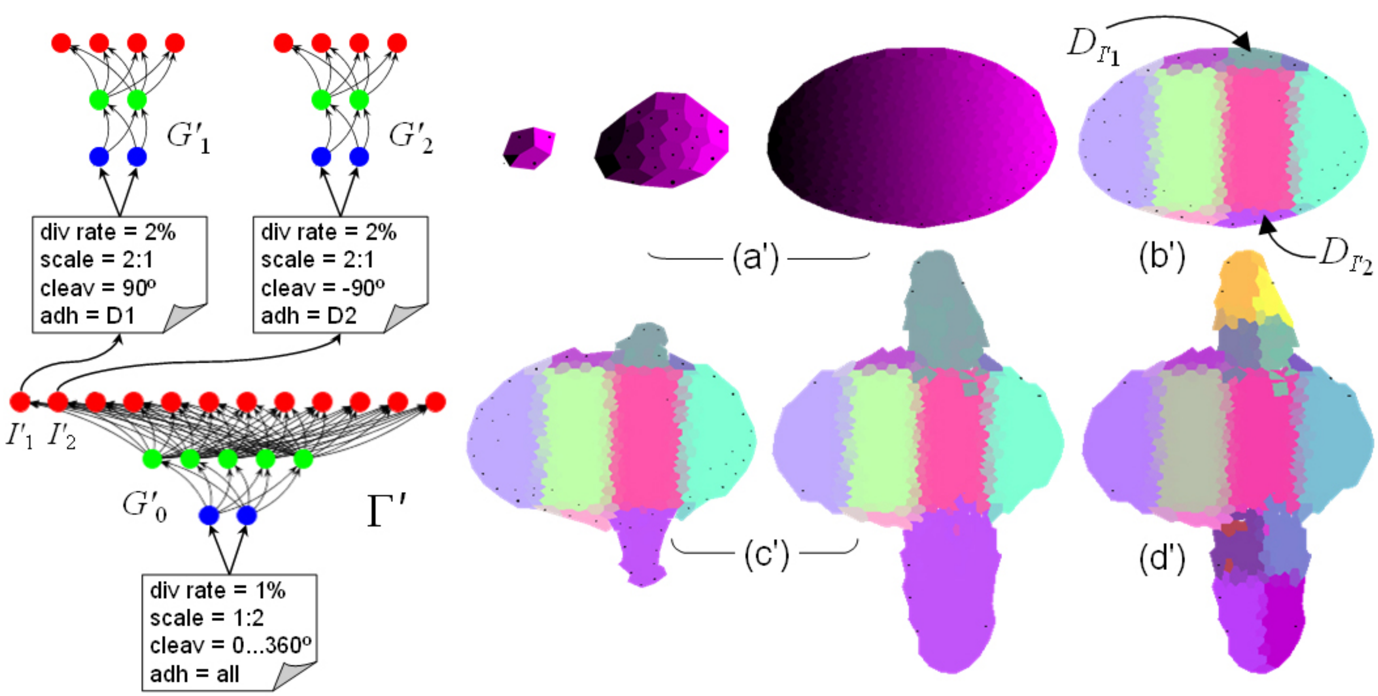


b) anistropic "limb" growth: only center domain I_2 divides (upward stretch due to $2x{:}y$ anisotropic rescaling); lateral cells have different identity I_1 and no adhesion to I_2 lineage



➢ 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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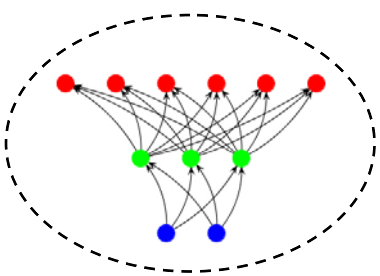
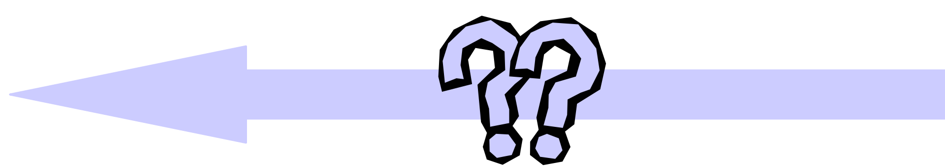
4. Bio-Inspired Evolutionary Meta-Design

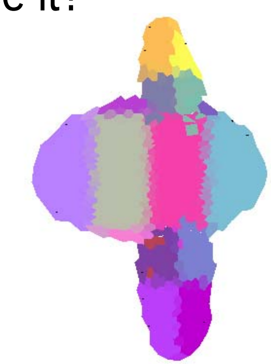
4. Evolutionary Meta-Design

➢ 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

parameters = “genetic code”

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?

