A Good Number of Forms Fairly Beautiful

Doctoral Thesis Defence

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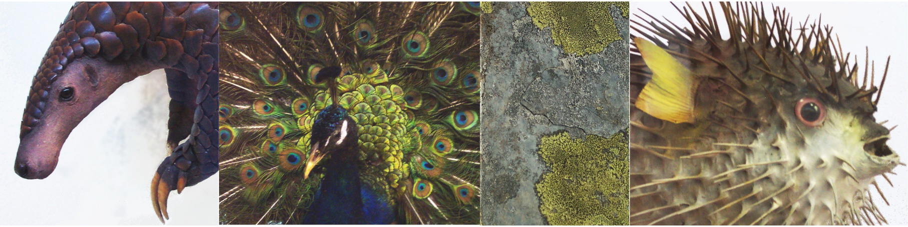
Motivation



Automated Design

Less concentration on *designing* systems, more on *finding* them, then demonstrating efficacy and reliability of discovered design.

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Design via search:

- Can approach numbers of components and connectivities usually requiring a team of human designers
- Can be free of hierarchical constraints, of human-imposed constraints on relation between hierarchy
- Is often competitive with human design (e.g. Humies at GECCO)
- Is sometimes faster / cheaper.
- Is free of human biases

Automated Design, But:

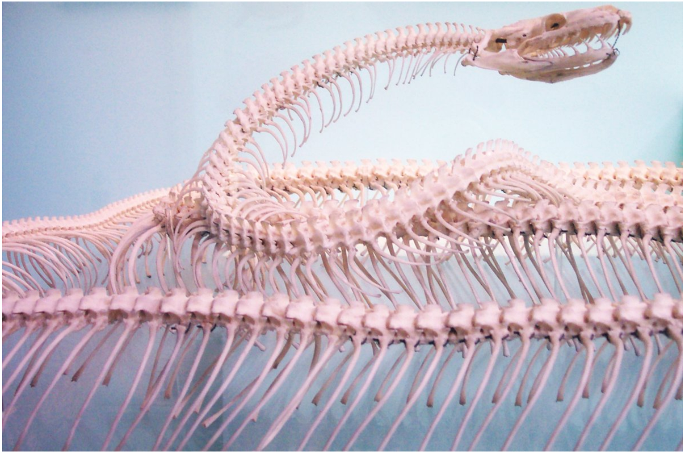
BUT:

- Usually impossible to understand naïvely
- Has a tendency to get bogged down when phenotypic space becomes too large / discontinuous (un-evolvable)
- Bijective techniques tend to search the space of all combinations of components, including the mind-bogglingly silly ones.

Biological Design

- In human development, appr. 30 000 genes specify the functioning positional information of appr. 100 trillion cells.
- It is clear that there exist exploitable canalizations and regularities in biological development.
- Multicellular organisms have many desirable properties: self-organization, self-repair, resistance to environmental perturbation, developmental plasticity, graceful degeneration.
- Hope that principles of biological development can be exploited in other contexts.

Canalization: Repetition with Variation



Artificial Embryogeny

- Inspired by, but not necessarily resembling, biological embryogenesis
- Includes a dynamical system as a mid-step between genotype and phenotype:

  $$G \xrightarrow{\Phi} P \xrightarrow{f} F$$

  where:
  - G is the space of genotypes
  - Φ is a dynamical system
  - P the space pf phenotypes
  - f is our fitness function
  - $F \subset \mathbf{R}$ is the space of fitness values.
- Focus now primarily on simple models of Genetic Regulatory Networks

Artificial Embryogeny

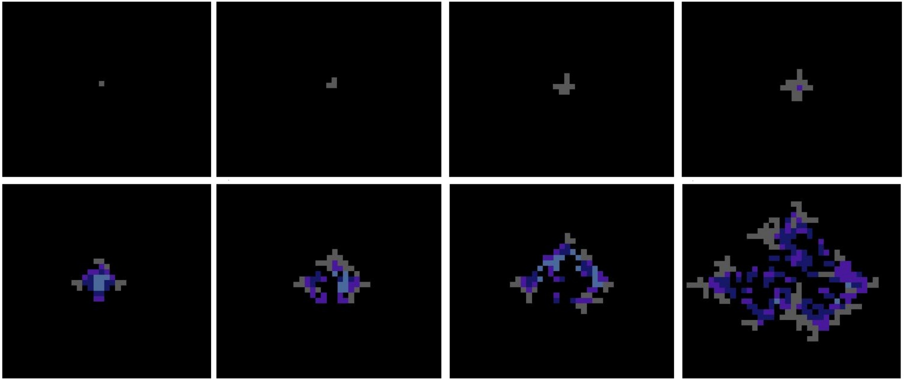
Some agreeable properties of AE:

- Evolution can function in domains where direct encodings become "bogged down" (Harding, Miller; 2006)
- Systems are capable of self-repair (Miller; 2004)
- Organisms can be re-grown at different sizes (Kowaliw, Grogono, Kharma; 2004)
- Developmental stage can be used as a blueprint for construction (Reiffel, Pollack; 2005)
- Organisms rediscover many regularities believed important in biology (Stanley; 2006)

Overview

- The Deva Family of AE Models
- Domain of Application: Structural Design
- Comparative Study of Model-Level Strategies
- Environment as a Spatial Constraint

The Deva Family of AE Models



The Deva Model

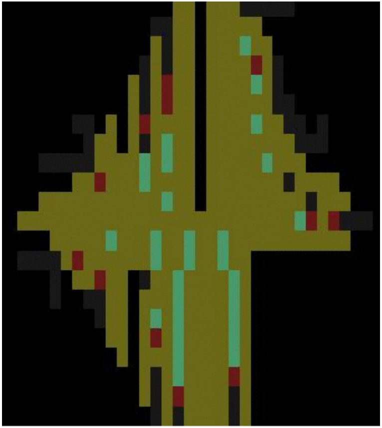
Consists of:

- A Developmental Space, $D \subset \mathbb{Z}^2$, with discrete time
- A set of cell types (colours) C, $|C| = n_c$
- A set of cell actions A
- A transition function, $\phi : N \rightarrow A$, where N is a description of a neighbourhood of cells from C.

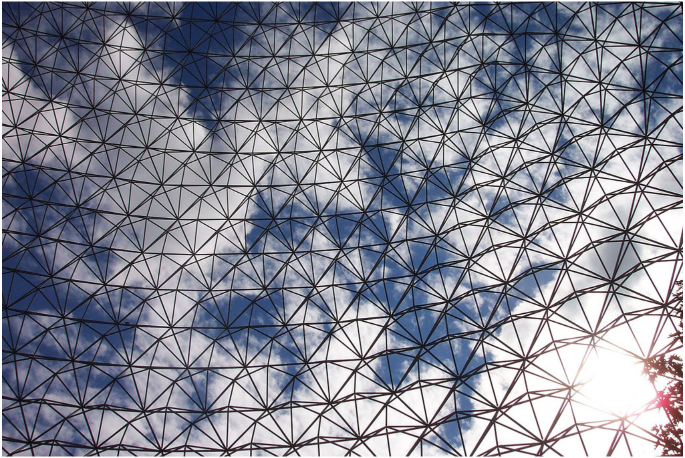
More Deva Model

- Starting from a single cell in D, the cells execute actions from A, leading to some sort of growth.
- Cell actions include operations like: *Nothing*, *Die*, *Divide*, *Specialize(x)*, *Elongate*

Clicky.



The Domain of Application: Structural Design

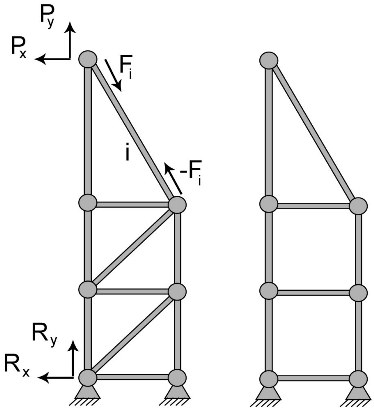


Trusses

- Simple models of structure
- Good approximations of bridges, towers, etc.
- Often form initial design stage of construction

Plane Trusses

- Consist of beams, joints, grounds.
- Want: stability, ability to withstand (distribute) external force.
- Can compute stability, pressure, displacement through system of linear equations ($O(n^3)$)

