Embryomorphic Systems Meta-Design:

Preparing for Self-Assembly, Self-Regulation and Evolution

René Doursat

Institut des Systèmes Complexes, CREA
CNRS & Ecole Polytechnique
1, rue Descartes, 75005 Paris

Embryomorphic Systems Meta-Design

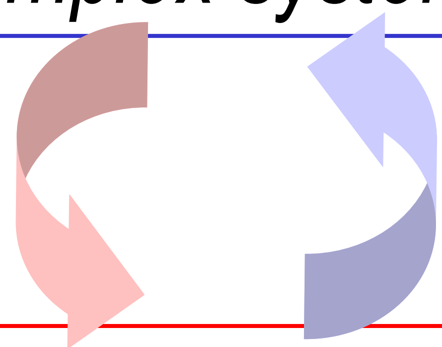
1. **Introduction: Designing Complexity**
2. The Genetic Causality of Biological Development
3. A Model of Genetically Guided Self-Assembly
4. Discussion: Planning the Autonomy

1. Introduction: Designing Complexity

➢ Complex systems engineering

understanding natural complex systems

exporting:
- **decentralization**
- **autonomy**
- **evolution**

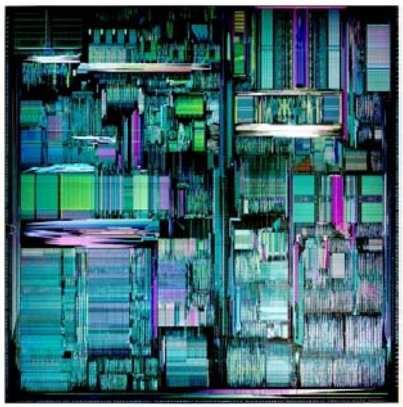


importing:
- **modeling**
- **simulation**

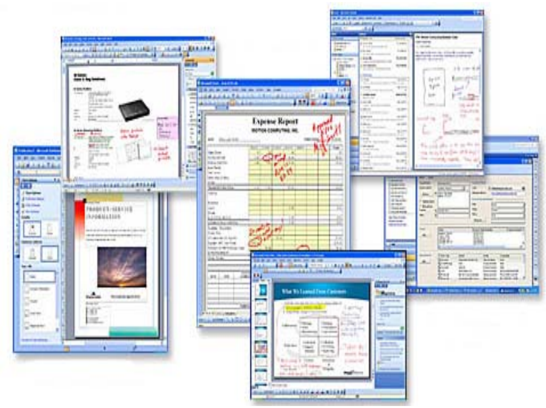
designing a new generation of artificial systems

1. Introduction: Designing Complexity

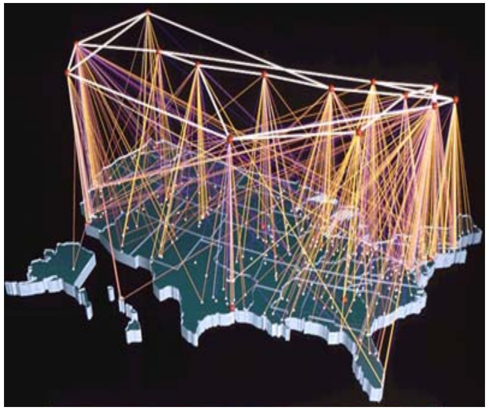
➢ **Rapid growth in size & complexity of computer systems,**



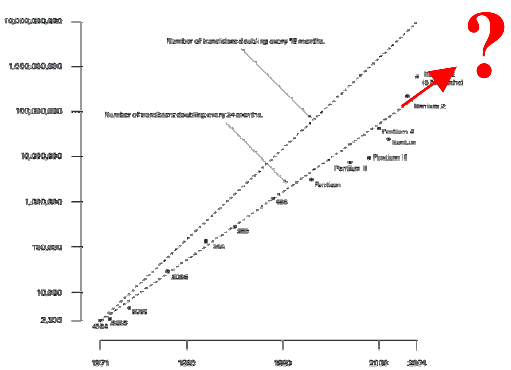
whether hardware,



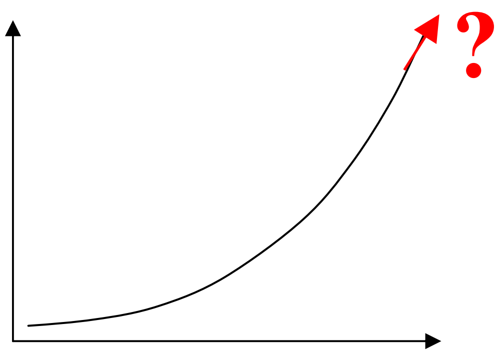
software,



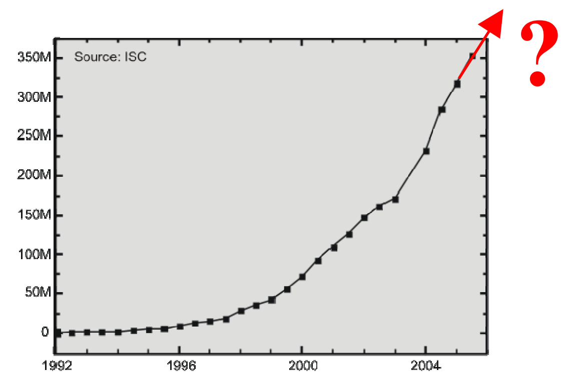
or networks, ...



number of transistors/year



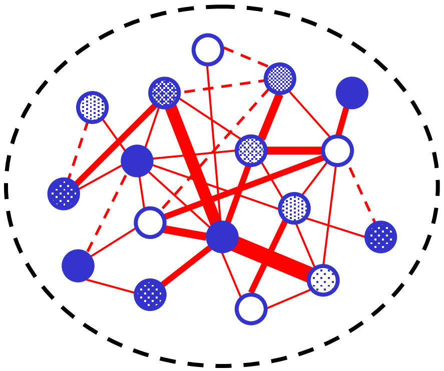
number of O/S lines of code/year



number of network hosts/year

1. Introduction: 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

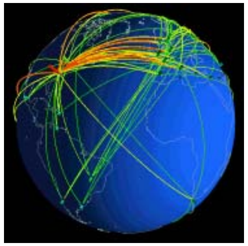
physical pattern formation

organism development

insect colonies

the brain

World Wide Web

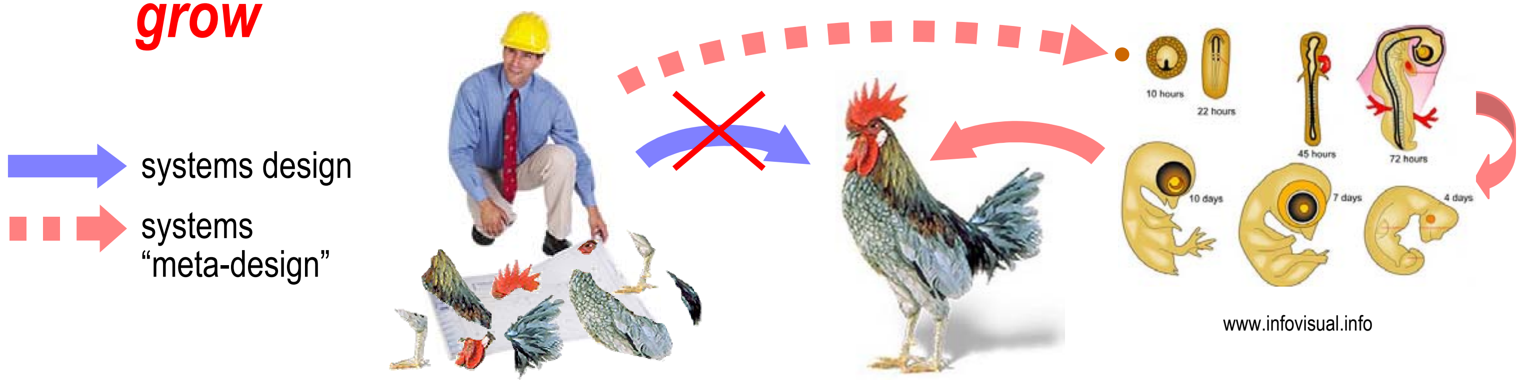


social networks

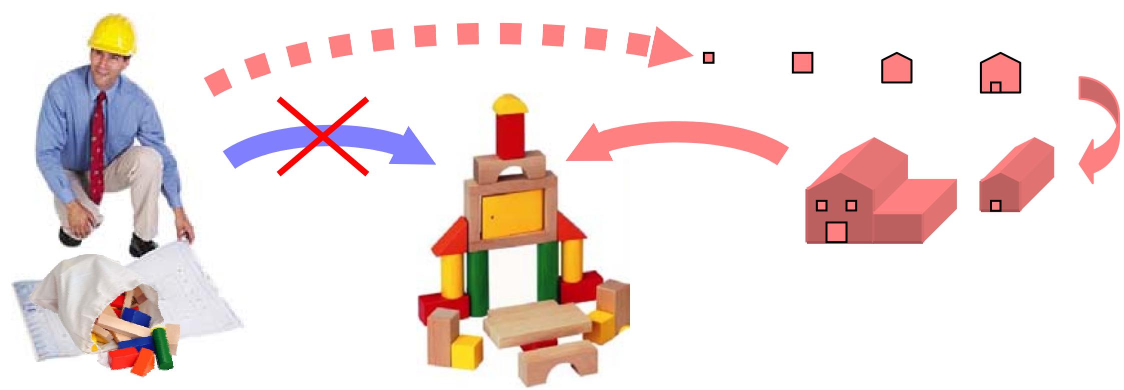
1. Introduction: Designing Complexity

➢ From centralized heteromy to decentralized autonomy

- ✓ artificial systems ***are built*** exogenously, organisms endogenously ***grow***

