Artificial Life & Complex Systems

Lecture 11

Artificial Evolution II

June 2, 2007

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Contents

- Bio-morphs
- Evolutionary art
- Co-evolution of brain and bodies
- Evo-devo (evolving shapes, artificial ontogeny)
- Evolvable hardware (circuits, robots, antennae)

Aesthetic Selection

- There are many different names for the same thing: Aesthetic Selection = Selective Breeding = Animal Breeder Selection = Subjective Selection = Evolutionary Art
- Essentially, boils down to aesthetic, emotional, and empathetic selection process applied to evolve (engineer) virtual creatures, forms, or shapes
- In other words: the creatures, forms, and shapes are produced by a process of simulated evolution inside a computer, guided by an artist's aesthetic fitness selection
- The resulting evolved artifacts can be beautiful or strange, and provoke strong reactions in human observers
- It may be possible to evolve virtual pets to which humans can form strong emotional bonds

Aesthetic Selection (AS)

- AS can be used to explore the “hyperspace” of possible organisms/systems/design in a simulated genetic system
- Given that the genetic codes and complexity of the results are managed by the computer, the results are not constrained by the limits of human design ability or understanding

Role of computer: offers choices, creates diversity

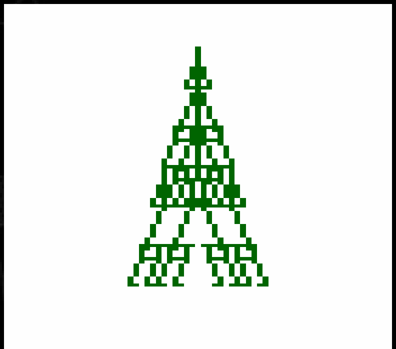
Role of human: makes choices, reduces diversity

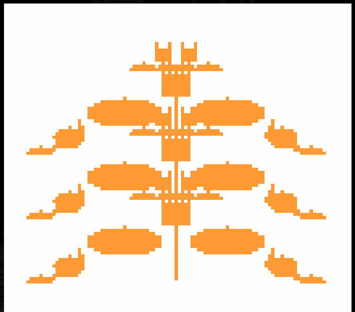
Selection (aesthetic, subjective) steers generation process towards *implicit* user preferences

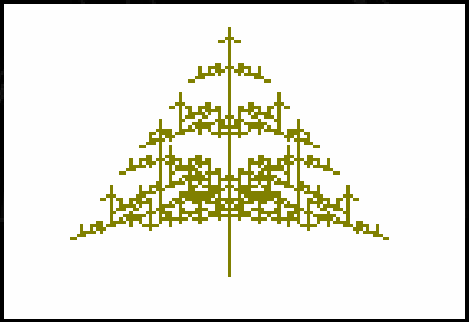
Question: Who is creative here?

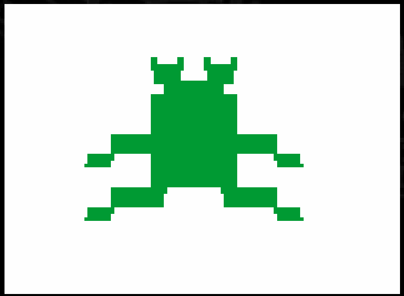
Biomorphs

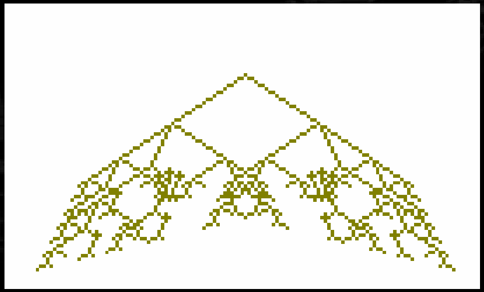
- From R. Dawkins ("The Blind Watchmaker", 1986)
- Tree-like structures used as graphical representations of a number of genes
- Demonstration of evolution through random mutation and non-random (cumulative) selection; process accumulates users decisions











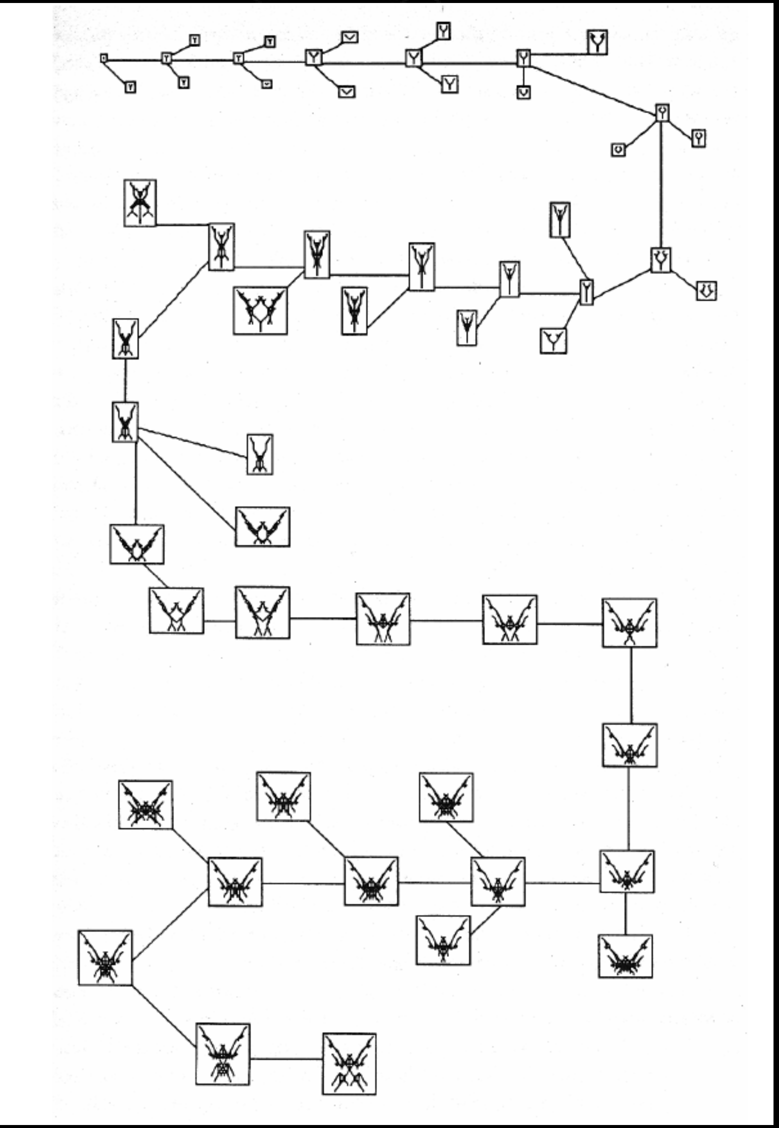
Biomorphs

Encoding of “creature” in genome (string of numbers) (“genotype”); genome = 9 genes (4 genes = length of lines, 4 genes = angles, 1 gene = recursion depth) – other encodings exist (e.g. include color, shape used to draw, …)

Expression of “genes” (graphical appearance) (“phenotype”); also called *genotype-phenotype mapping* (or *development*)

Sources of variation:

- (Cumulative) selection of individuals for reproduction (based on fitness – aesthetic appeal)
- Mutation



Biomorphs

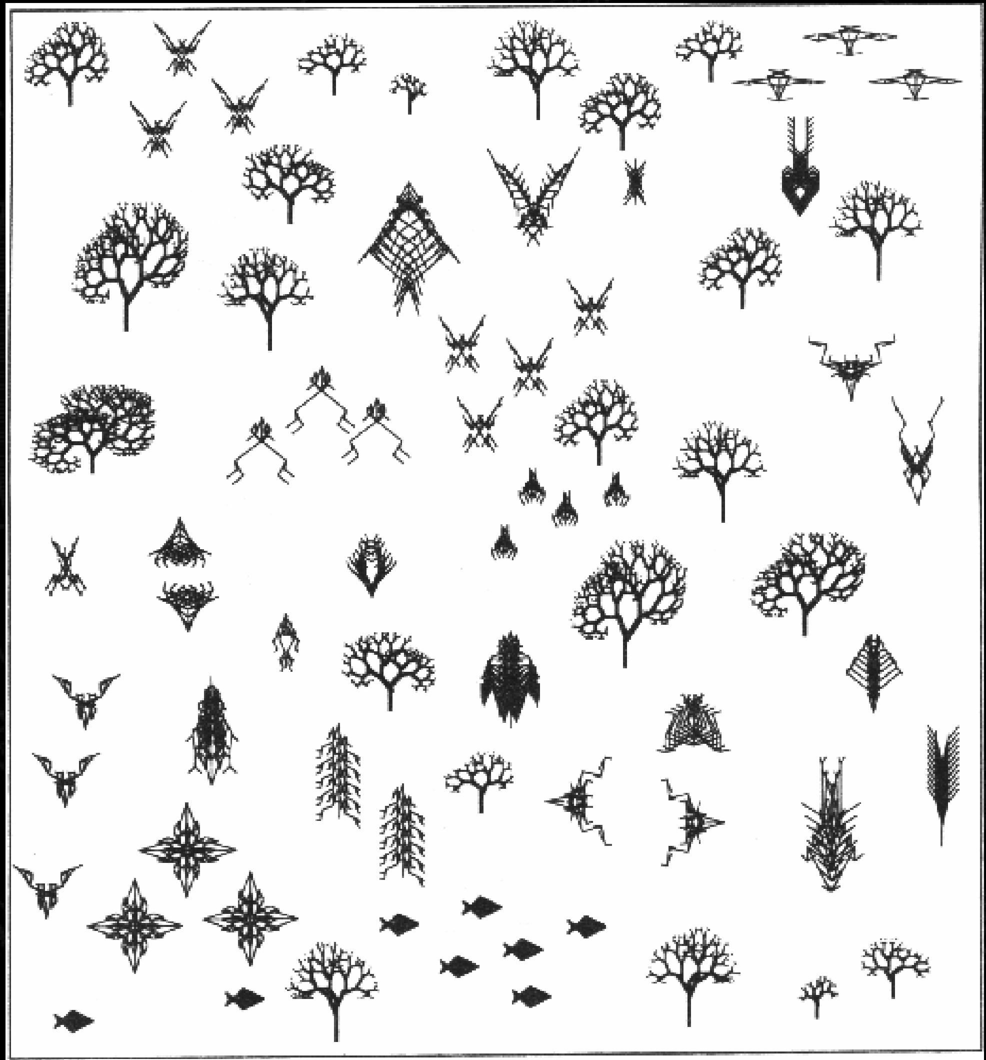


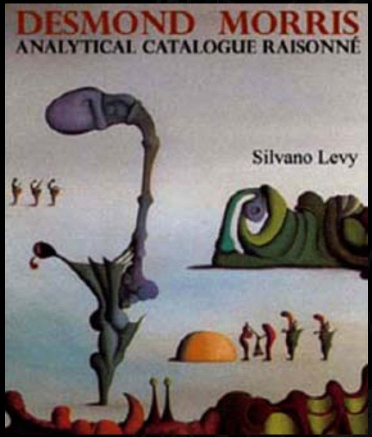
Figure 1.16 Safari park of black-and-white biomorphs, bred with the 'Blind Watchmaker' computer program.