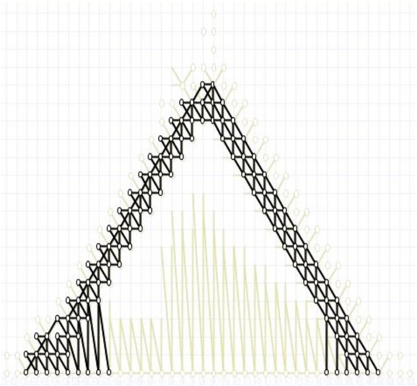


Interpretation of Deva Growth

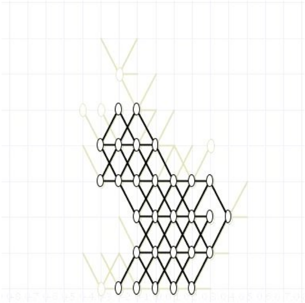
- We can map from a lattice of cell colours to a Plane Truss
- We can interpret Deva as a means of growing Plane Trusses developmentally
- Deva genomes can be evolved by using fitness to select for good Trusses

Evolved Trusses

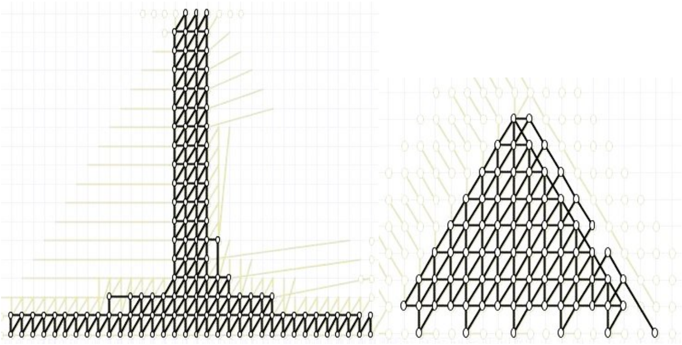
Fitness function 1



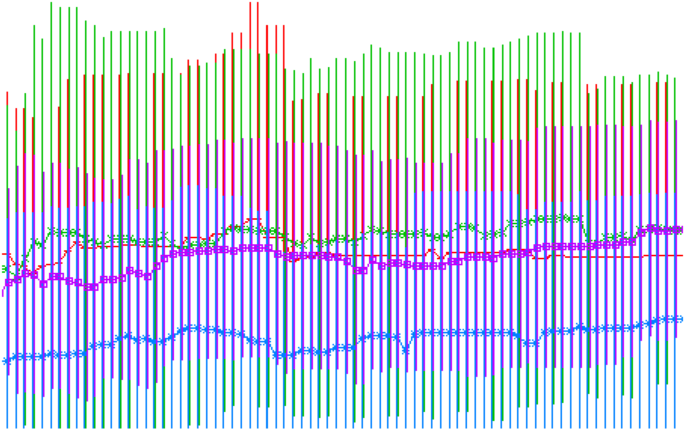
Fitness Function 2



Cheaters!



Comparative Study of Model-Level Strategies



Two Competing Forces

- AE (typically) involved the inclusion of a nonlinear dynamical system as a mid-step between genotype and phenotype in Evolutionary Computation.
- Dynamical systems tend to be unpredictable and nonlinear
- Evolutionary Computation tends to move towards optima or attractors
- Interplay between these two tendencies is a key but unknown factor in the design of AE systems.

Comparative Study

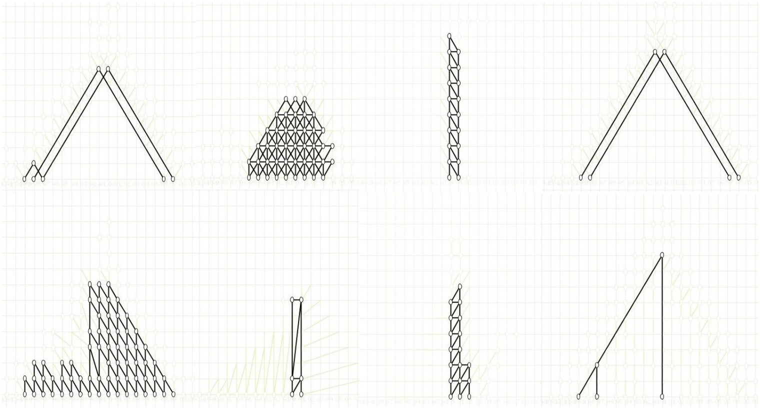
- Given an external means of evaluating design success (Plane Trusses), we can empirically approach this interplay
- Using the Deva family of models, we can easily introduce model-level perturbations
- Some strategies for exploration:
  - Inclusion of a cleavage stage
  - Description of a cell's neighbourhood
  - Description of a cell's internal state
  - Implementation of cell division on a lattice
  - Inheritance of a parent's cell specialization

Example: Cell Division

- Cell division on a lattice must involve some sort of bias: first division occurs in which direction? In all directions simultaneously?
- Some strategies:
  - *Best free location*, emulating natural division away from the centre of mass
  - Clockwise
  - Genetically-controlled
  - All directions simultaneously
- The four strategies were evolved many times at different phenotypic sizes (values of r_c) and compared.