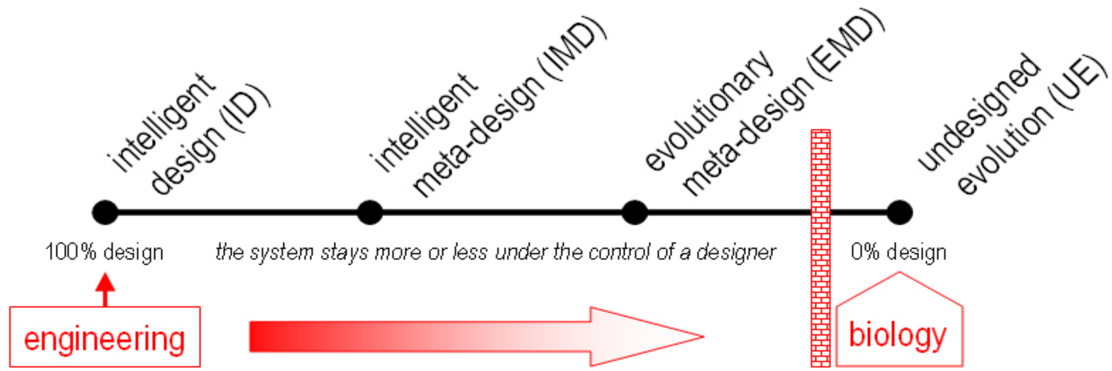


- ✓ future engineers should “step back” from their creation and only set ***generic*** conditions for systems to self-assemble and evolve



1. Introduction: Designing Complexity

➢ 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?

1. Introduction: Designing Complexity

➢ 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

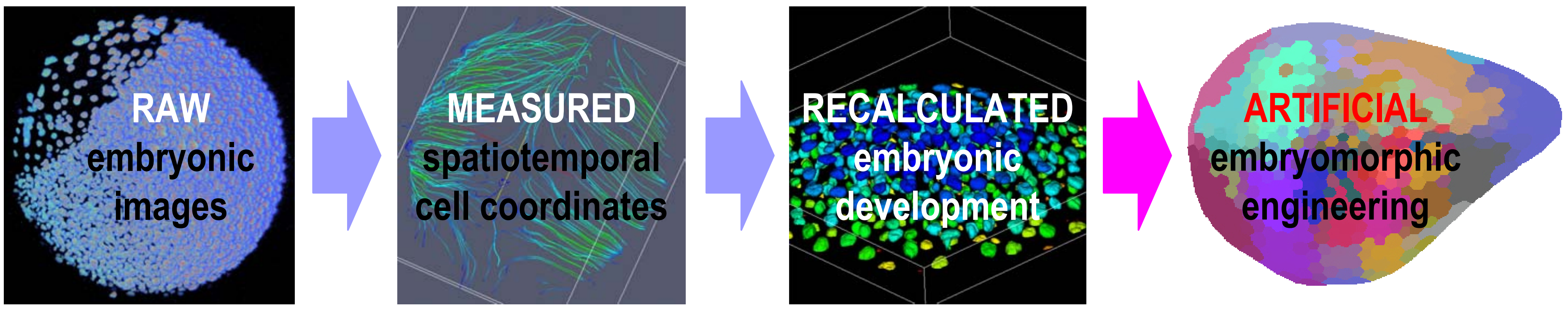
1. Introduction: Designing Complexity

➢ Toward a new discipline: "Embryomorphic Engineering"

✓ observing, modeling & transferring 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"



Embryomorphic Systems Meta-Design

1. Introduction: Designing Complexity
2. **The Genetic Causality of Biological Development**
3. A Model of Genetically Guided Self-Assembly
4. Discussion: Planning the Autonomy

2. The Genetic Causality of Biological Development

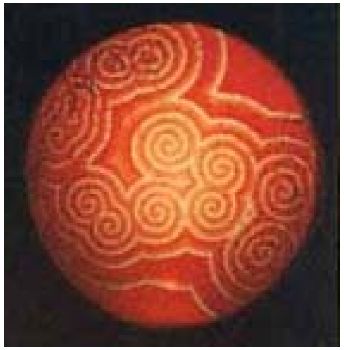
➢ Self-organized forms of nature: physical, biological

thermal convection
sand dunes, www.scottcamazine.com

plant
pomegranate, by Köhler
www.plant-pictures.de

insect colony

animal
gecko, www.cepolina.com



chemical reaction
BZ, by A. Winfree, University of Arizona

the brain

animal spots
www.scottcamazine.com

2. The Genetic Causality of Biological Development

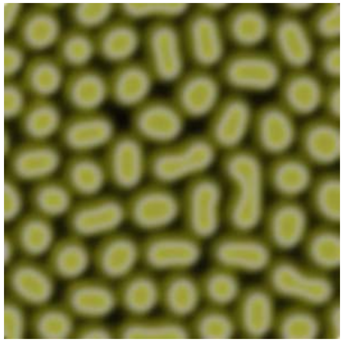
➢ Different types and taxonomies of pattern formation

- ✓ natural forms can be inert / living, individual-level / collectivity-level, small-scale / large-scale, etc.
- ✓ major distinction here: **free** forms / **guided** forms

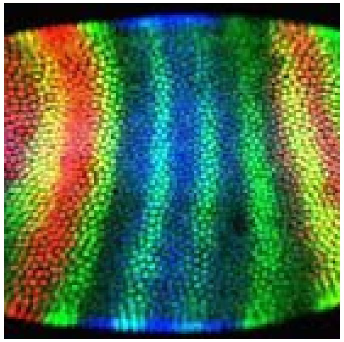
- **free**: Turing, reaction-diffusion
- randomly amplified fluctuations
- unpredictable: 4, 5 or 6 spots?
- statistically homogeneous; 1 scale

- **guided**: most of organism developmt
- deterministic genetic control
- reproducible: exactly 4 limbs, 5 digits
- heterogeneous, rich in information

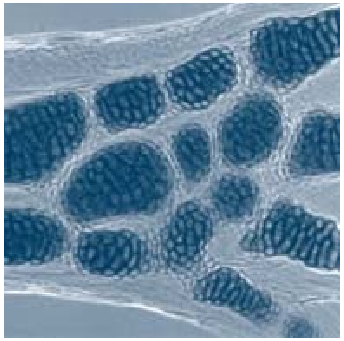
convection cells
www.chabotspace.org



reaction-diffusion
texturegarden.com/java/rd



fruit fly embryo
Sean Caroll, U of Wisconsin



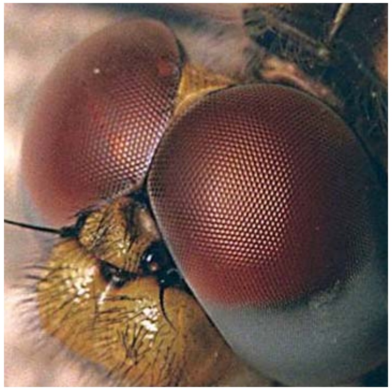
larval axolotl limb
Gerd B. Müller

2. The Genetic Causality of Biological Development

➢ Biological forms are a combination of free and guided...