Biomorphs

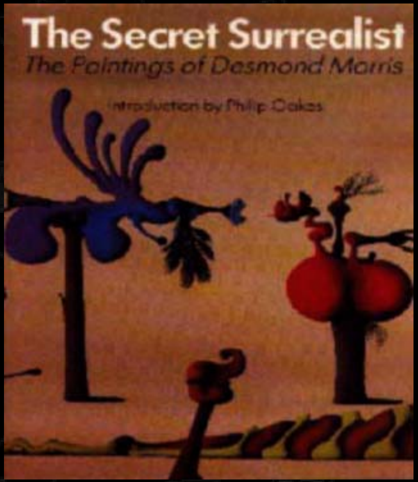
Applet:

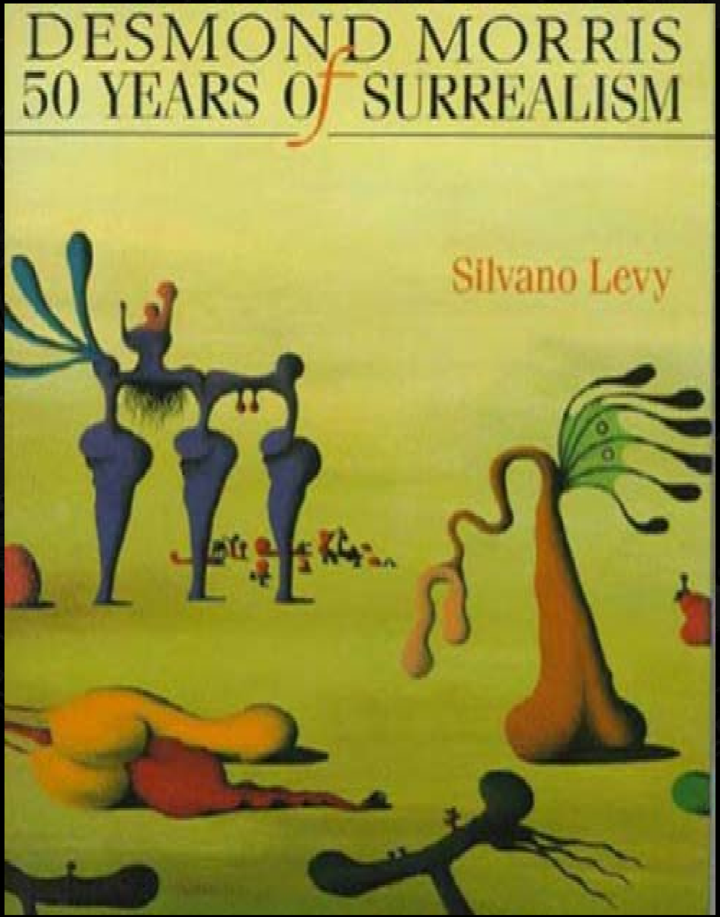
http://suhep.phy.syr.edu/courses/mirror/biomorph/

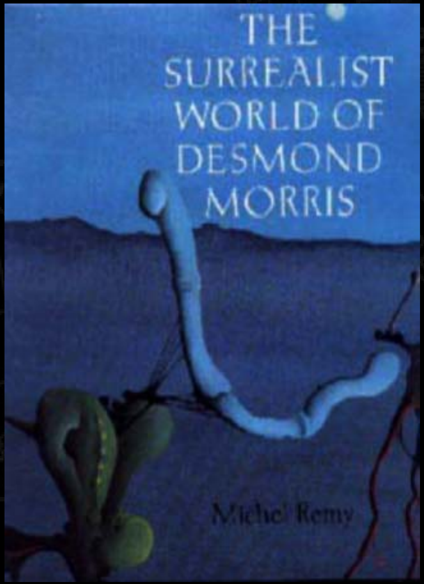
Biomorphs: Expression by Desmond Morris

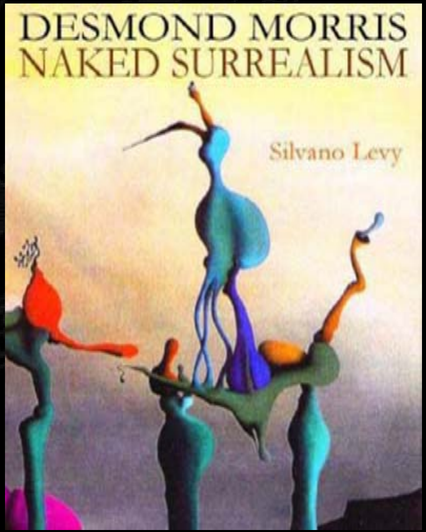


First exhibition in 1948









Evolutionary Art

Stephen Todd and William Latham built an artistic system called “Mutator”

Computer program based on mutation and natural selection to help an artist explore the world of three dimensional art forms

Produces horns, pumpkins, shells, mathematical shapes and many other shapes

Evolutionary Art

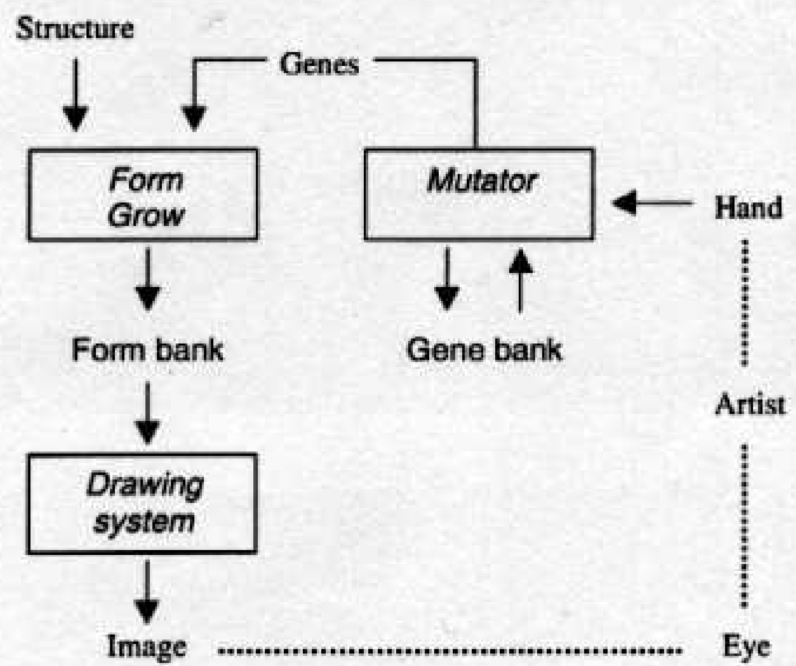


Figure 9.1 *Mutator* keeps a bank of genes and their forms (generated by *Form Grow*), which it displays to the artist. Based on judgements made by the artist, *Mutator* generates and displays new forms, assisting the artist to search for interesting forms and bank the results.

Evolutionary Art

structure expression:

horn

ribs (*gene1*)
grow (*gene2*)
stack (*gene3*)
bend (*gene4*)
twist (*gene5*)

corresponding gene vector:

< *gene1*, *gene2*, *gene3*, *gene4*, *gene5* >

Figure 9.5 An example of a structure expression (created by the artist) and its corresponding gene vector (to be evolved by *Mutator*).

Evolutionary Art Forms

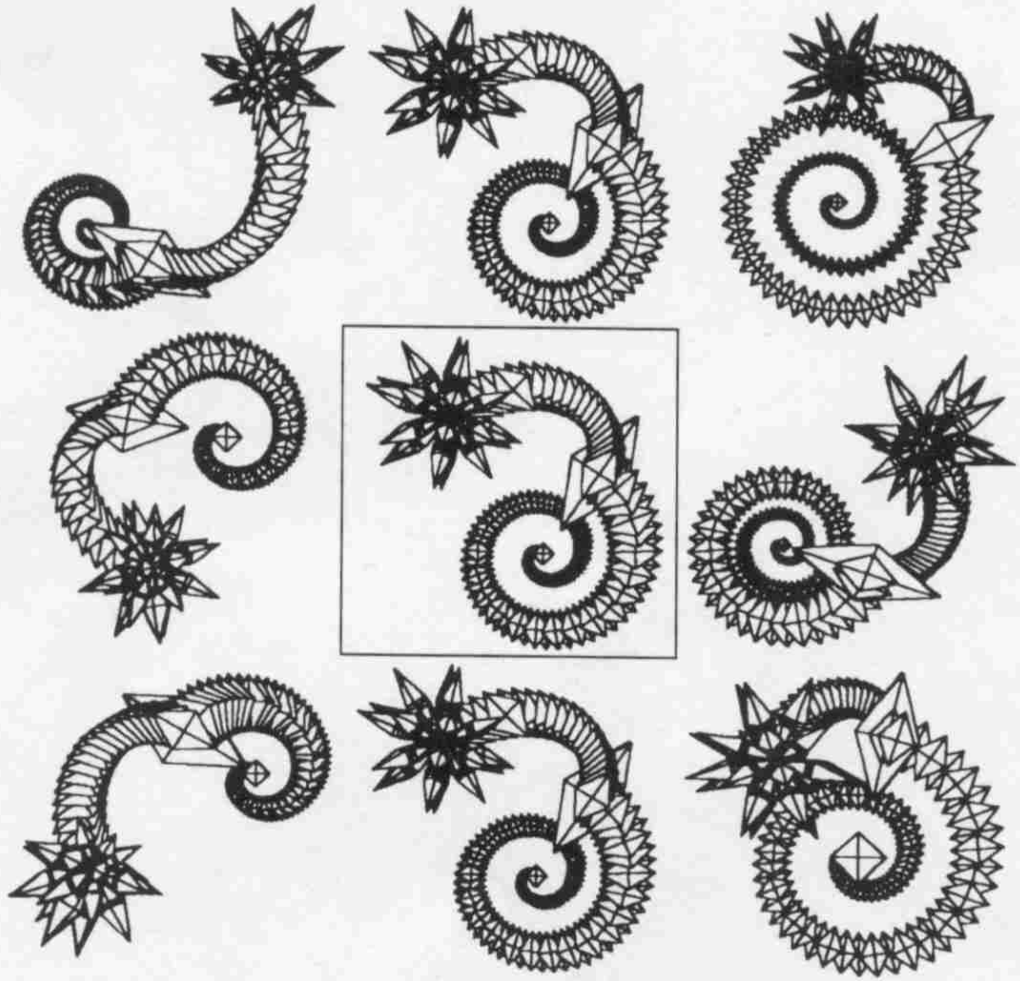
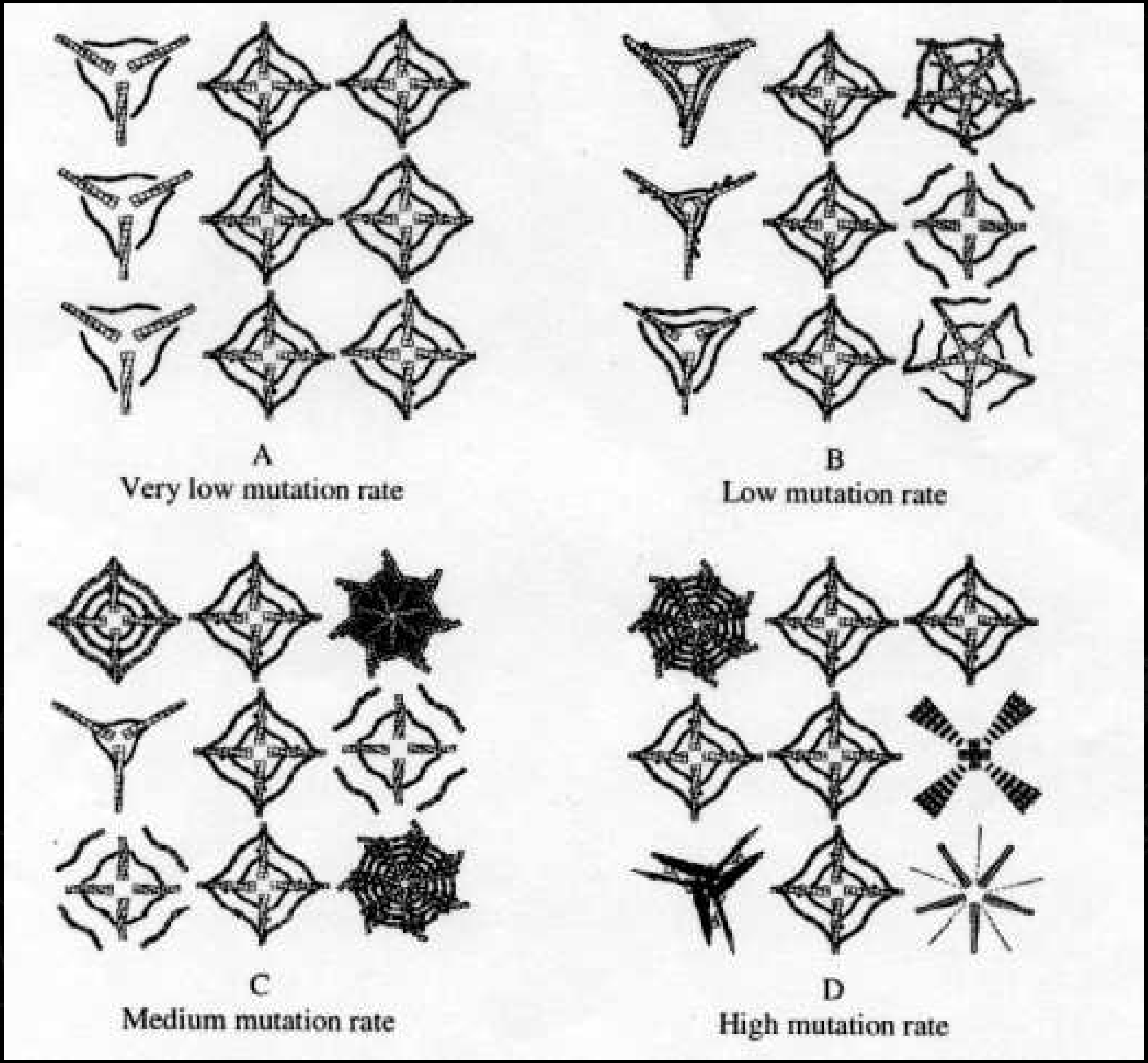
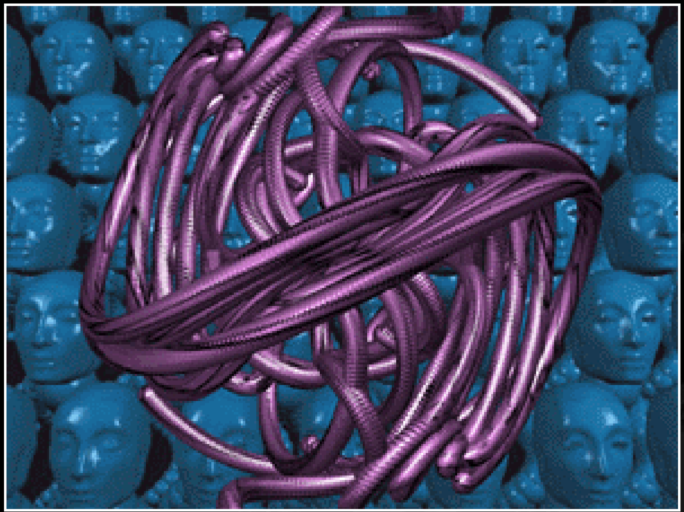