Example: Cell Division Con't

A very clear difference between the strategies! The all-direction division found the global optimum far faster and more reliably than other models.

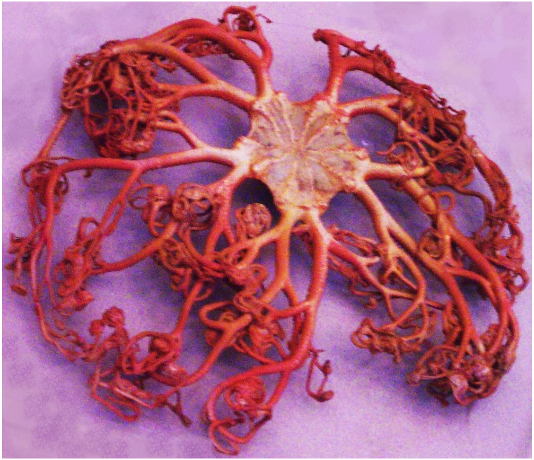


Overall Comparative Study Results

Some of the more general results of the comparative study:

- search depends on genotypic representation
- decision that seem small can have major effects
- alternative mechanisms can sometimes recover regularities

Environment as a Spatial Constraint



Some Informal Questions...

- Does the genome of a tree encode the information that the top is skinny and the bottom fat?
- Do the genes controlling the development of a circulatory system encode a description of the organism's overall morphology?

Role of Genes

- Bilaterals: bilaterally symmetric morphology, vascular system for blood
- Echinoderms: radial symmetry, vascular system for water
- Homeodomain associated with the development of the vascular system underwent radical changes in role and expression domain between Echinoderms and their bilateral ancestors (Lowe and Wray, Nature, 1997)

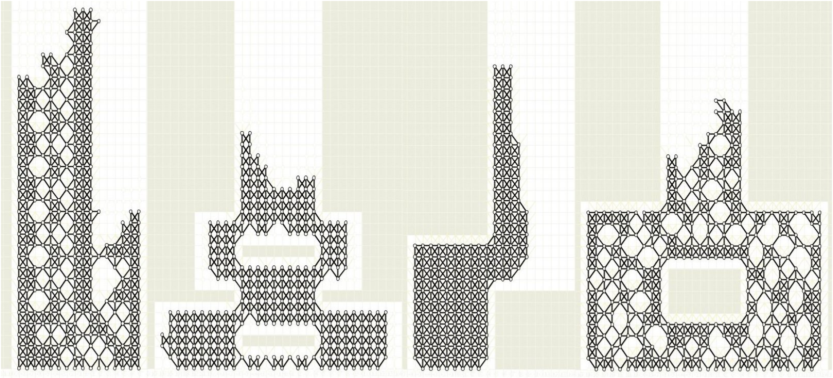
Environment Experiments

- We define several types of environment
- We can evolve organisms in some environment, at some phenotypic size
- We can then re-grow organisms at different sizes, in different environments

Clicky.

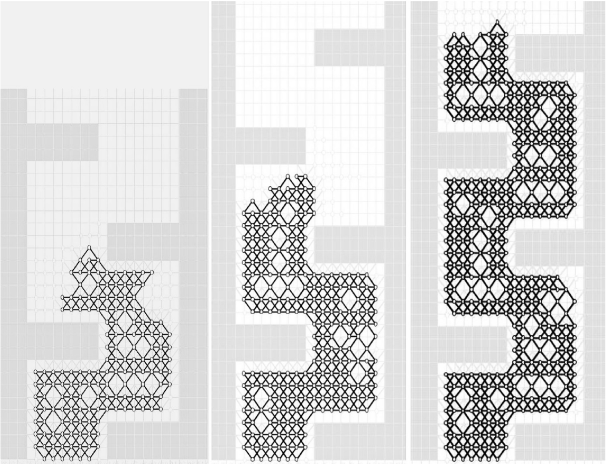
Some Successful Organisms...