✓ domains of free pattern embedded in a guided morphology

spots, stripes in skin
angelfish, www.sheddaquarium.org



ommatidia in eye
dragonfly, www.phy.duke.edu/~hsg/54

✓ repeated copies of a guided form, distributed as a free pattern

flowers in tree
cherry tree, www.phy.duke.edu/~fortney

segments in insect
centipede, images.encarta.msn.com

2. The Genetic Causality of Biological Development

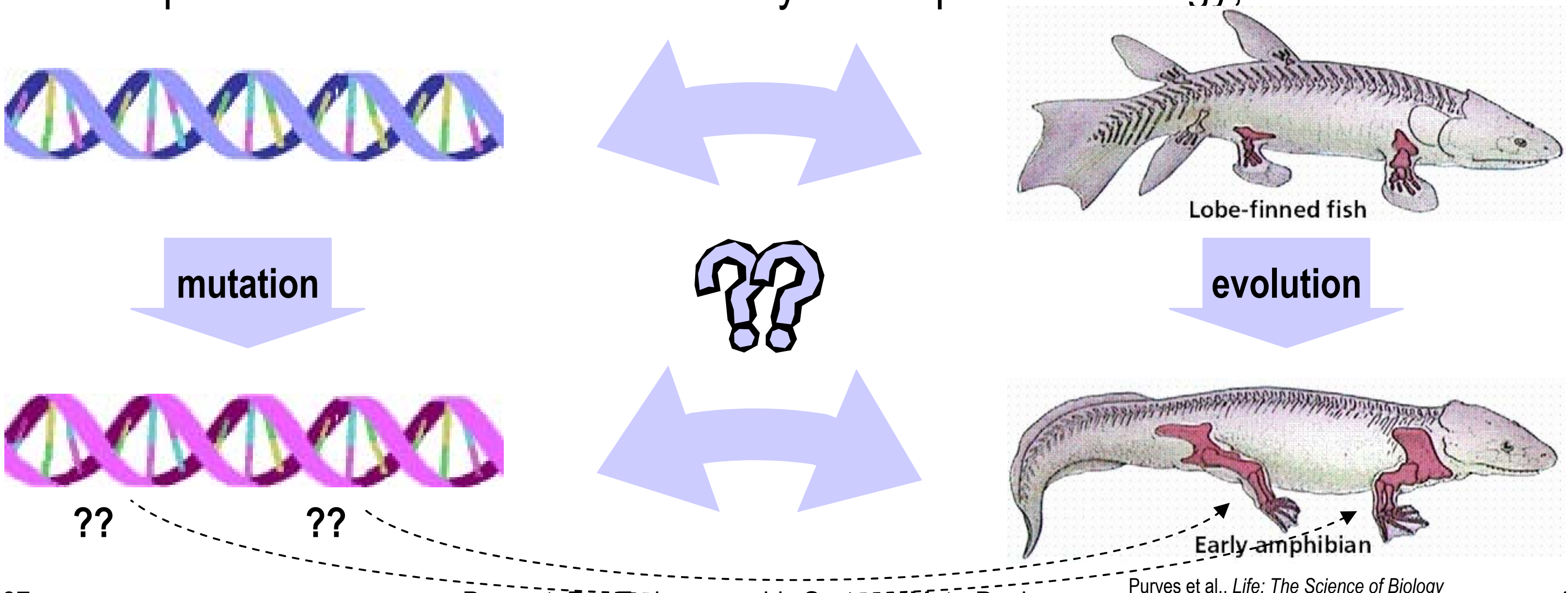
... but they are mostly guided (regulated)

- ✓ organism development is only ***marginally*** (superficially) the result of free-forming random instabilities: animal coat pigmentation, etc.
- ✓ for the most part, the precisely arranged body plan of animals, made of modules and articulated segments, arises from a genetically guided (regulated) morphogenesis process
- ✓ it is the latter kind that could serve as a new paradigm of reliable, information-driven systems growth

2. The Genetic Causality of Biological Development

➢ Development: the missing link of the Modern Synthesis

- ✓ biology's "Modern Synthesis" demonstrated the existence of a fundamental correlation between genotype and phenotype, yet the molecular and cellular mechanisms of development are still unclear
- ✓ the genotype-phenotype link cannot remain an abstraction if we want to unravel the generative laws of development and evolution
- ✓ understanding variation by comparing the actual development of different species is the focus of evolutionary developmental biology, or "evo-devo"



Purves et al., *Life: The Science of Biology*

2. The Genetic Causality of Biological Development

"When Charles Darwin proposed his theory of evolution by variation and selection, explaining selection was his great achievement. He could not explain variation. That was Darwin's dilemma."

"To understand novelty in evolution, we need to understand organisms down to their individual building blocks, down to their deepest components, for these are what undergo change."

—Marc W. Kirschner and John C. Gerhart (2005)
***The Plausibility of Life*, p. ix**

2. The Genetic Causality of Biological Development

How does a static, nonspatial genetic code dynamically unfold in time and 3-D space?

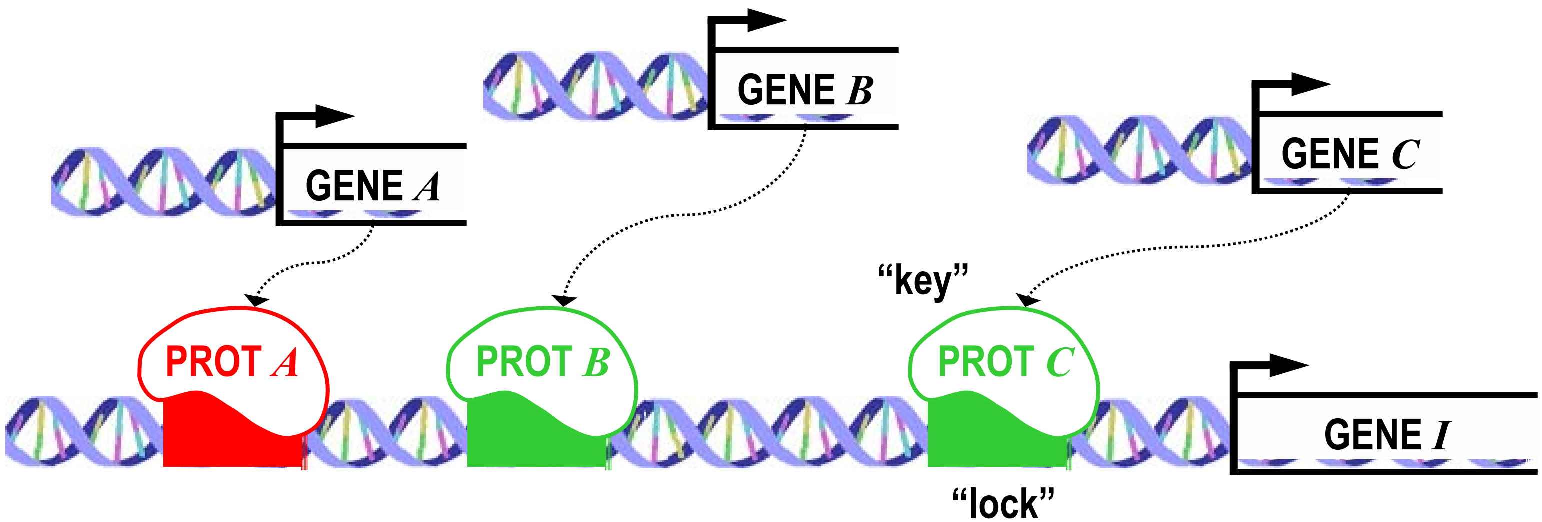
How are morphological changes correlated with genetic changes?

Embryomorphic Systems Meta-Design

1. Introduction: Designing Complexity
2. The Genetic Causality of Biological Development
3. **A Model of Genetically Guided Self-Assembly**
    a. **The self-painting canvas**
    b. The modular canvas
    c. The deformable canvas
4. Discussion: Planning the Autonomy