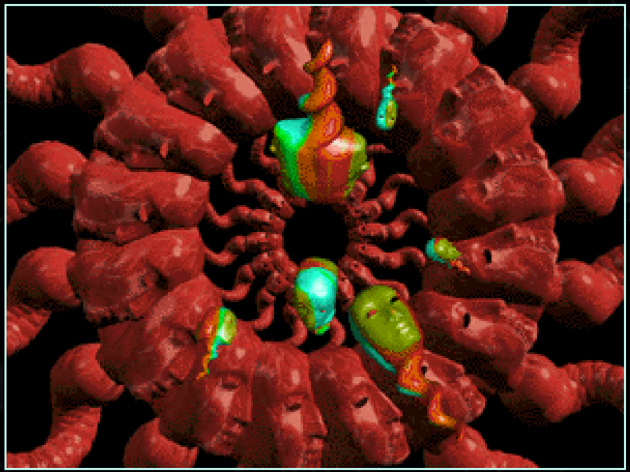
Figure 9.6 A frame of nine mutations. The parent is in the centre surrounded by offspring.

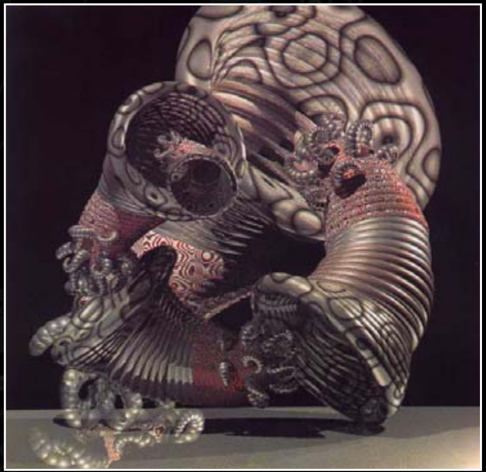
Evolutionary Art Forms

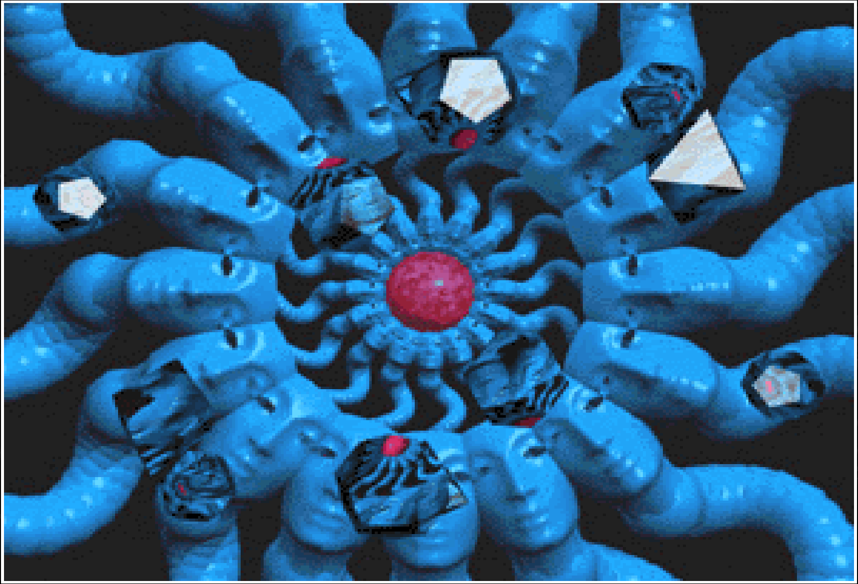


Evolutionary Art Forms









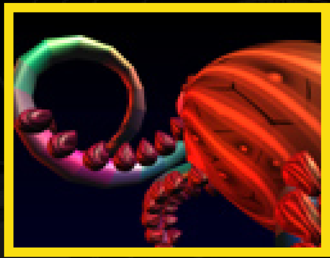
Galapagos (Karl Sims: Digital Artist)

"Galápagos is an interactive Darwinian evolution of virtual "organisms. Twelve computers simulate the growth and behaviors of a population of abstract animated forms and display them on twelve screens arranged in an arc. The viewers participate in this exhibit by selecting which organisms they find most aesthetically interesting and standing on step sensors in front of those displays. The selected organisms survive, mate, mutate and reproduce. Those not selected are removed, and their computers are inhabited by new offspring from the survivors. The offspring are copies and combinations of their parents, but their genes are altered by random mutations. Sometimes a mutation is favorable, the new organism is more interesting than its ancestors, and is then selected by the viewers. As this evolutionary cycle of reproduction and selection continues, more and more interesting organisms can emerge."