Stable trusses capable of supporting external load evolved in nearly all environments



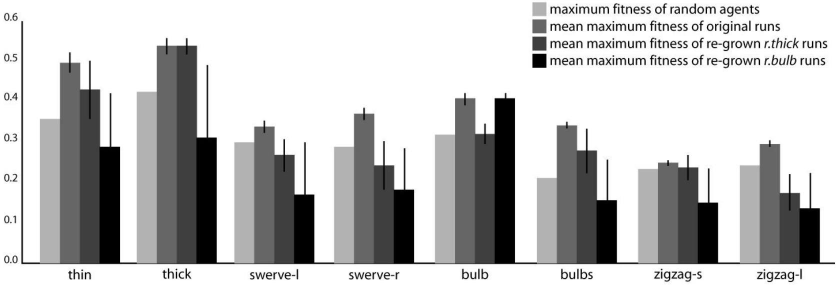
Phenotypic Re-growth

Organisms are usually capable of regrowth at different phenotypic sizes:



Environmental Re-growth Comparative

Not true for environments: no significant difference between random and re-grown genomes. Much variance in data!

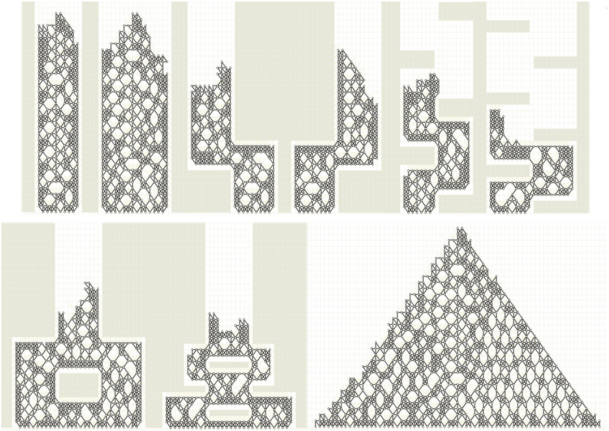


Phenotypic Re-growth Unsuccessful Visual

Many organisms overspecialized, performed far more poorly than random genomes in all novel environments.

Phenotypic Re-growth Successful Visual (Zelig)

Some genomes performed well in nearly all environments.

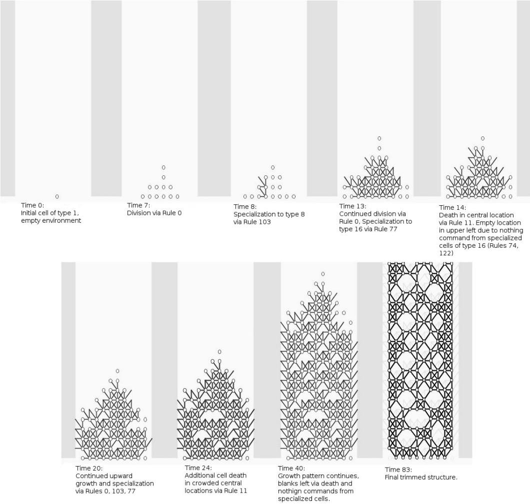


Zelig

- Zelig performed well in all environments in which evolution was successful generally (nine of ten)
- 7 used rules in the genome (compared with average 10-12)
- Similar appearance in all environments, adapting to fit provided space

Clicky 1. Clicky 2.

Zelig


Time 0:
Initial cell of type 1,
empty environment
Time 7:
Division via Rule 0
Time 8:
Specialization to type 8
via Rule 103
Time 13:
Continued division via
Rule 0, Specialization to
type 16 via Rule 77
Time 14:
Death in central location
via Rule 11.Empty location
in upper left due to nothing
command from specialized
cells of type 16 (Rules 74,
122)
Time 20:
Continued upward
growth and specialization
via Rules 0, 103, 77
Time 24:
Additional cell death
in crowded central
locations via Rule 11
Time 40:
Growth pattern continues,
blanks left via death and
nothign commands from
specialized cells.
Time 83:
Final trimmed structure.

Summary of Results

- Deva, a new family of AE models, introduced
- Organisms may be interpreted as Plane Trusses, providing a discipline-independent evaluation
- Successful truss designs can be evolved, and different optima reached through choice of fitness
- Model-level strategies can be evaluated through empirical evaluation
- New measures for complexity proposed which include environment and dynamics "for free"
- Environment may be used as a spatial constraint
- Genomes exist which adapt to nearly all environments, showing high developmental plasticity.

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