3. Gene-Guided Self-Assembly – a. Self-painting canvas

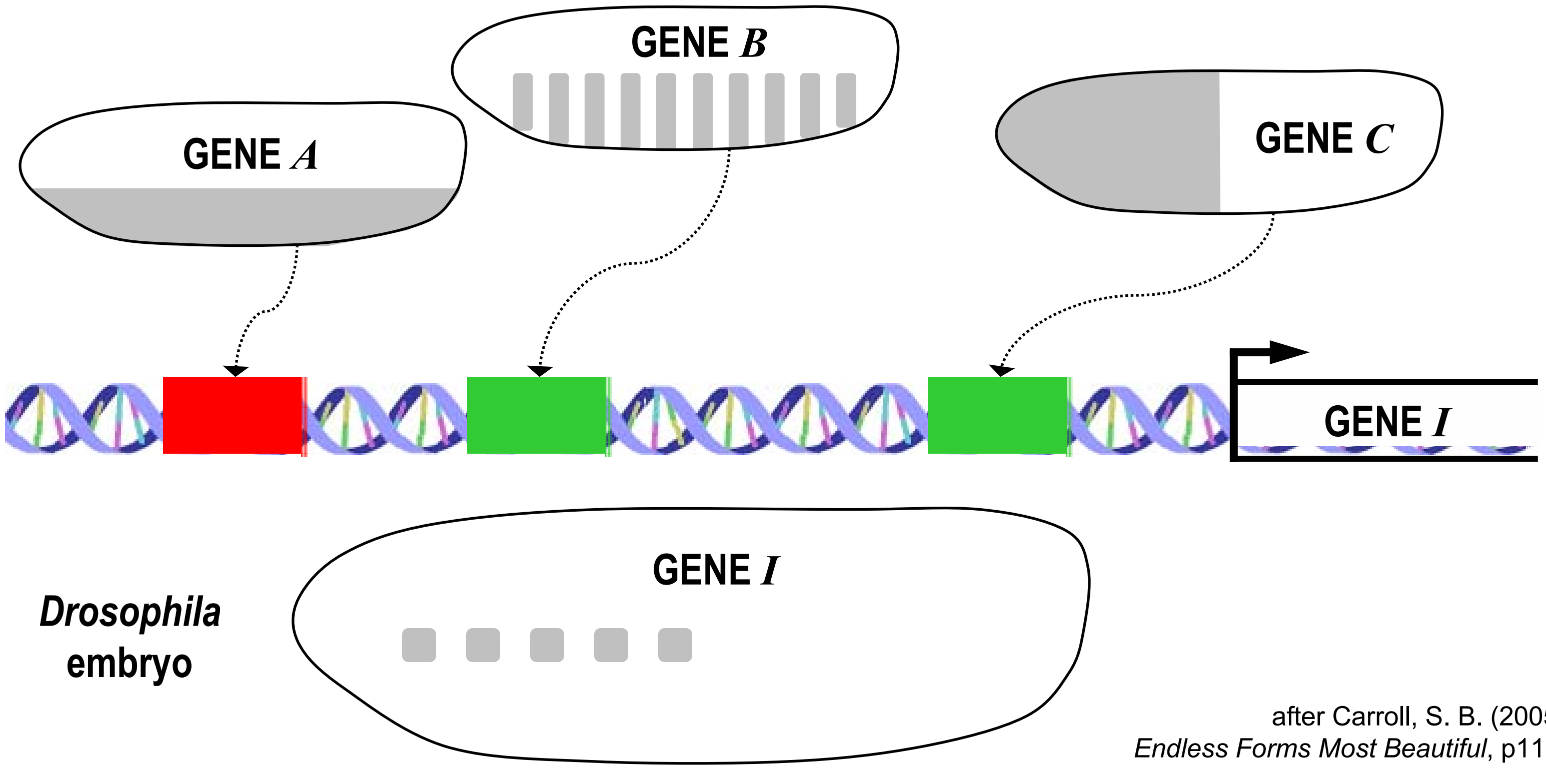
- **Genetic switches are controlled by genetic expression**
  - ✓ switch = regulatory site on DNA (“lock”) near a gene + protein that binds to this site (“key”), promoting or repressing the gene



  - ✓ switches can combine to form complex regulatory functions
  - → *since switch proteins are themselves produced by genes, a cell can be modeled as a* ***gene-to-gene regulatory network*** *(GRN)*

3. Gene-Guided Self-Assembly – a. Self-painting canvas

- **Developmental genes are expressed in spatial domains**
  - ✓ thus combinations of switches can create patterns by union and intersection, for example: $I = (\text{not } A) \text{ and } B \text{ and } C$

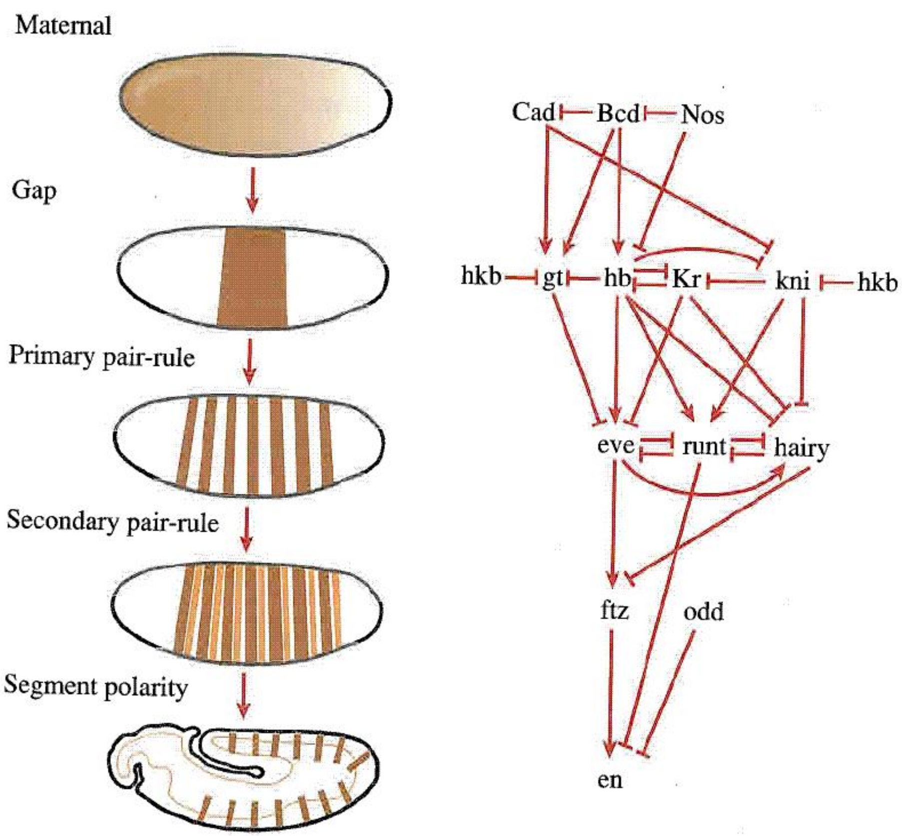


after Carroll, S. B. (2005)
Endless Forms Most Beautiful, p117

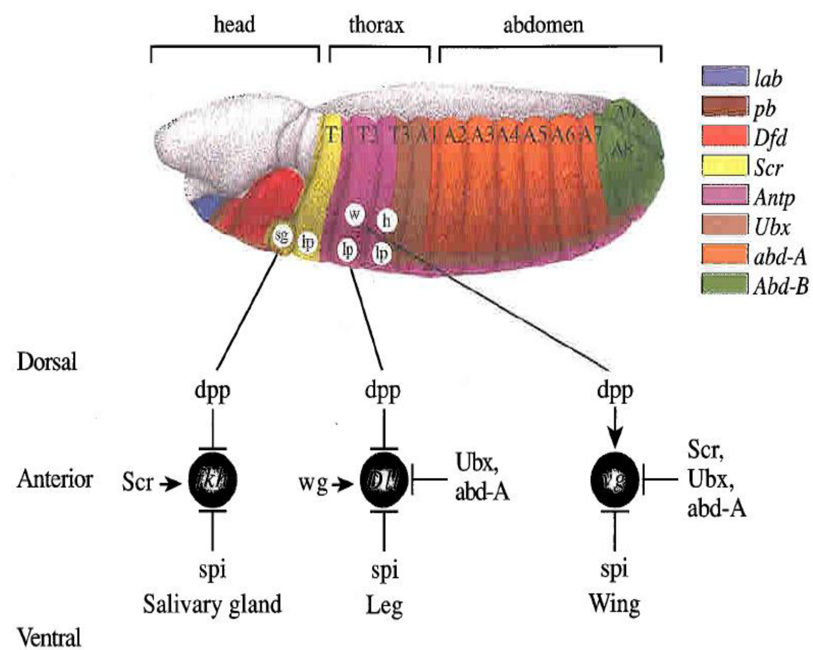
3. Gene-Guided Self-Assembly – a. Self-painting canvas

➢ Segmentation & identity domains in *Drosophila*

✓ periodic A/P band patterns are controlled by a 5-tier gene regulatory hierarchy



✓ intersection with other axes creates organ primordia and imaginal discs (identity domains of future legs, wings, antennae, etc.)