http://www.genarts.com/galapagos/index.html

Galapagos

Box insect

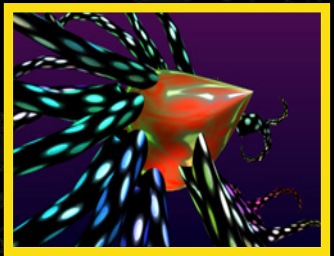


Beaded arms

Multipus-green

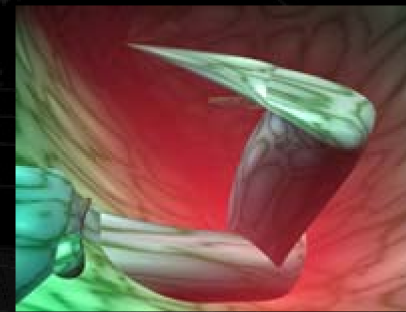
Jellyfish

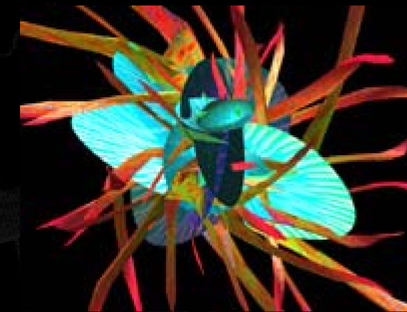
Bfly larva

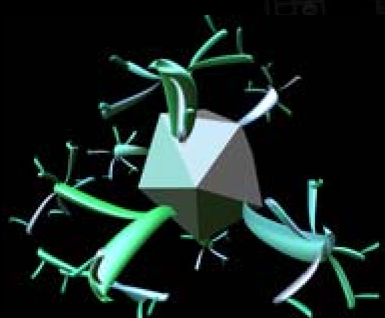


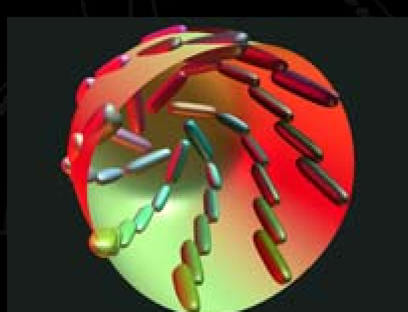
Multipus-purple

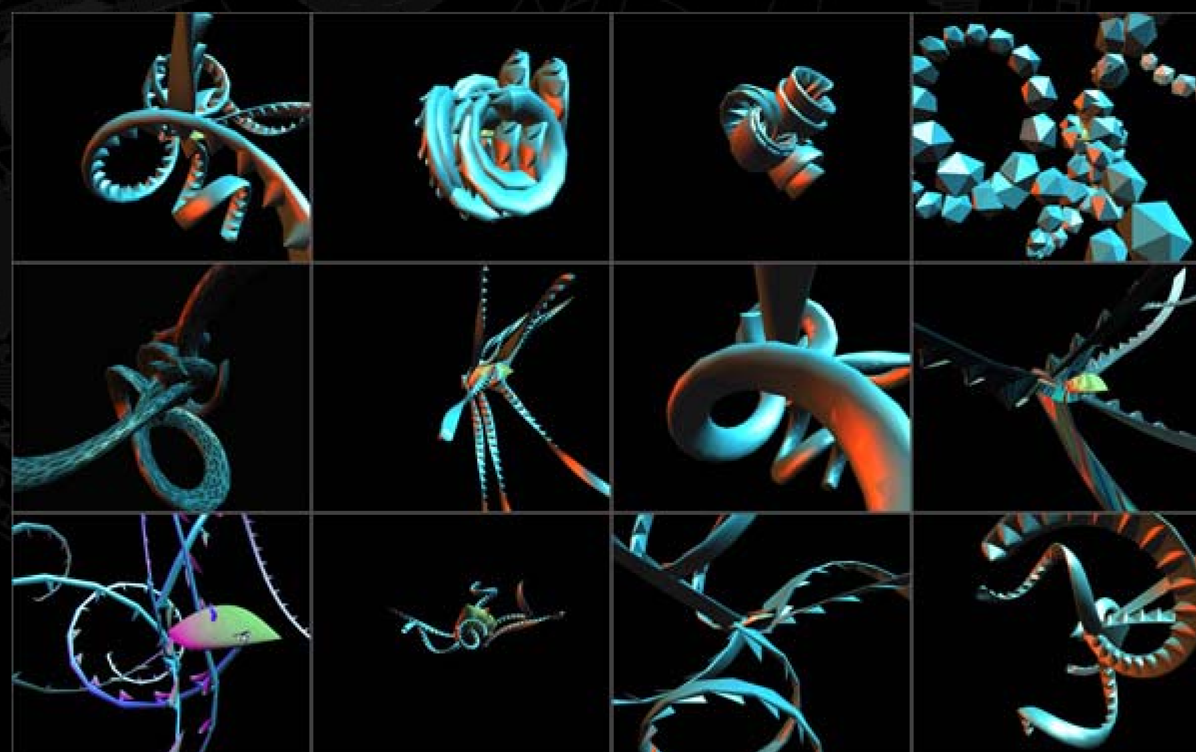
Galapagos



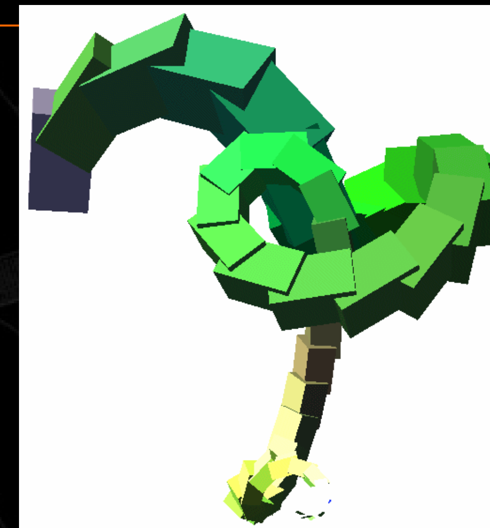


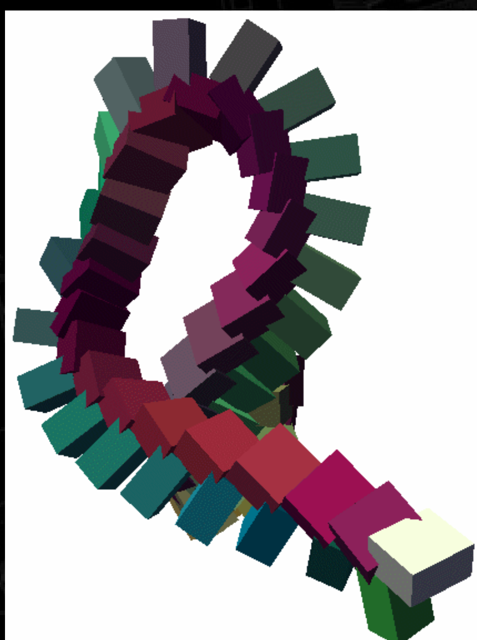


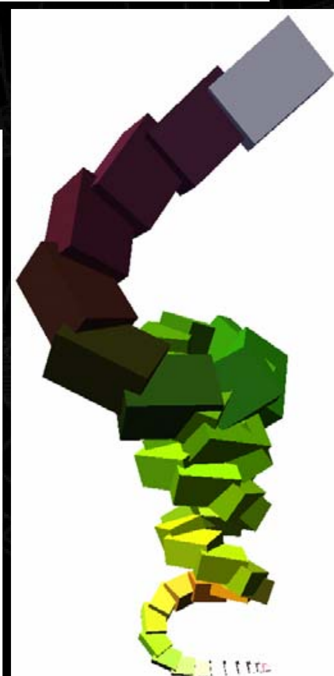


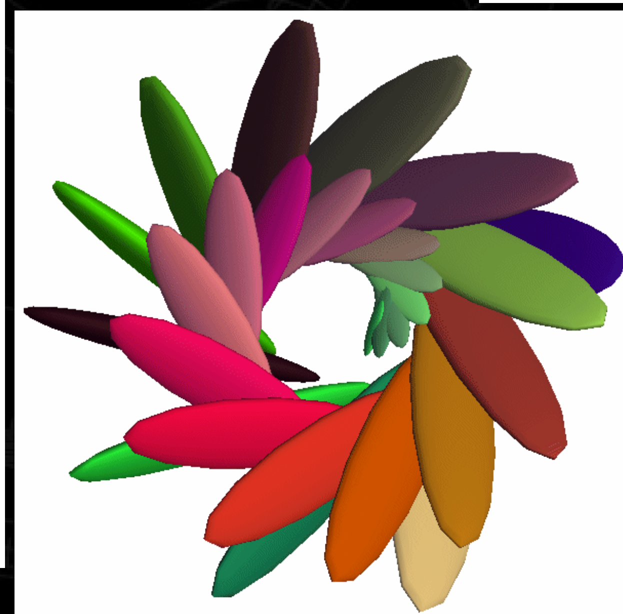


Virtual Life





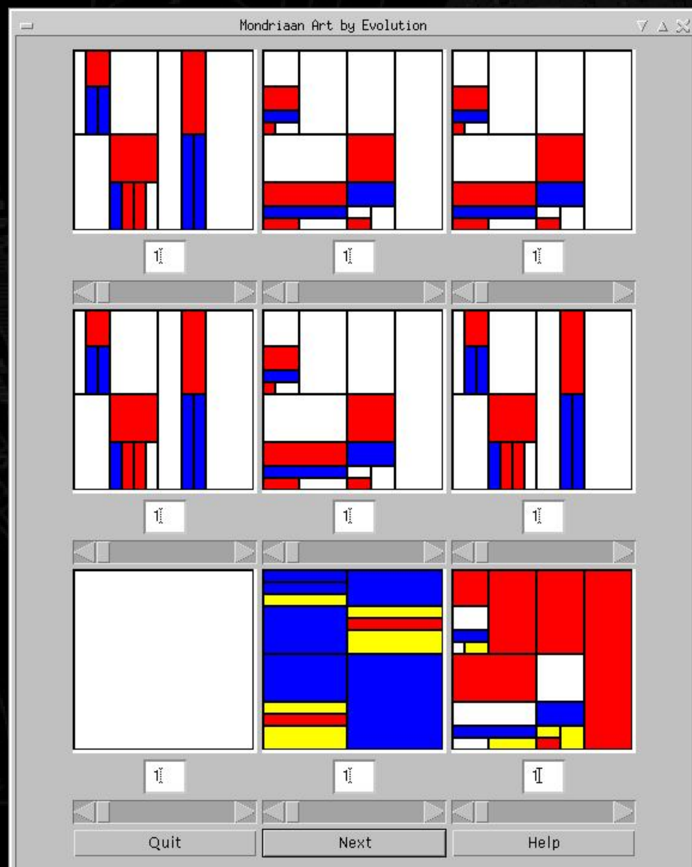




Mondriaan Evolver

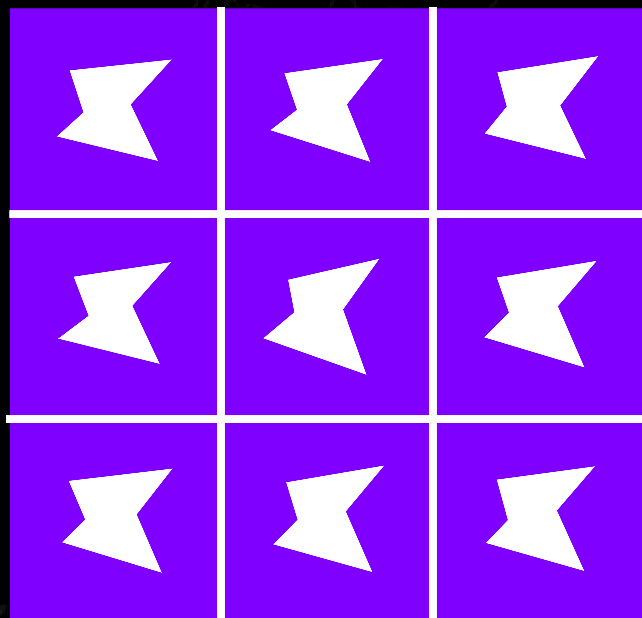
Craenen, Eiben, van Hemert

http://www.cs.vu.nl/ci/Mondriaan/



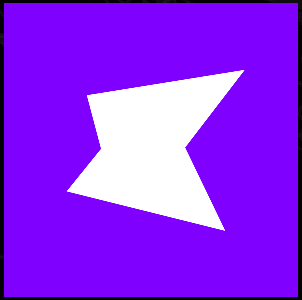
Subjective Selection: Evolution of a Square

Selection screen

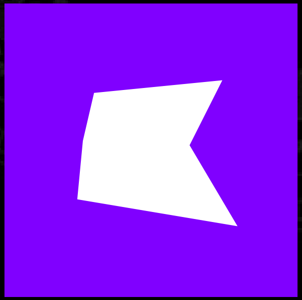


Actual figure after:

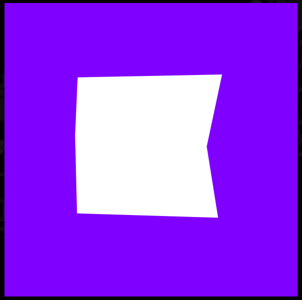
Generation 0



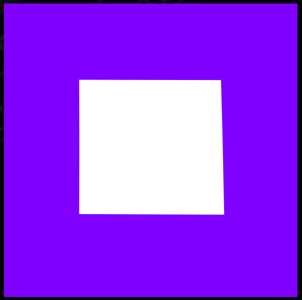
Generation 20



Generation 40



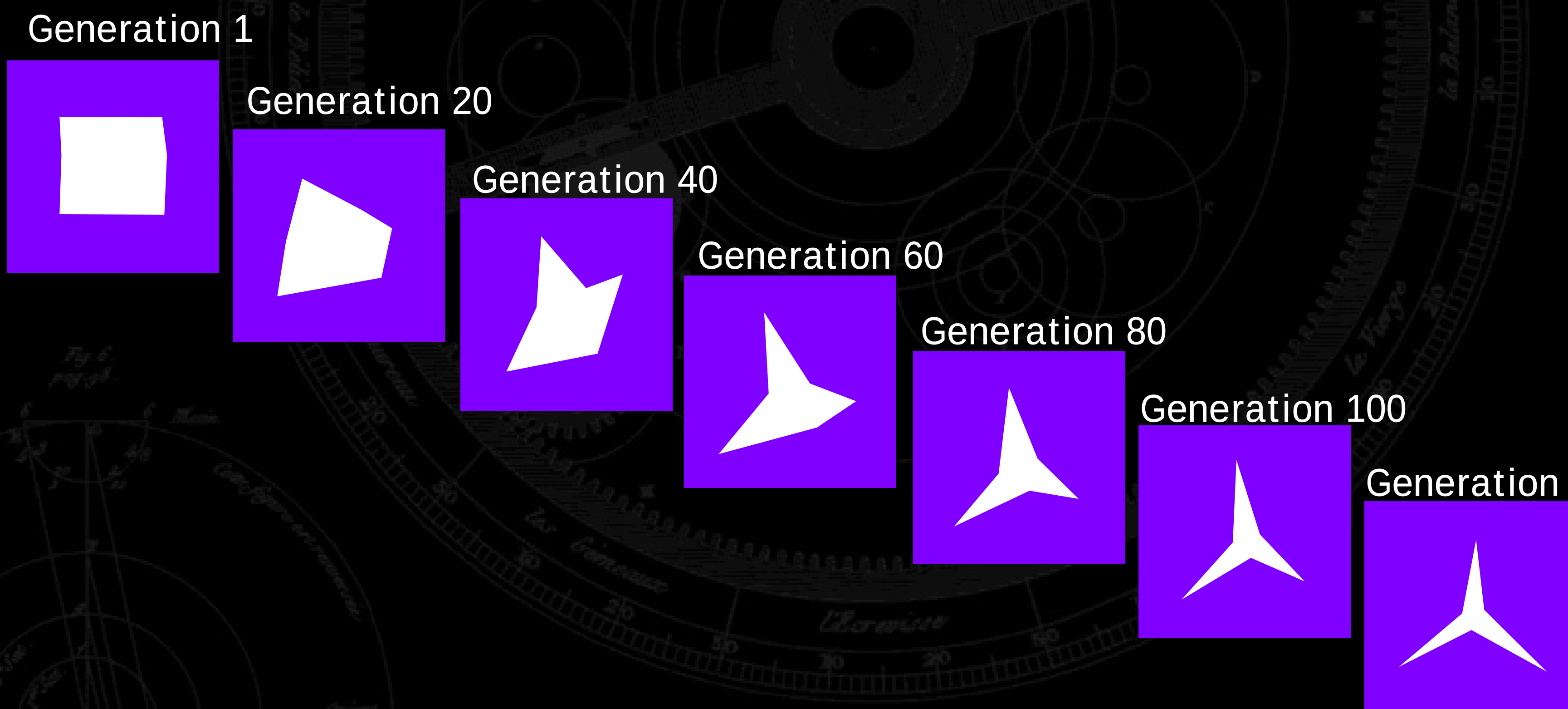
Generation 80



Subjective Selection

Continuation of the evolution: From of a square to a Mercedes-Star through subjective selection

Actual figure after:



Subjective Selection

Coffee composition using the Evolution Strategy

Subjective Selection

Parent	
25%	Columbia
40%	Sumatra
13%	Java
5%	Bahia
17%	Jamaica

O1

Offspring 1	
20%	C
34%	S
23%	J
5%	B
18%	J

O2

Offspring 2	
23%	C
37%	S
12%	J
10%	B
18%	J

O3

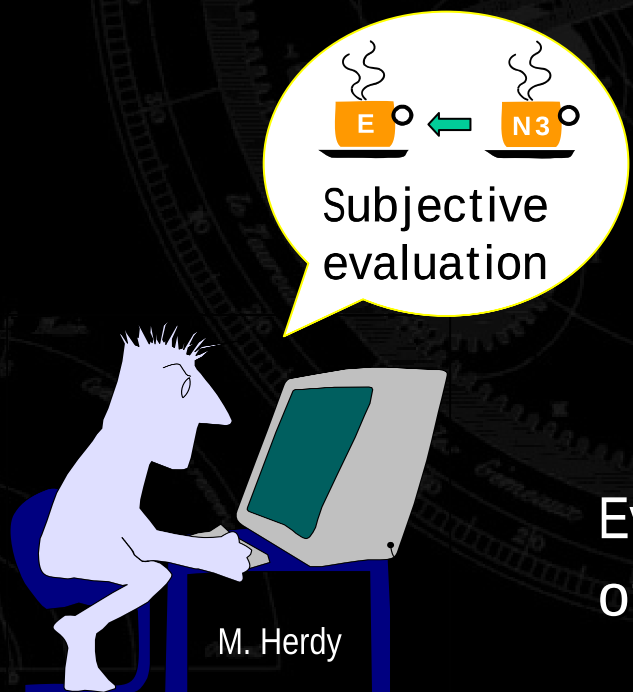
Offspring 3	
25%	C
32%	S
15%	J
8%	B
20%	J

O4

Offspring 4	
30%	C
38%	S
8%	J
2%	B
22%	J

O5

Offspring 5	
33%	Columbia
38%	Sumatra
9%	Java
8%	Bahia
12%	Jamaica



Evolution-strategic development of a coffee blend

Musical Gene Pool

J.J. Ventrella (2006)