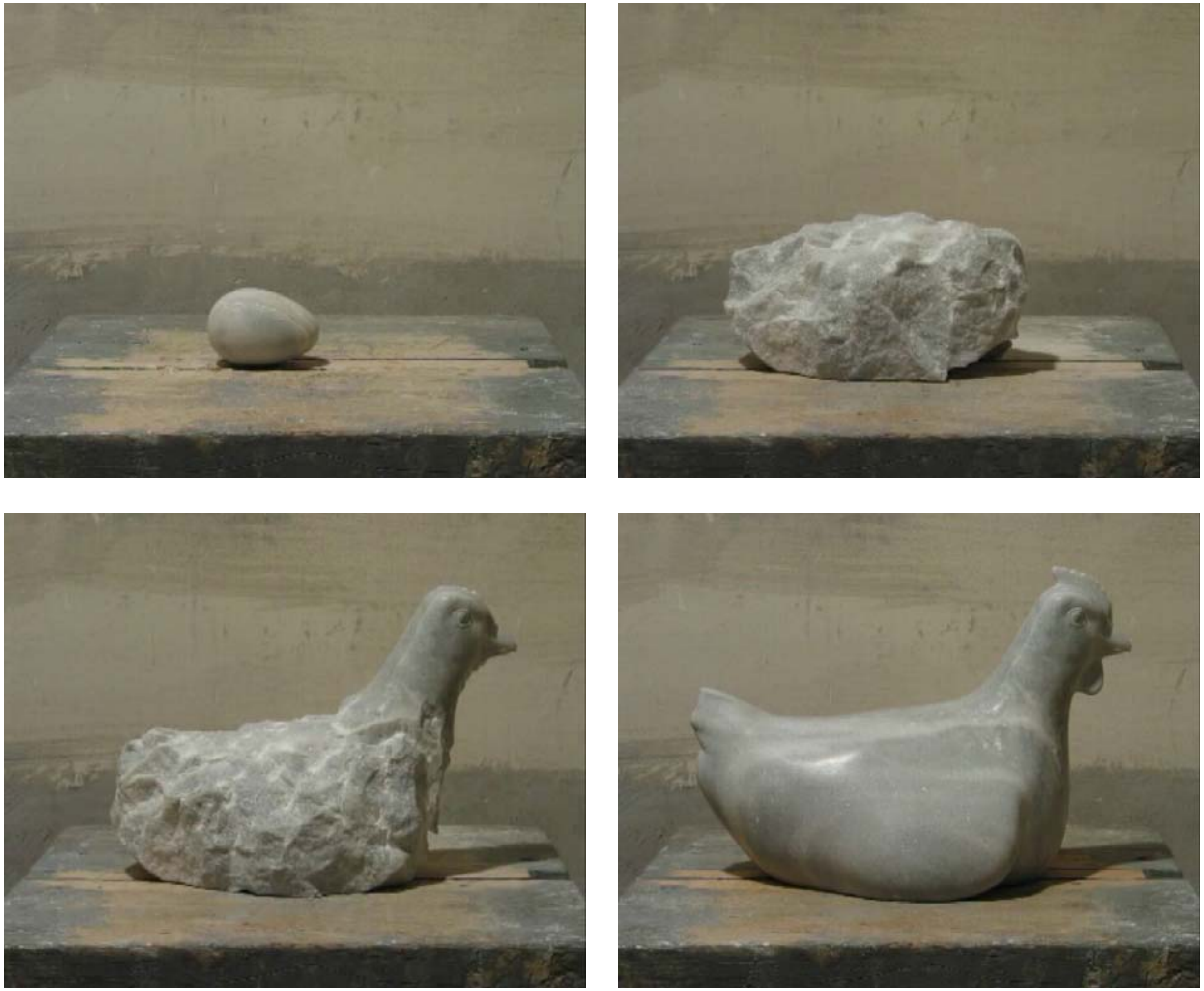
- ✓ different degrees of fitness constraints

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