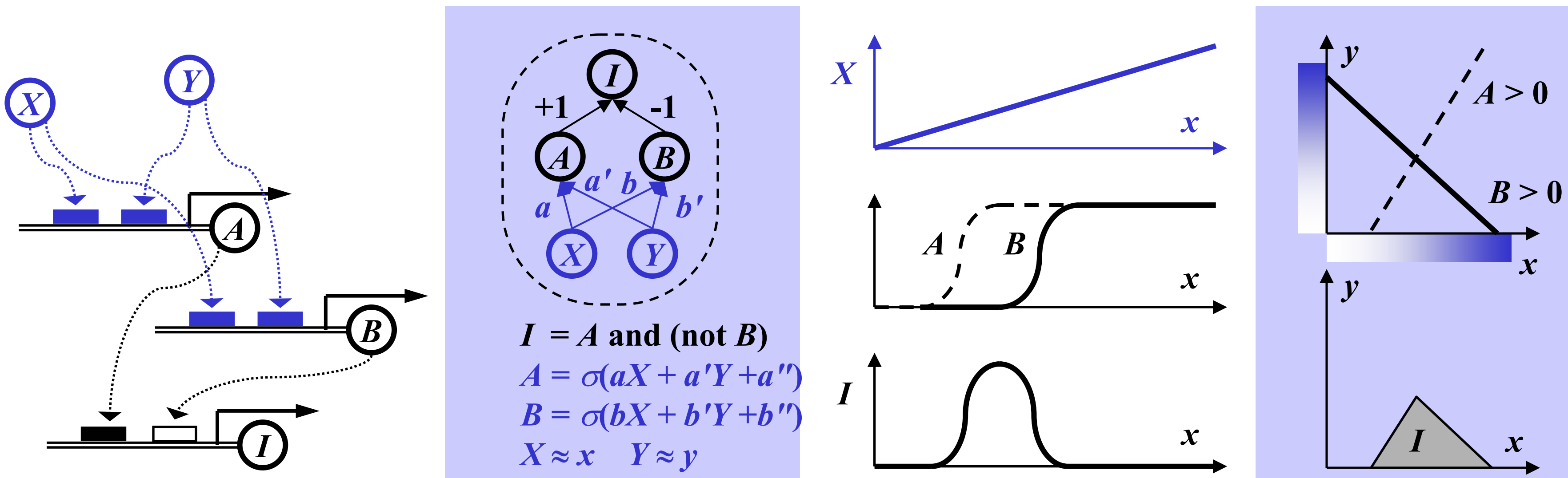


from Carroll, S. B., et al. (2001)
***From DNA to Diversity*, p63**

3. Gene-Guided Self-Assembly – a. Self-painting canvas

➢ **Three-tier GRN model: integrating positional gradients**

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



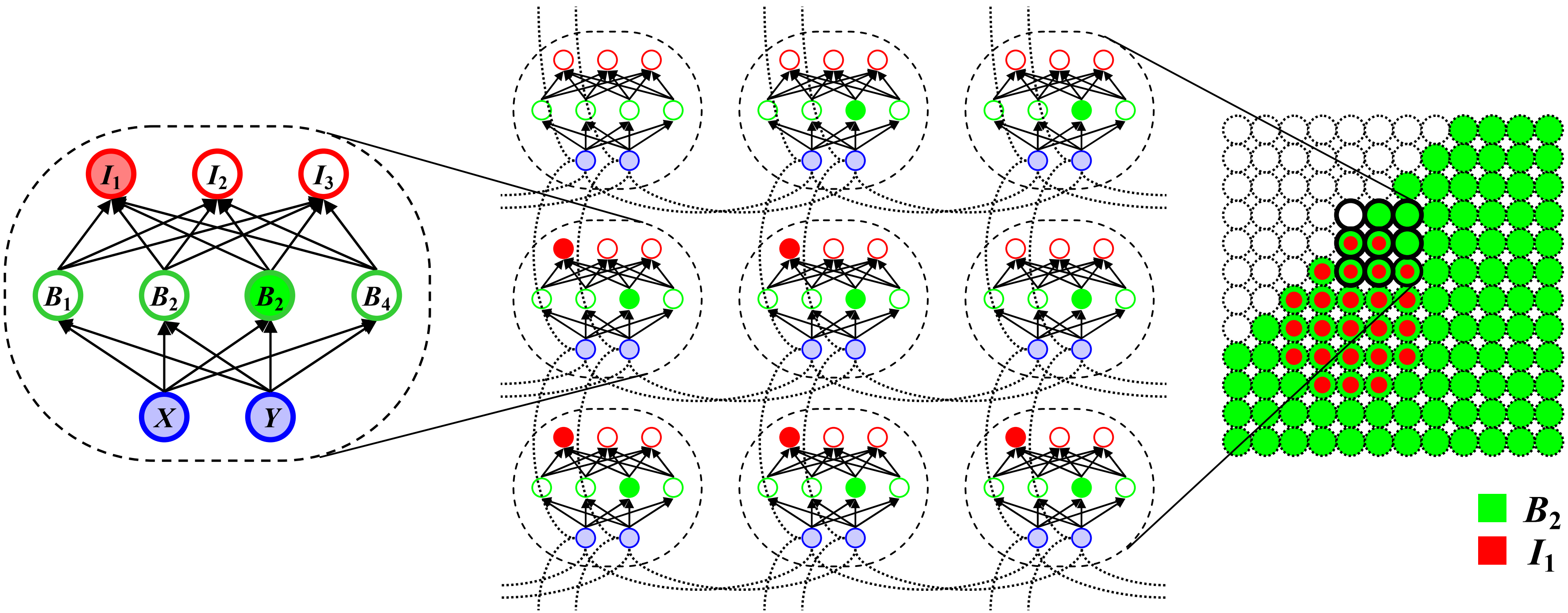
✓ X and Y diffuse along two axes and form concentration gradients

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

3. Gene-Guided Self-Assembly – a. Self-painting canvas

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

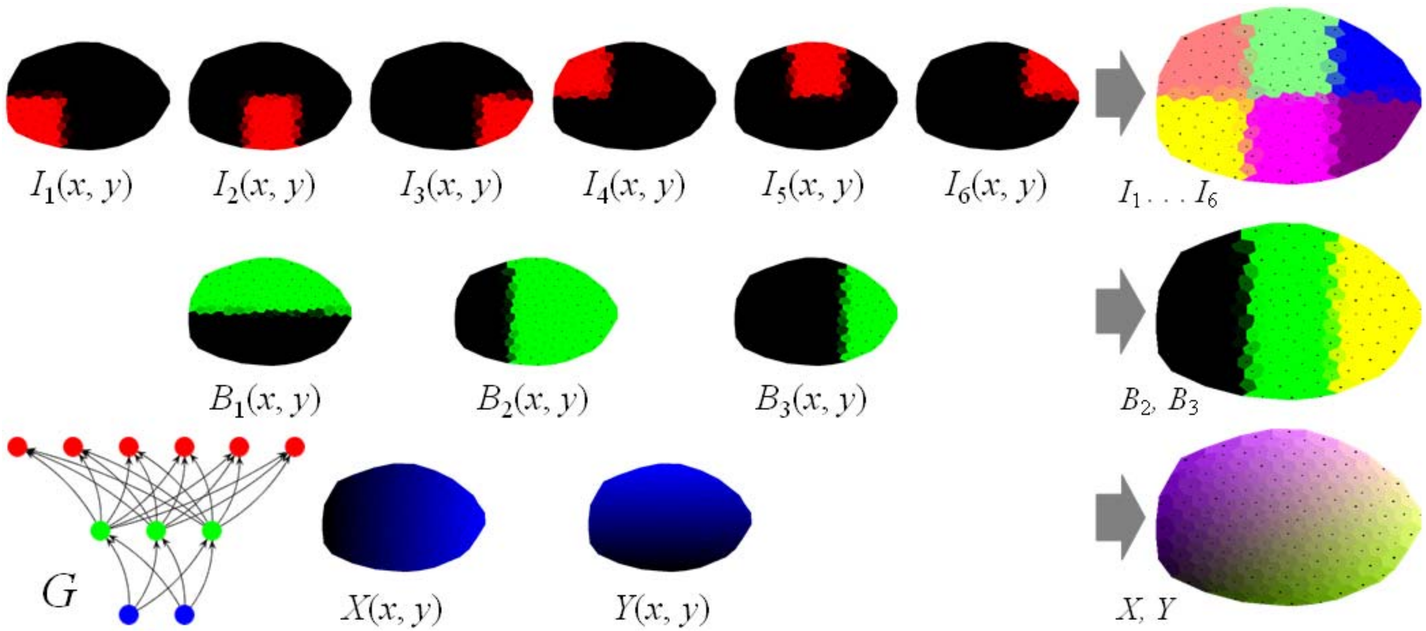
- ✓ network of networks: each GRN is contained in a cell, coupled to neighboring cells via the positional nodes (for diffusion)
- ✓ a pattern of gene expression is created on the lattice



3. Gene-Guided Self-Assembly – a. Self-painting canvas

➢ 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.: $B1 = \sigma(Y - 1/2)$, $B2 = \sigma(X - 1/3)$, $I6 = B1B3$ ...



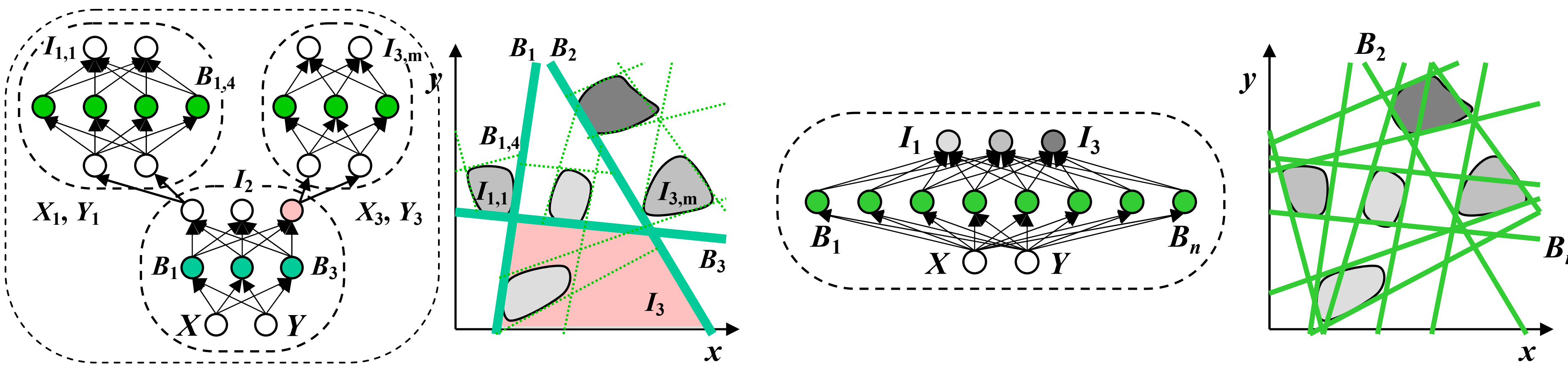
Embryomorphic Systems Meta-Design

1. Introduction: Designing Complexity
2. The Genetic Causality of Biological Development
3. **A Model of Genetically Guided Self-Assembly**
   a. The self-painting canvas
   b. **The modular canvas**
   c. The deformable canvas
4. Discussion: Planning the Autonomy