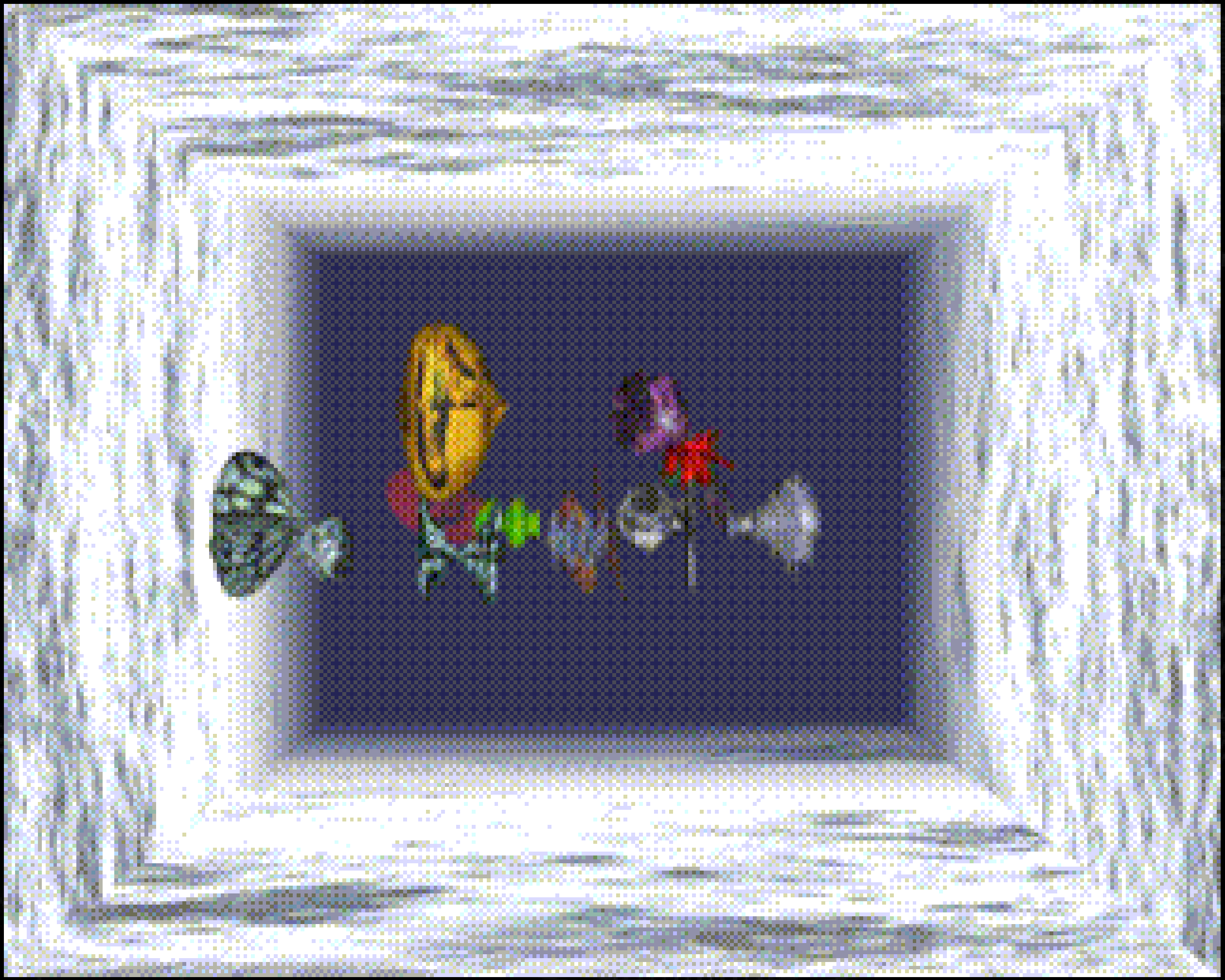
http://www.ventrella.com/EvoMusic/EvoMusic.html

Disney Meets Darwin

Eddie Elliott and Jeffrey Ventrella

http://www.disneymeetsdarwin.com/

A-Volve



Gene Pool

Gene Pool is an artificial life simulation in which populations of physics-based organisms evolve swimming capabilities over time. These organisms are called "swimbots".

Time for some “gene pool”.

Evolving Morphologies

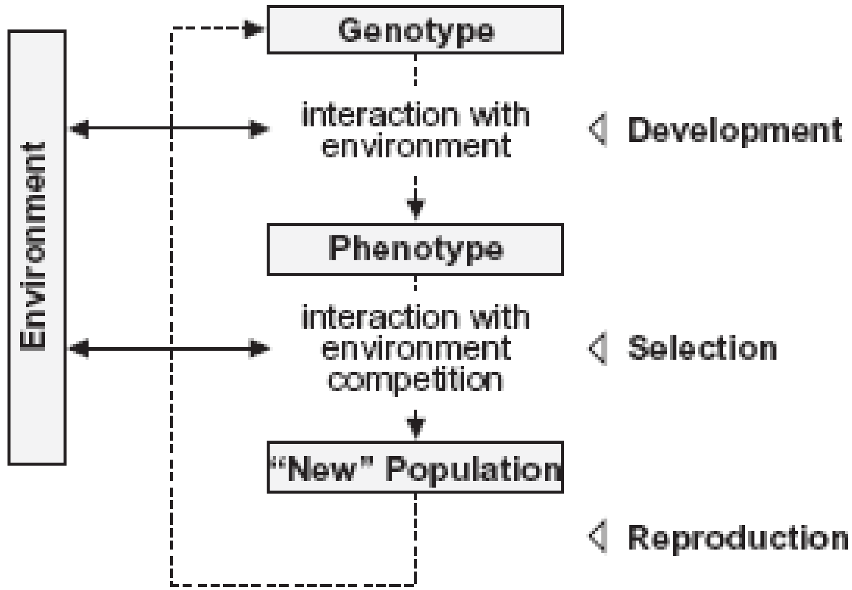
- Karl Sims (coevolution of brain and bodies)
- Peter Eggenberger (evolving shapes)
- Josh Bongard (artificial ontogeny)

Sim's Creatures

- Two papers:
  - Evolving virtual creatures" (1994) – evolution paper
  - "Evolving 3D morphology and behavior by competition" (1994) – co-evolution paper
- Evolution and co-evolution (through competition) of morphology and (neural) control system
- Sims was one of the first to use a physically simulated 3-D world with realistic dynamics simulation of gravity, friction, collision detection and response, viscous fluid effects, ...

Genetic Algorithm: Basic Structure

a.



b.

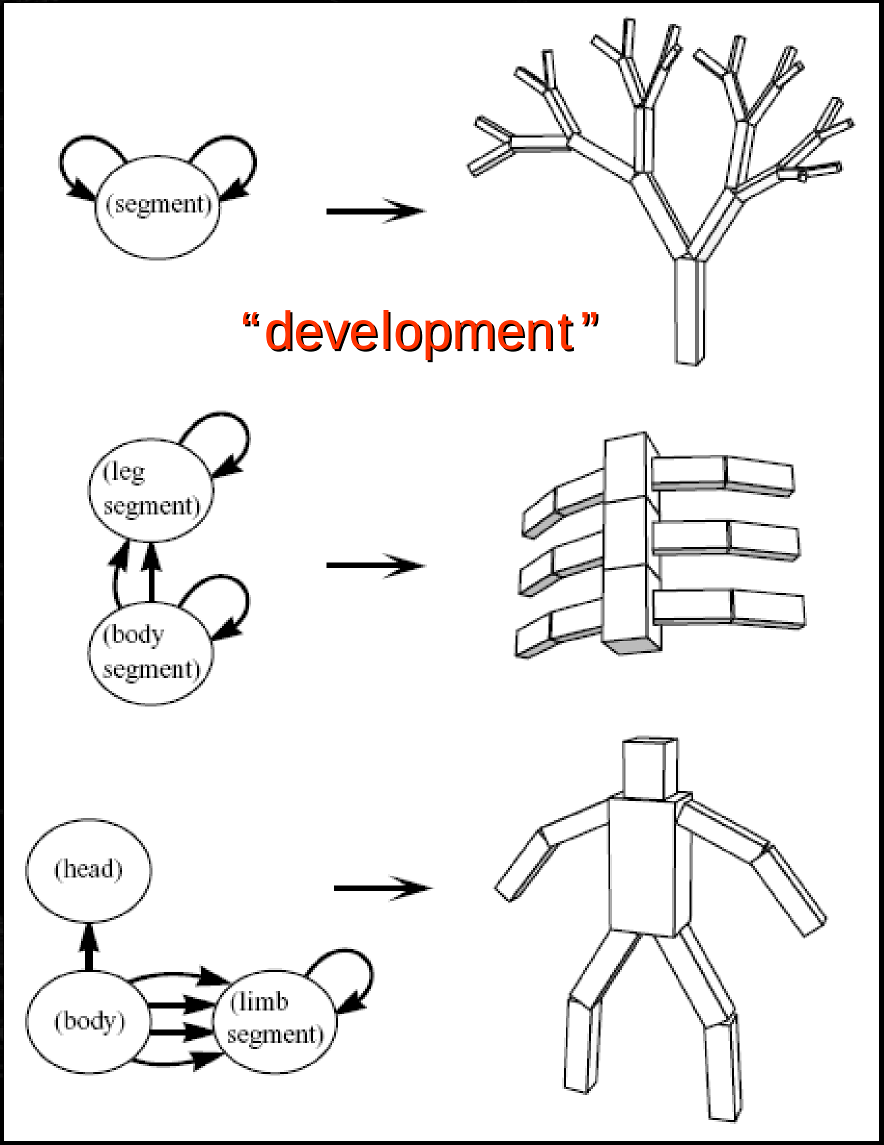
encoding	development	selection	reproduction
• binary • many-character • real-valued	• no development (phenotype = genotype) • development with and without interaction with the environment	• "roulette wheel" • elitism • rank selection • tournament • truncation • steady-state	• mutation • crossover

Encoding and Development (?)

Genotype is represented as a directed graphs of nodes and connections (reminds a little bit of L-systems)

The genotype is mapped/expressed into a phenotype through a “developmental process” (in other words: each graph contains developmental instructions to grow a creature)

No interaction with the environment during development



Encoding: Morphology

Each node in graph (genes in genome) contains information describing a rigid body part

- Dimensions: size
- Joint-types: rigid, revolute, twist, universal, spherical, …
- Joint-limits
- Recursive-limit parameter

Each connection (link) also contains information

- Placement of child relative to parent node (position, orientation, scale, …)

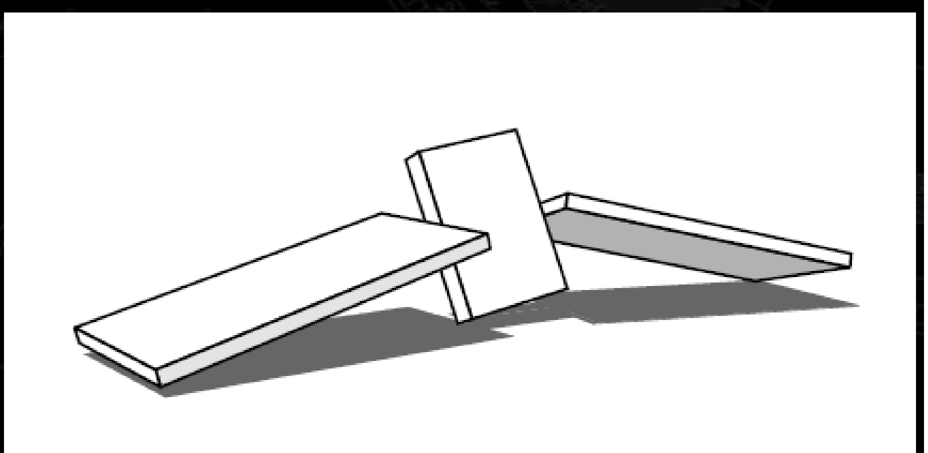
Encoding: Controller

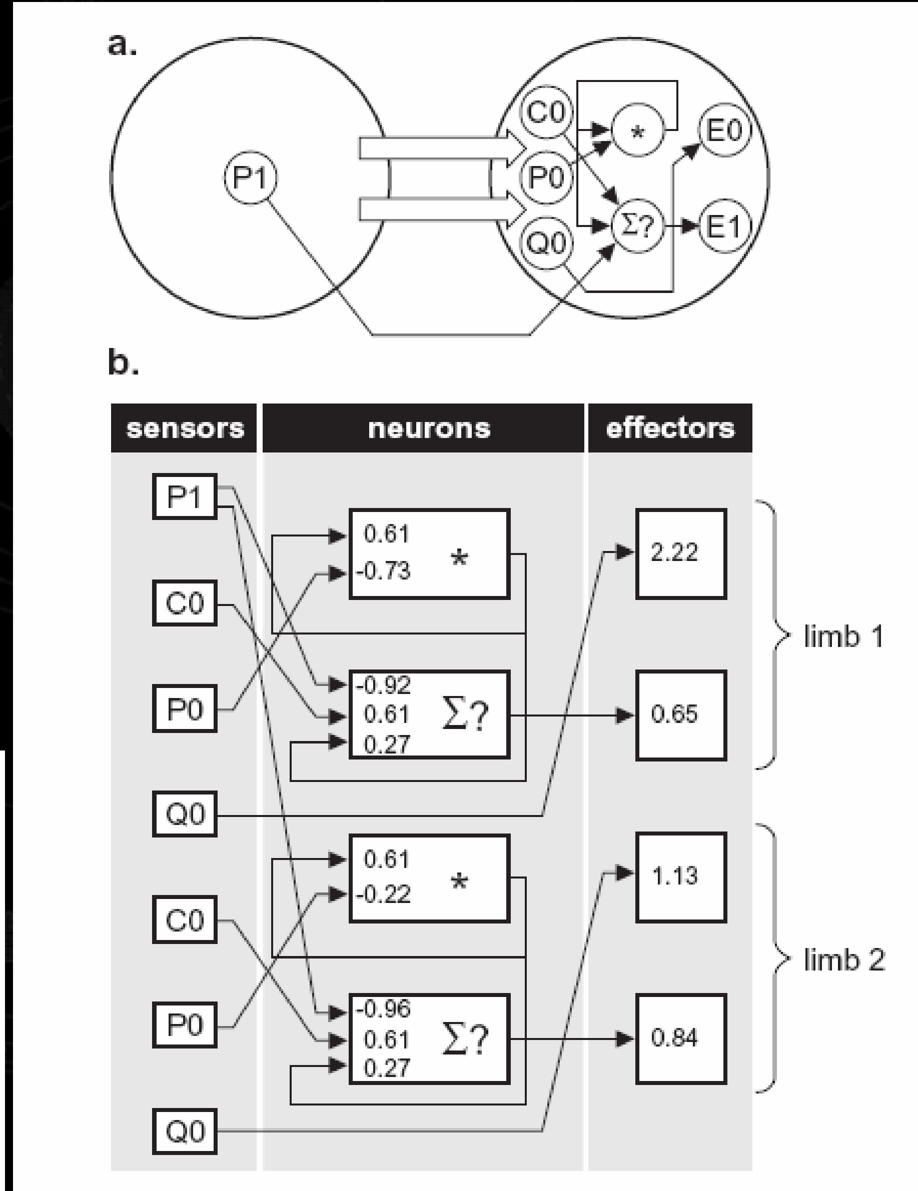
Consists of:

- Sensors (joint angle sensors, contact sensors, photosensors)
- “Neurons” (sum, product, divide, atan, cos, oscillate-wave, oscillate-saw, ...)
- Effectors (maximum strength is proportional to cross section area of two joined parts; force scales with area and not volume!)

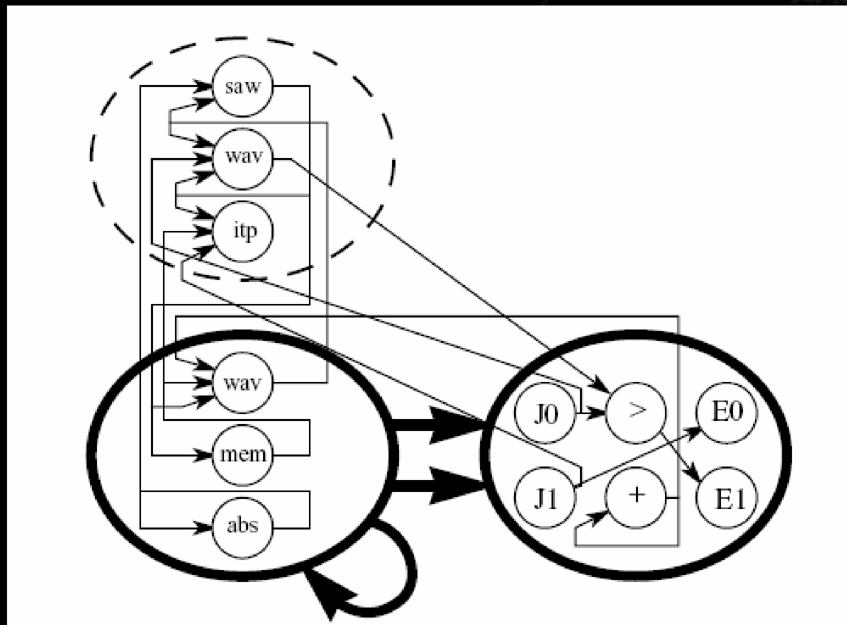
Encoding: Merging Morphology and Controller

Genotype encodes information about sensors, effectors, and "neurons" connecting sensors and effectors, position and size of body parts, type of joints, joint limits …





Example 2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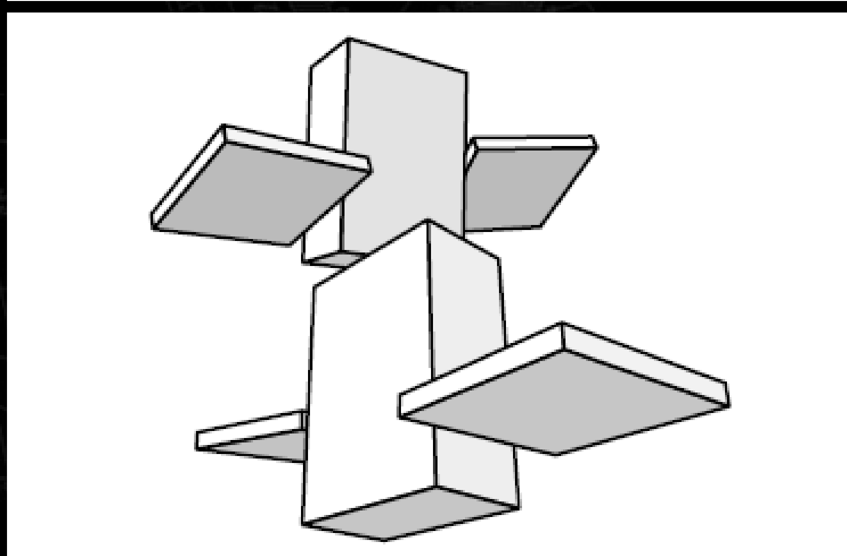

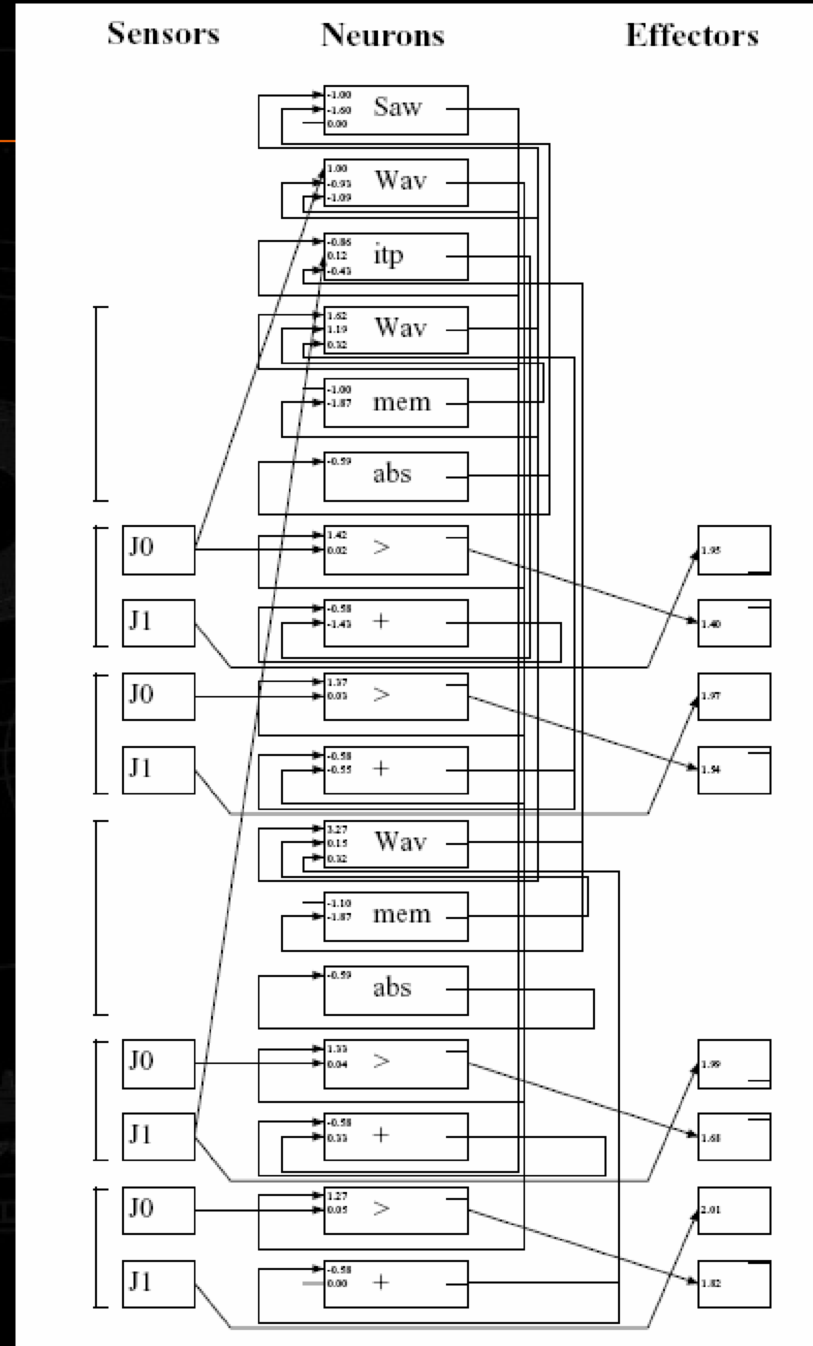
Sensors
Neurons
Effectors
Saw
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abs
J0
>
J1
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J1
+
Wav
mem
abs
J0
>
J1
+
J0
>
J1
+

Fitness and Selection

Once phenotypes are generated, they have to perform in simulated world of physics

Fitness function: The creatures are selected for swimming speed, crawling/walking speed, jumping height, ability to follow, possession of a block (co-evolution)

Selection mechanism: *Truncation* (only 1/5 best creatures survive for reproduction; population size = 300)

Mutation and Recombination

Number of offspring that each surviving individual generates is proportional to its fitness – most successful creatures make the most children

Offspring are generated by:

- *Mutation:*
  - Internal parameters subject to alteration (holds for nodes and connections)
  - Add random node to graph (garbage collected if not connected!)
  - Add random connection or remove connection from graph
- *Sexual reproduction:*
  - crossover (30%)
  - grafting (30%)
  - asexual (40%)

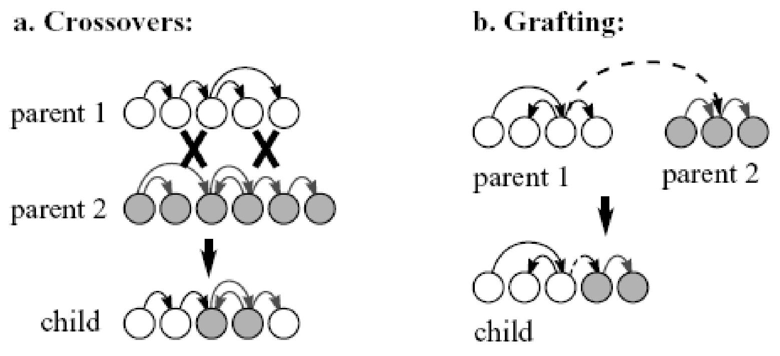
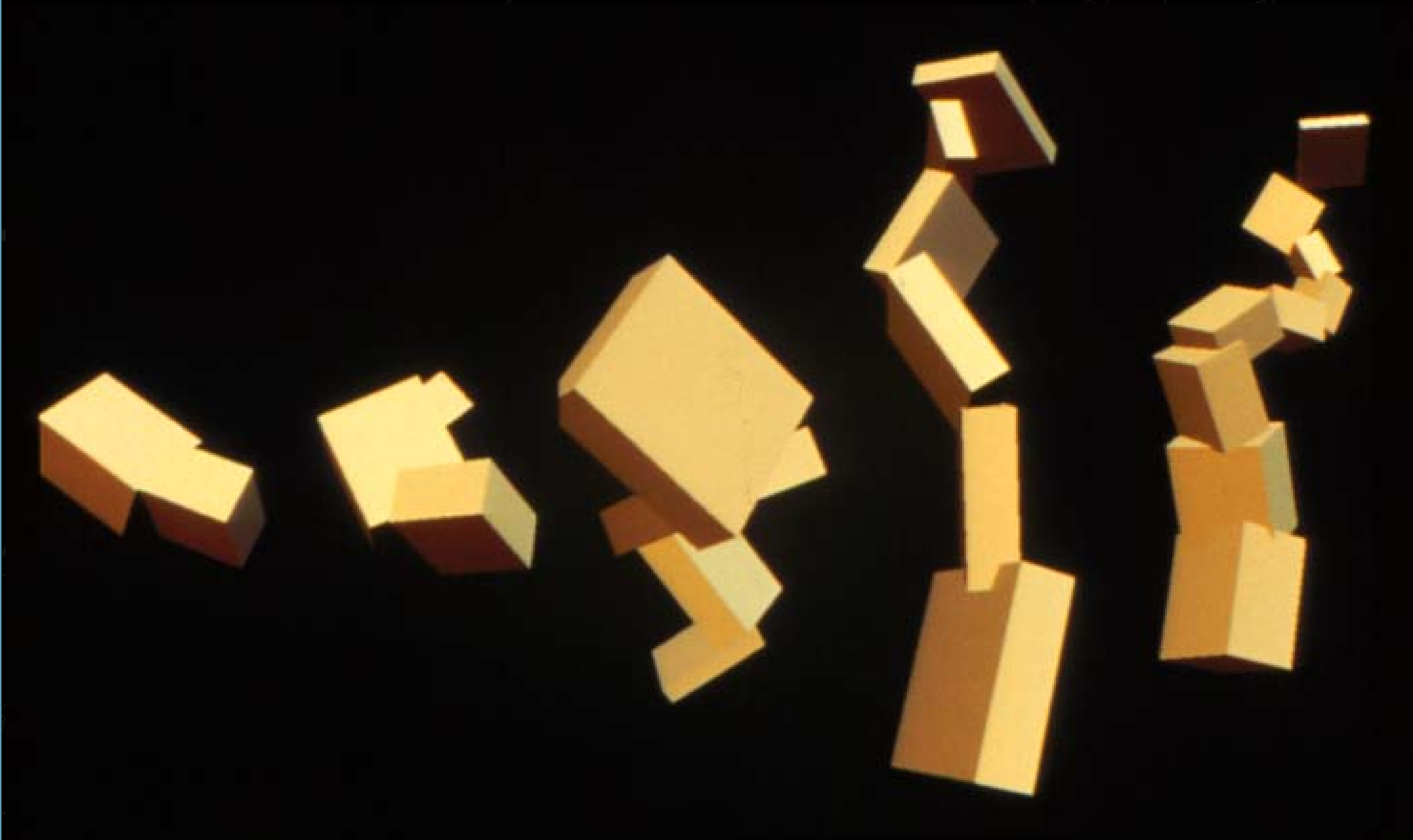


Figure 5: Two methods for mating directed graphs.

Evolved Creatures

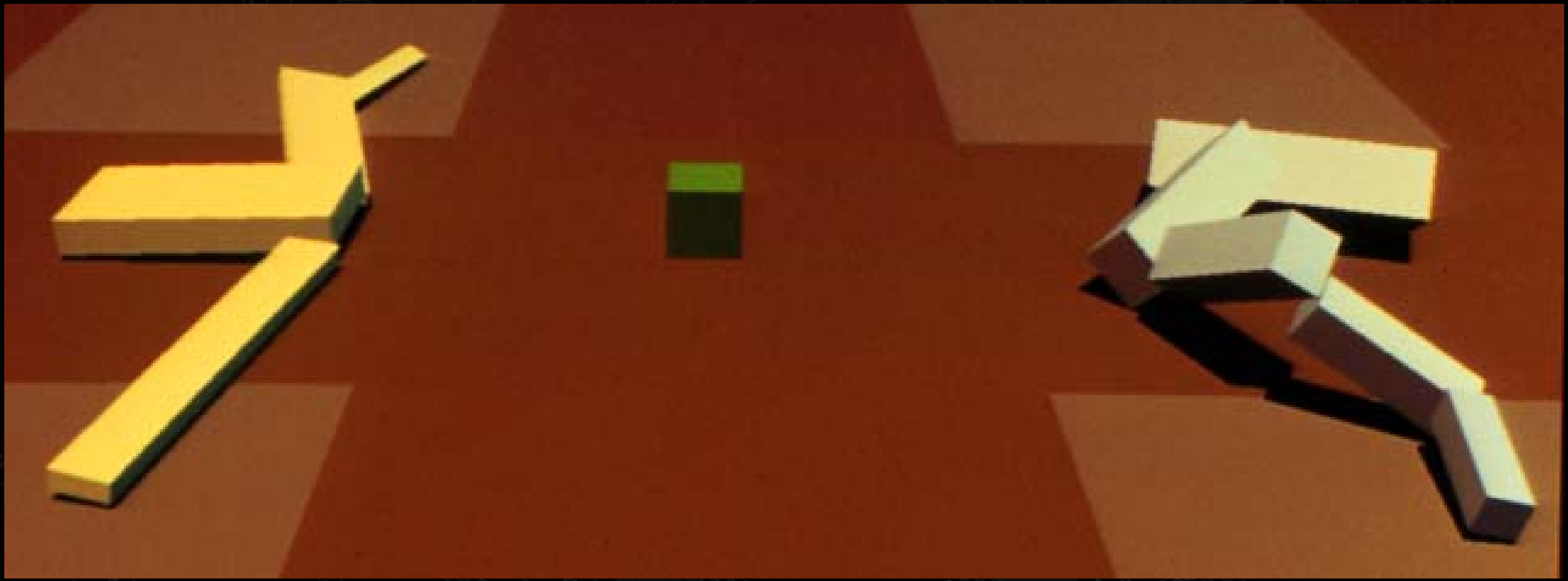


Evolved Creatures

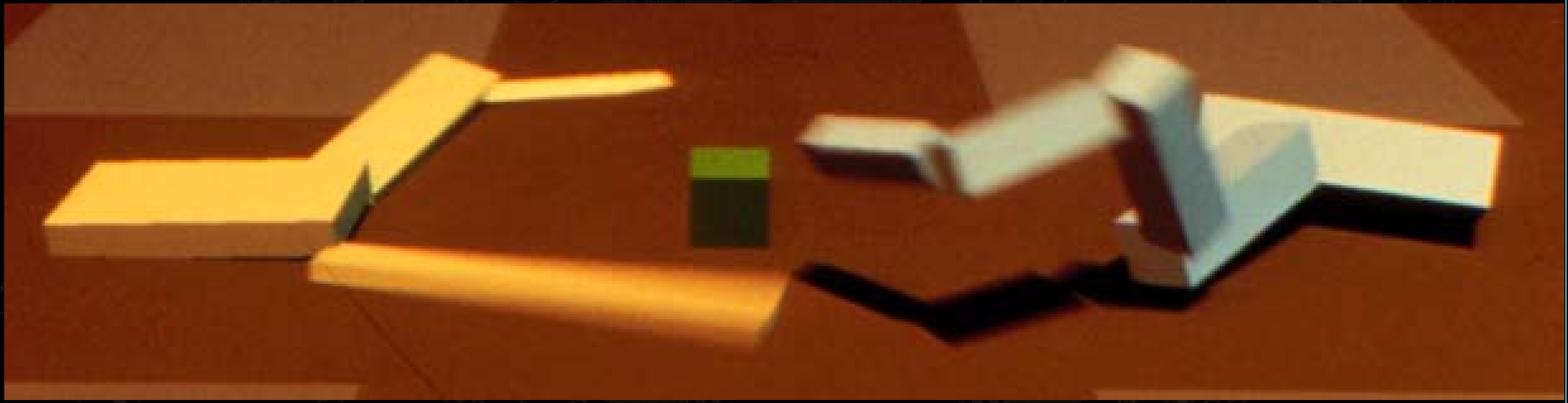
Lessons Learned

- It is possible to evolved morphology and control
- Results are sometimes surprising and funny
- The larger the search space the more computation is required (but the more surprising the results)
- Exploration-exploitation trade-off

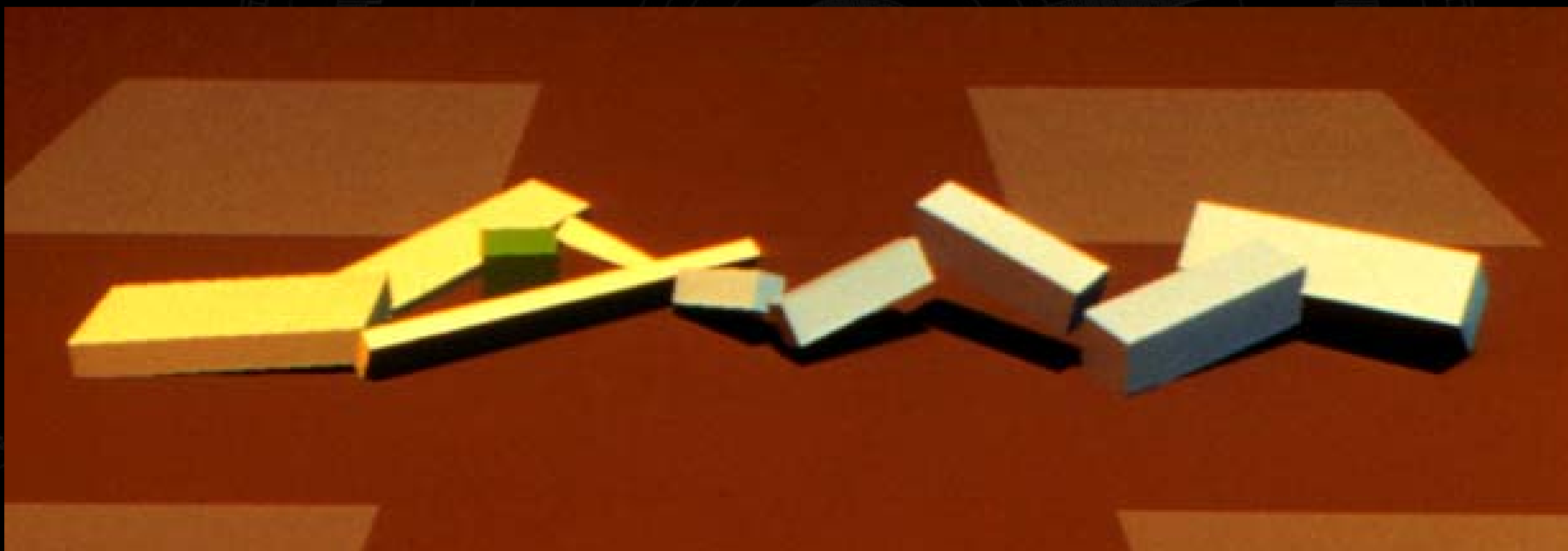
Catch-the-Block!



Catch-the-Block!



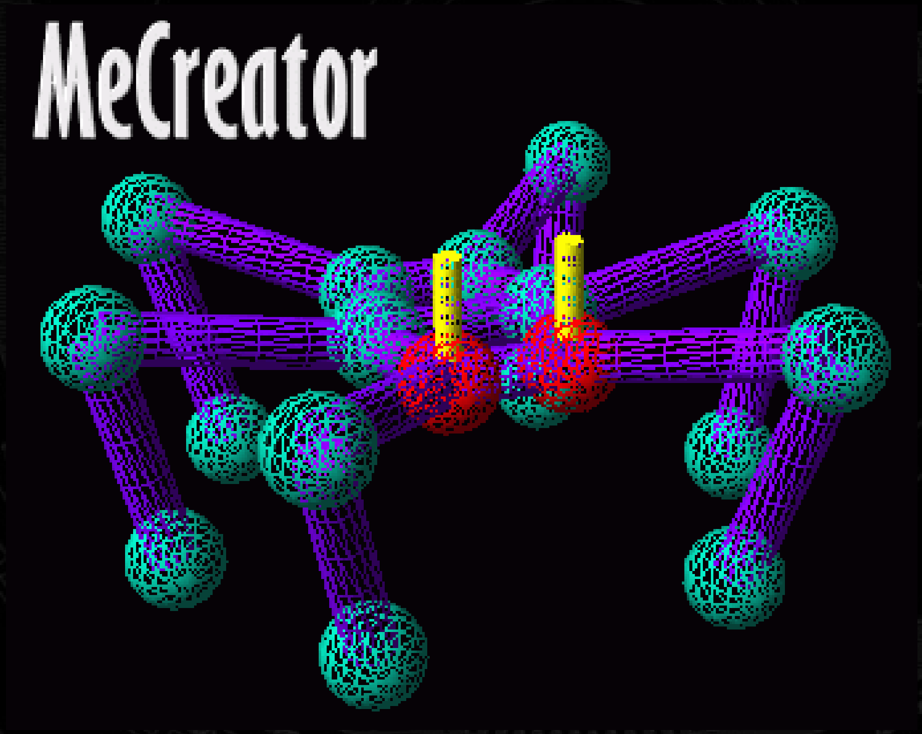
Catch-the-Block!



Virtual Life Realizes Sims!