3. Gene-Guided Self-Assembly – b. Modular canvas

➢ 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



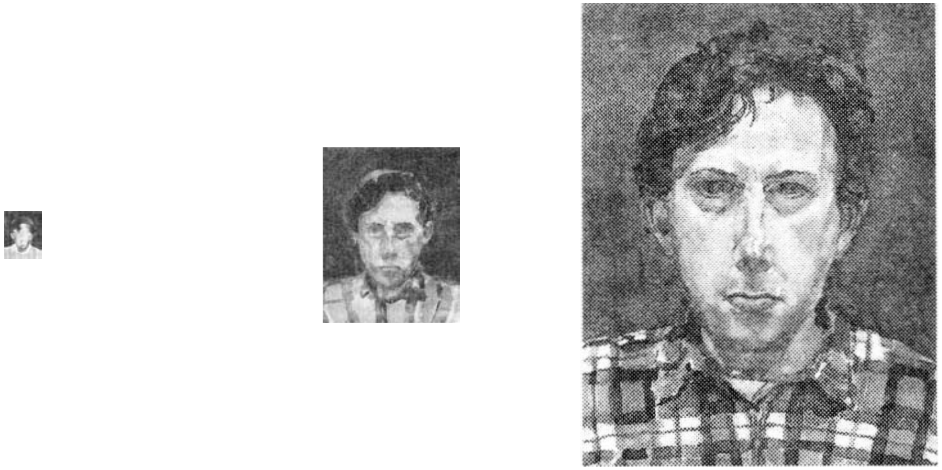
- ✓ in the next stage, another set of PBI networks subdivide these domains into compartments at a finer scale, etc.

3. Gene-Guided Self-Assembly – 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

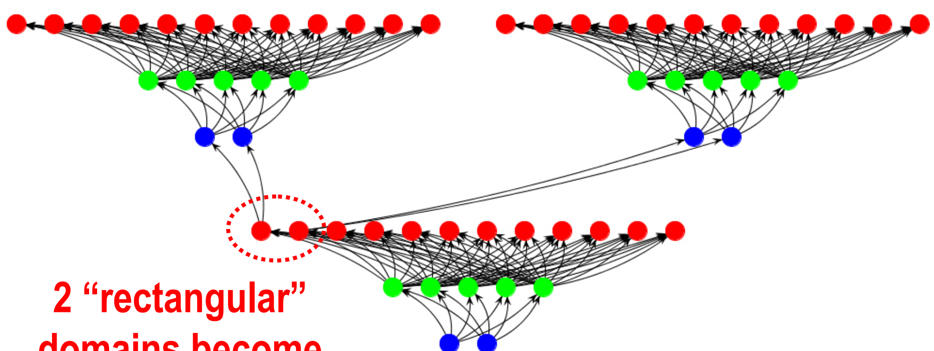


from Coen, E. (2000)
The Art of Genes, pp131-135

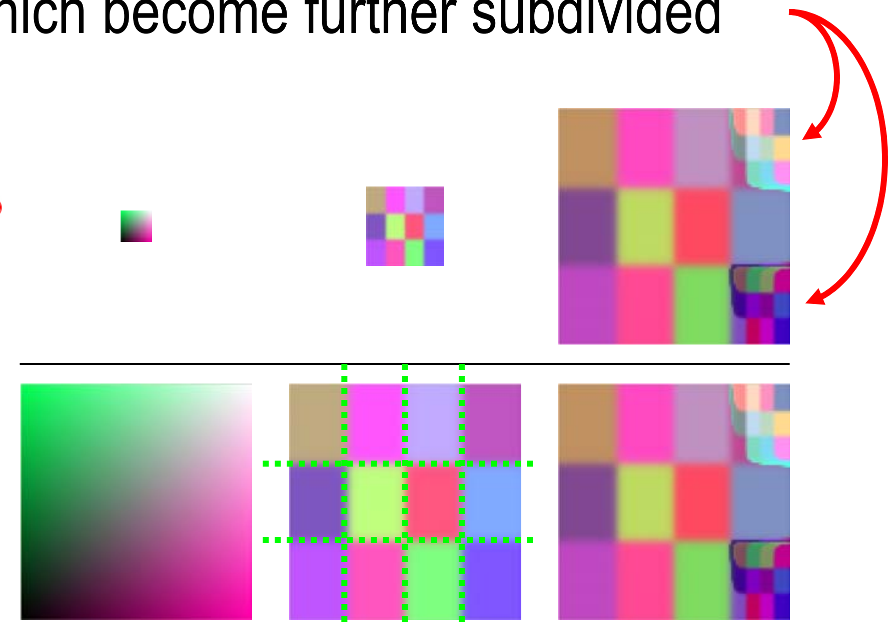
3. Gene-Guided Self-Assembly – b. Modular canvas

➢ Example of numerical simulation with preset weights

- ✓ small stained glass embedded into bigger stained glass
- ✓ here, a 2-layer architecture of GRNs: 5 boundary nodes, 12 rectangular domains, 2 of which become further subdivided



2 “rectangular” domains become further subdivided

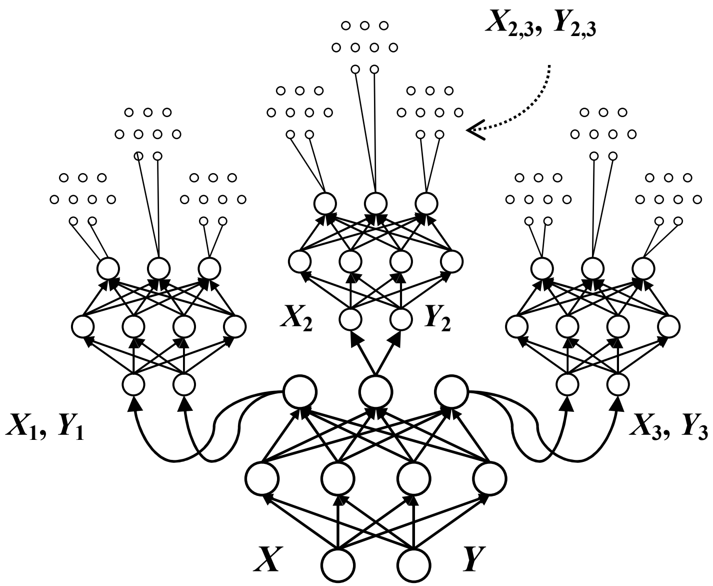


2 “horizontal” + 3 “vertical” boundary nodes

3. Gene-Guided Self-Assembly – b. Modular canvas

➢ General idea of guided multiscale self-patterning

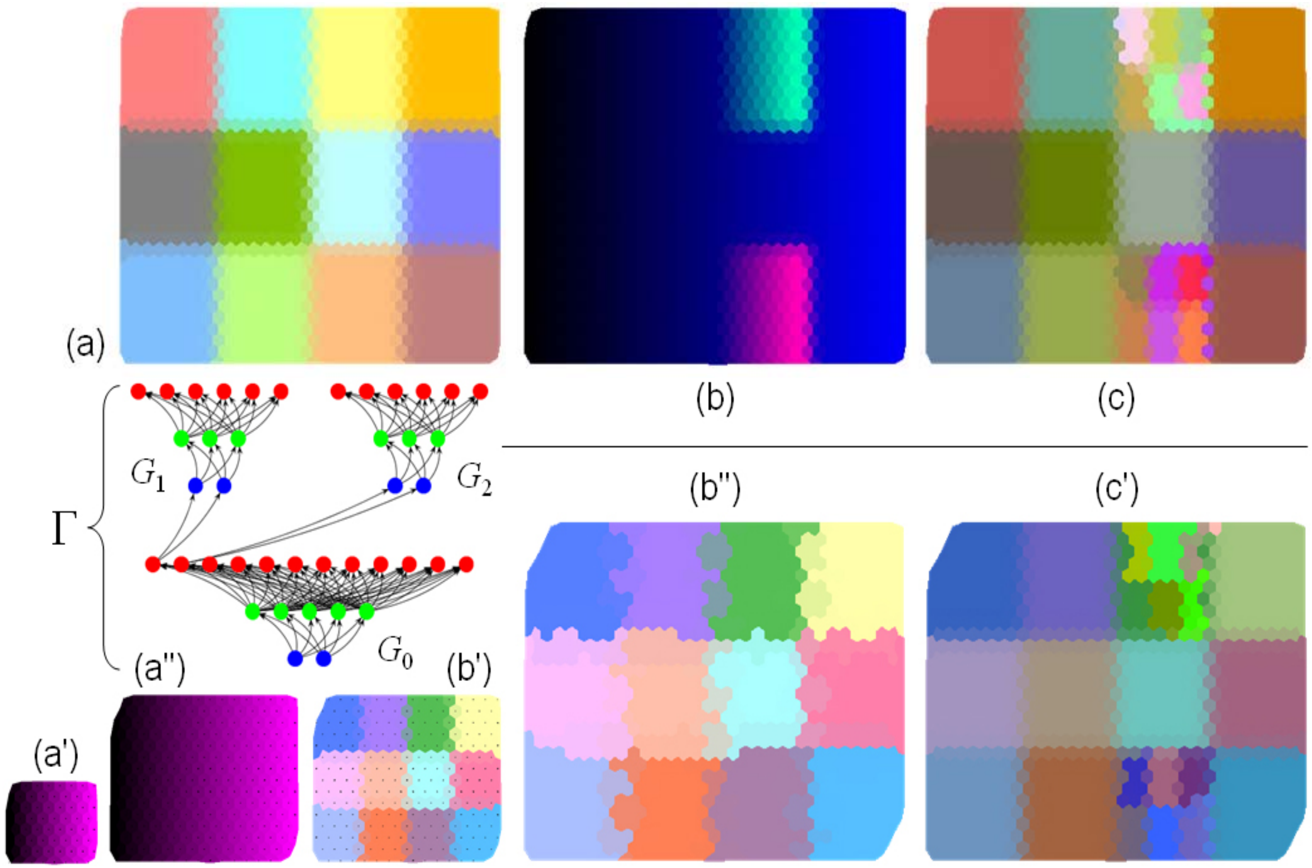
- ✓ possibility of image generation based on a generic hierarchical GRN
- ✓ (here: illustration, not actual simulation)



3. Gene-Guided Self-Assembly – b. Modular canvas

➢ Static vs. growing multiscale canvas

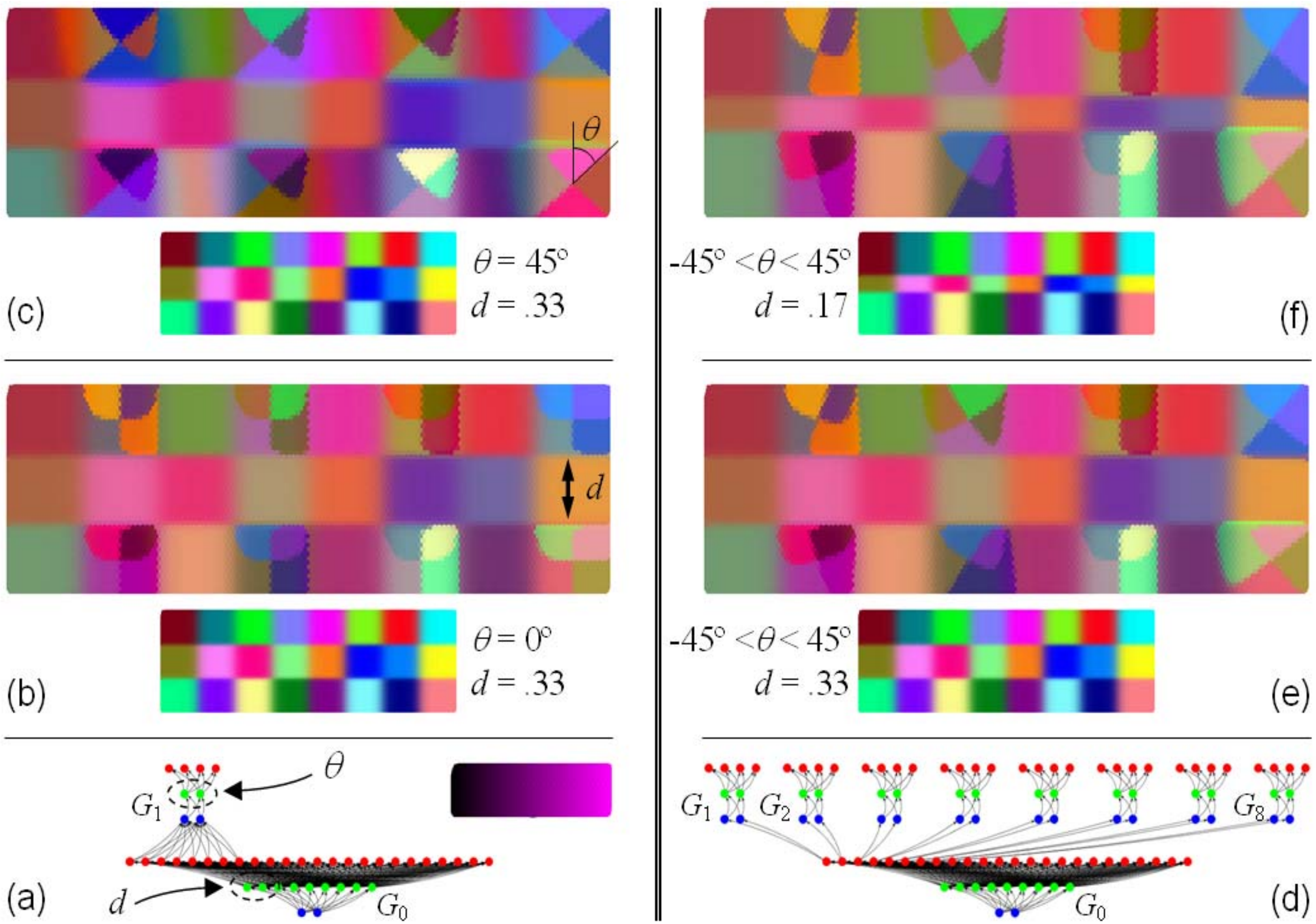
- ✓ 32x32 hexagonal lattice of cells, two-level gene network Γ: base subnet G_0, then 2 subnets G_1, G_2 triggered by I_1 and I_2



equivalent pattern obtained by ***uniform expansion*** from 8x8 cells

3. Gene-Guided Self-Assembly – b. Modular canvas

➢ 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***

Embryomorphic Systems Meta-Design

1. Introduction: Designing Complexity

2. The Genetic Causality of Biological Development

3. **A Model of Genetically Guided Self-Assembly**

   a. The self-painting canvas

   b. The modular canvas

   c. **The deformable canvas**

4. Discussion: Planning the Autonomy

3. Gene-Guided Self-Assembly – c. Deformable canvas

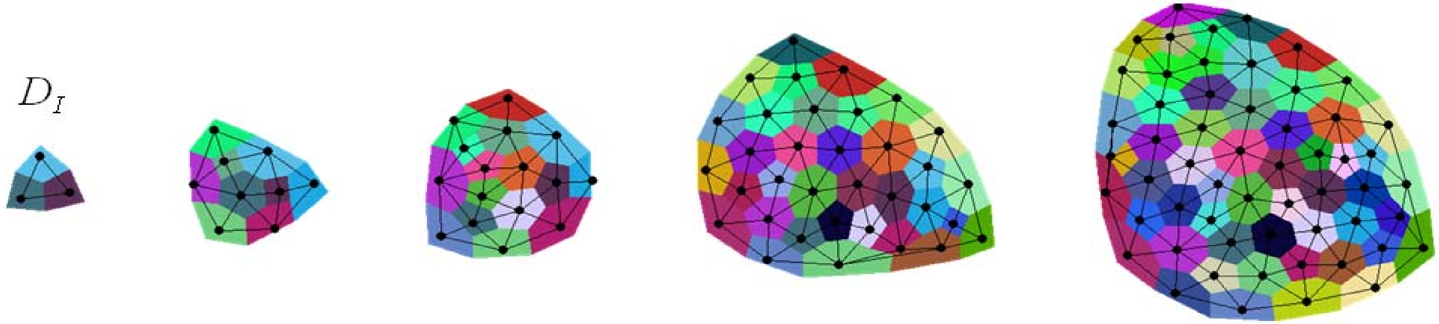
➢ Cell adhesion, division and migration

- ✓ 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

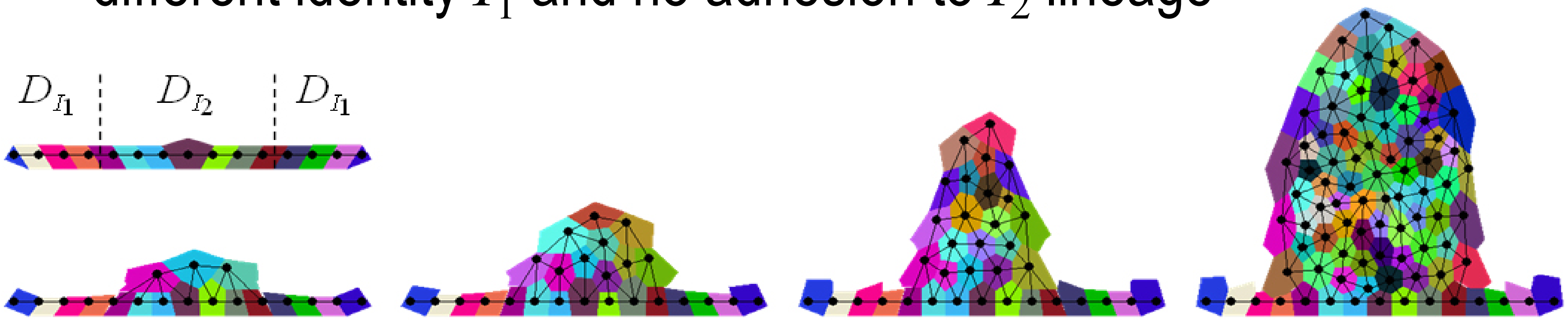
3. Gene-Guided Self-Assembly – c. Deformable canvas

➢ 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



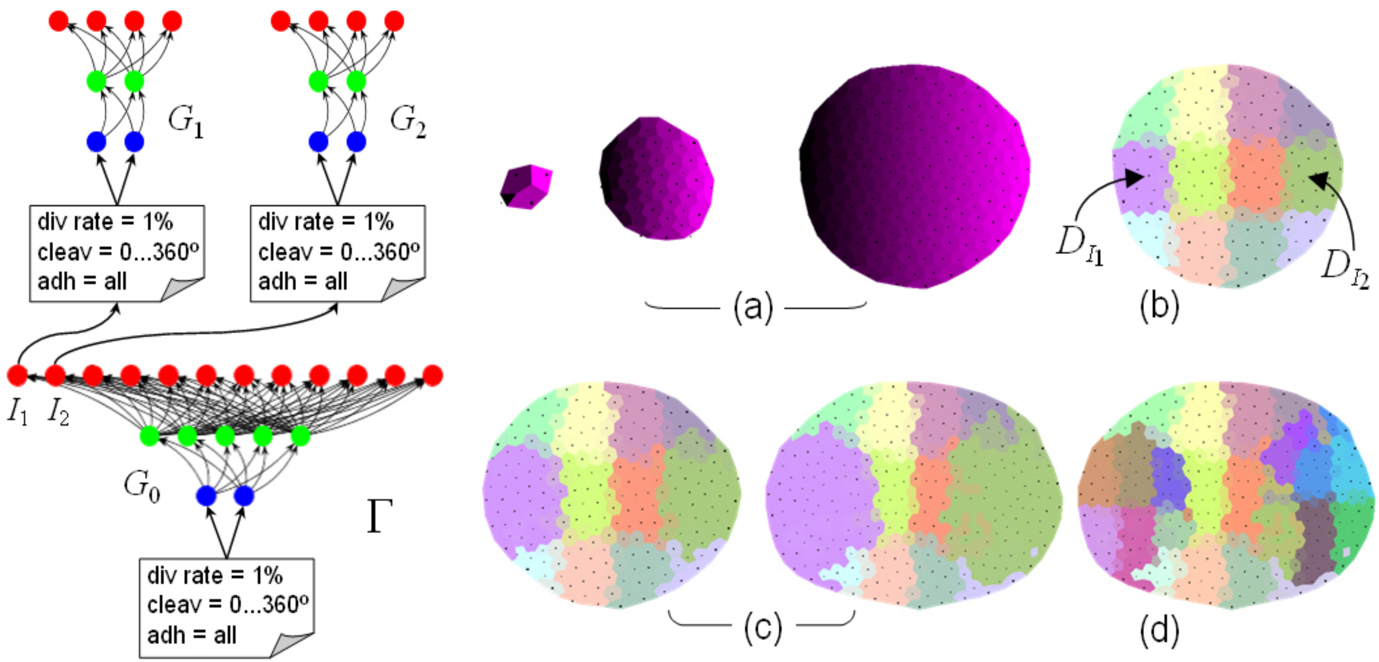
b) anistropic "limb" growth: only center domain I_2 divides (upward stretch due to $2x{:}y$ anisotropic rescaling); lateral cells have different identity I_1 and no adhesion to I_2 lineage



3. Gene-Guided Self-Assembly – c. Deformable canvas

➢ Inhomogeneous cell division

- ✓ cells divide according to a ***nonuniform*** probability that depends on their ***genetic identity***, i.e., the domain of high I-node expression to which they belong

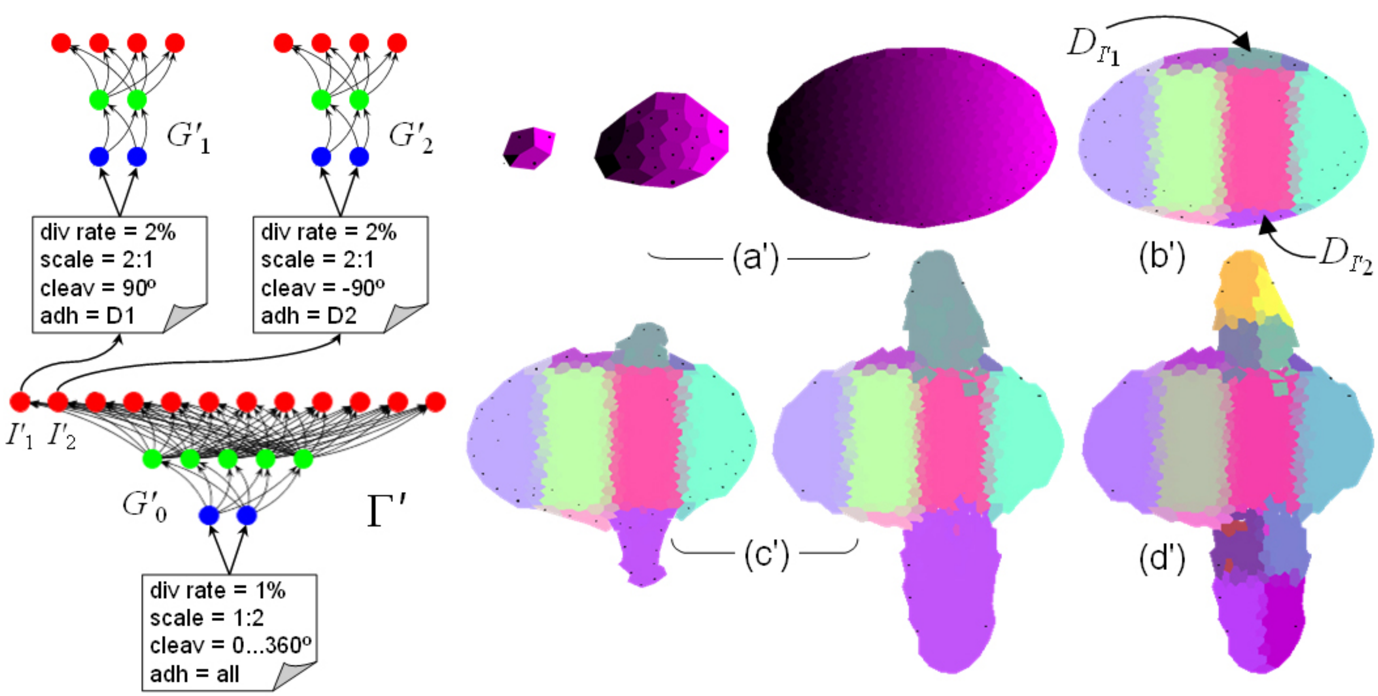


- ✓ new cell behavior rules are added: cells with high levels of I_1 and I_2 further divide at rate 1% (c), while others stop
- ✓ then, as usual, they express subpatterns G_1 and G_2 in their newly formed territories (d)

3. Gene-Guided Self-Assembly – c. Deformable canvas

➢ 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

Embryomorphic Systems Meta-Design

4. Discussion: Planning the Autonomy

➢ Growth, function, selection

✓ the three challenges of complex systems engineering:

1. how does the system **grow**?
   - 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 and parameters
2. how does the system **function**?
   - task (2) is about defining the nature of the elements their functionality: hardware components? software modules? robot parts? are they computing? or physically moving? etc.
3. how does the system **evolve** and how is it **selected**?

parameters = "genetic code"

4. Discussion: Planning the Autonomy

➢ **The paradox of complex systems engineering**

How can we control complexity?

How can we both "let go" and still have requirements at the same time?

How can we "optimize" the parameters (genetic code) of a self-organized process?

4. Discussion: Planning the Autonomy

➢ 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 diversifying the requirements
   - "harvest" interesting organisms from a free-range menagerie

Embryomorphic Systems Meta-Design

1. Introduction: Designing Complexity
2. The Genetic Causality of Biological Development
3. A Model of Genetically Guided Self-Assembly
4. Discussion: Planning the Autonomy