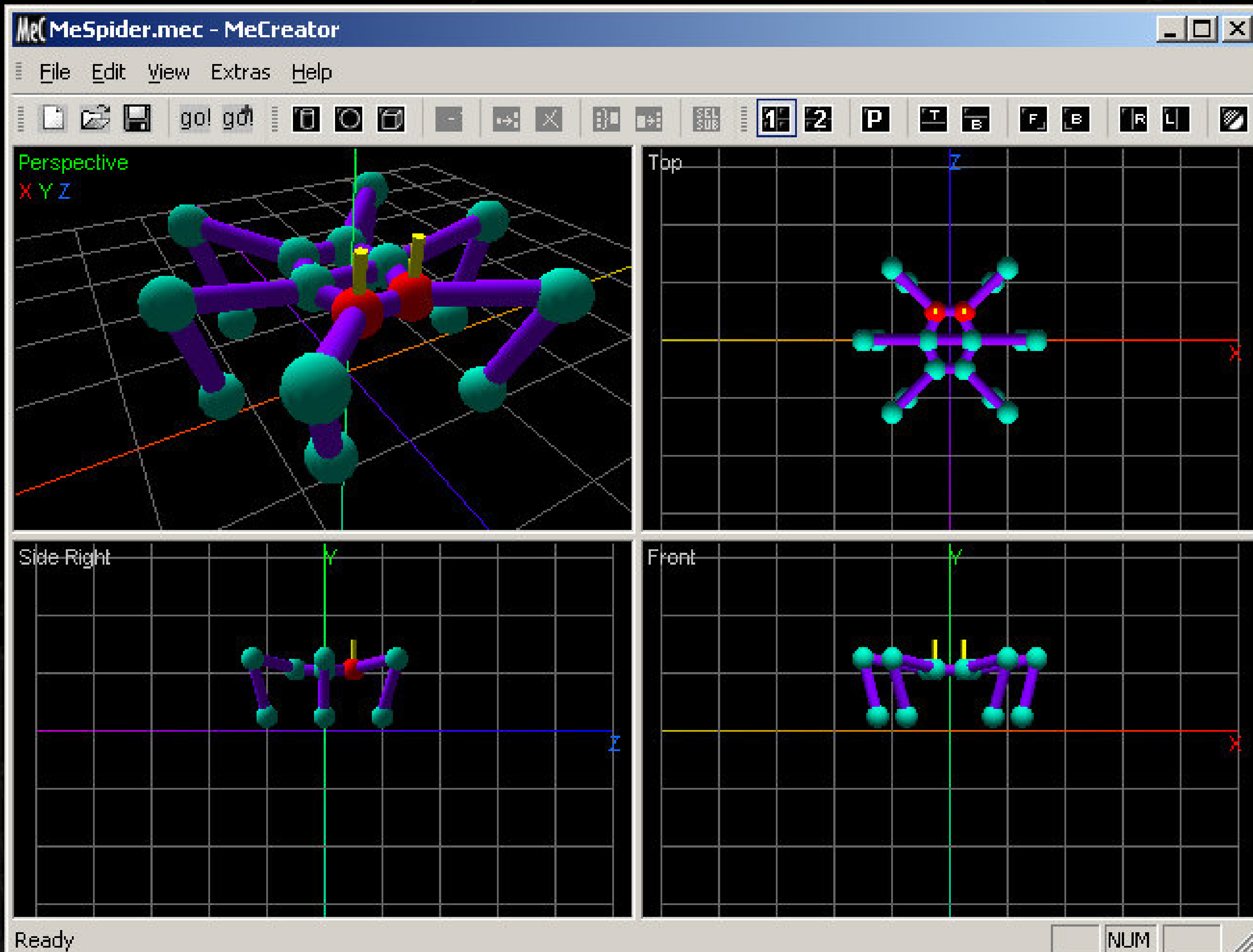
Virtual Life → options → genetic algorithm → run

Do-It-Yourself

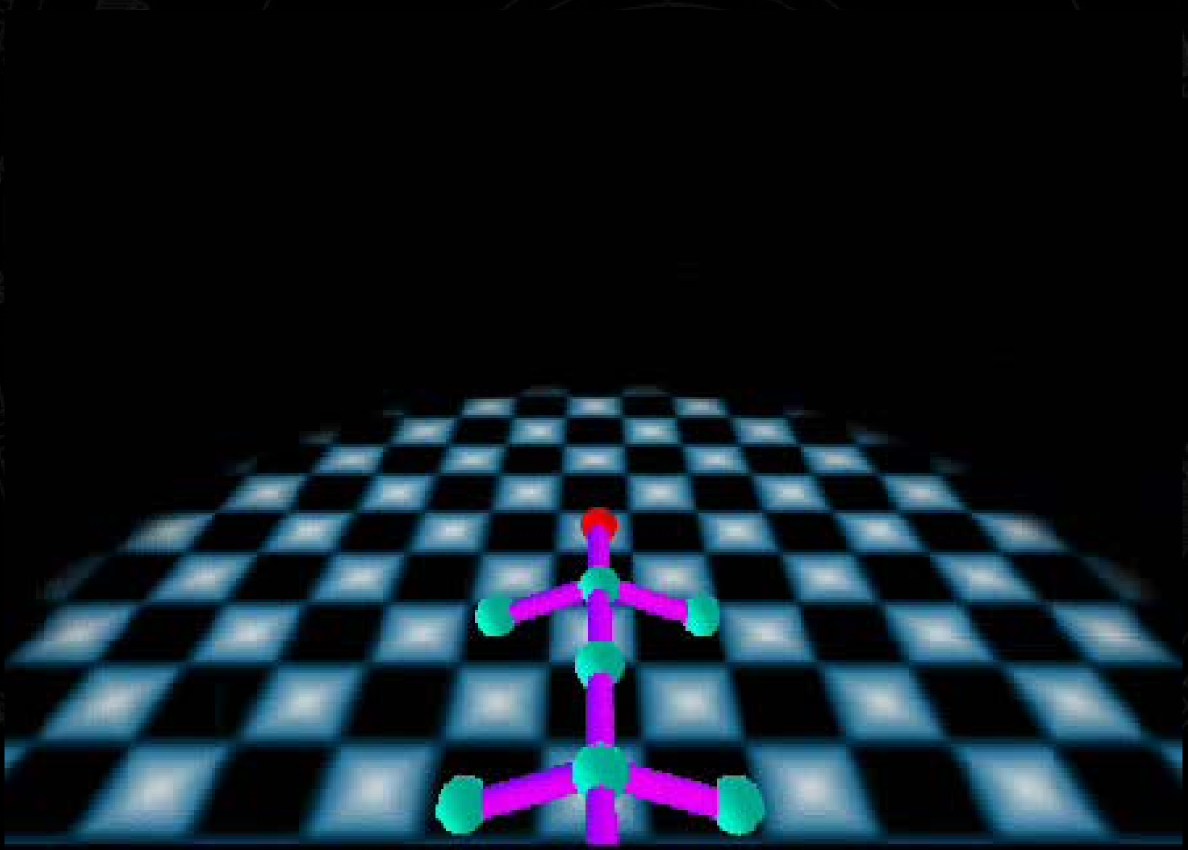


http://www.madtoaster.com/mecreator/

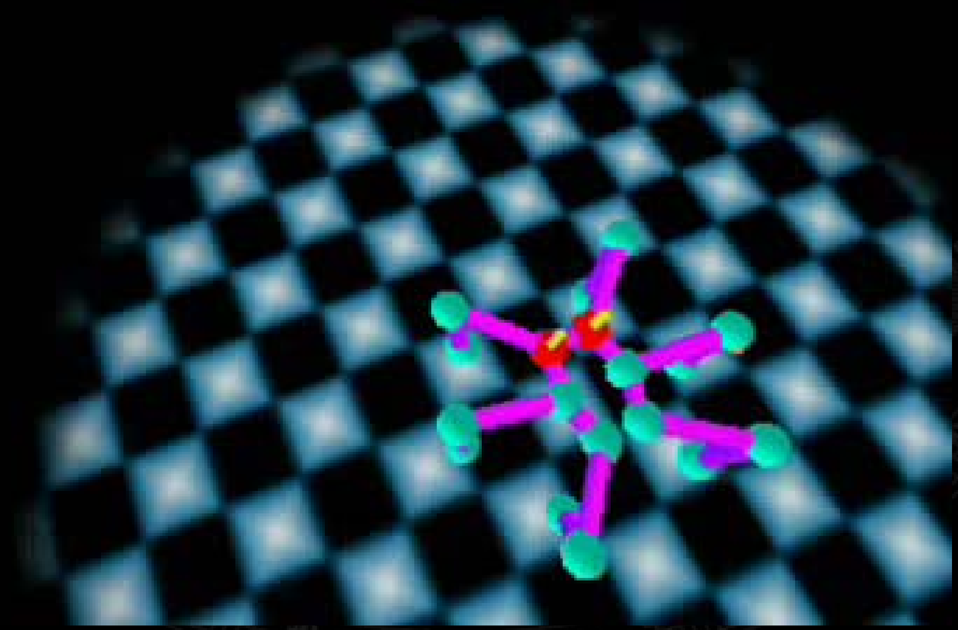
Do-It-Yourself



Movies



Movies



Sims' Creatures

Movie time!

Anguilliform Swimming

See movie ...

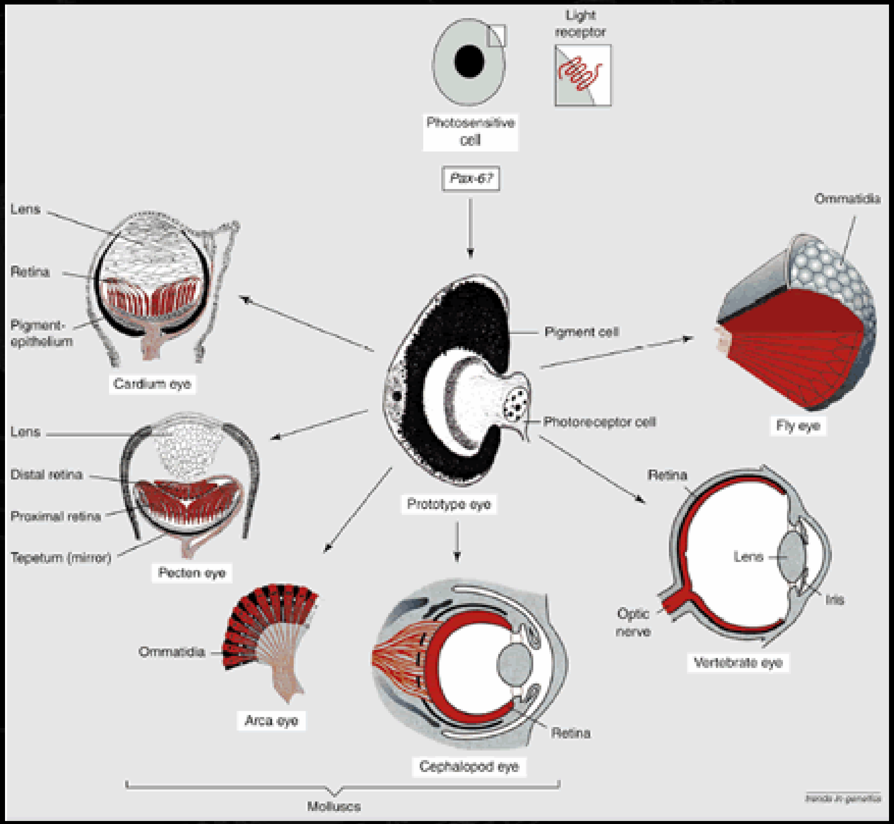
(by Stefan Kern and Petros Koumoutsakos)

Artificial Evolution System (AES)

- Peter Eggenberger (1996; 1997)
- Study of interaction of how genetic and environmental factors influence developmental process
- Objective: *Evolution of shapes*

Genome-Physics Interaction

- Evolution can climb "mount improbable" through a mixture of random mutation and selection – no intelligent designer required
- Often neglected aspect: mutation and selection can exploit self-organizing characteristics of the physical world



Example: evolution of the eye

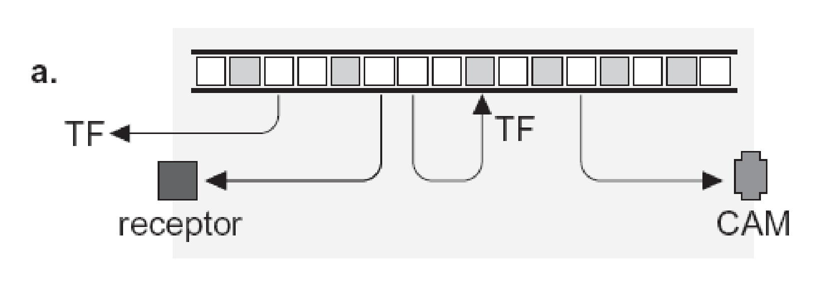
AES

- Foundation: genome-based <u>cell-to-cell communication</u>
- What is encoded in the genome is not the organism's structure (as in Sims work) but rather the <u>growth processes</u>
- Key idea: place cells on 3-D grid and immerse them in a solution of transcription factors which are proteins produced by different cells; the concentration of the TF determines how cells work

AES: Basic Mechanisms

Each cell contains genome consisting of:

- Regulatory genes (determine which structural gene is turned on)
- Structural genes; if turned “on”, e.g. perform a pre-defined function:
  - Produce a TF (diffuse from cell)
  - Form a receptor on surface of cell
  - Form a cell-adhesion molecule (CAM) on surface of cell
  - Search for matching CAM in environment
  - Cell division
  - Cell death



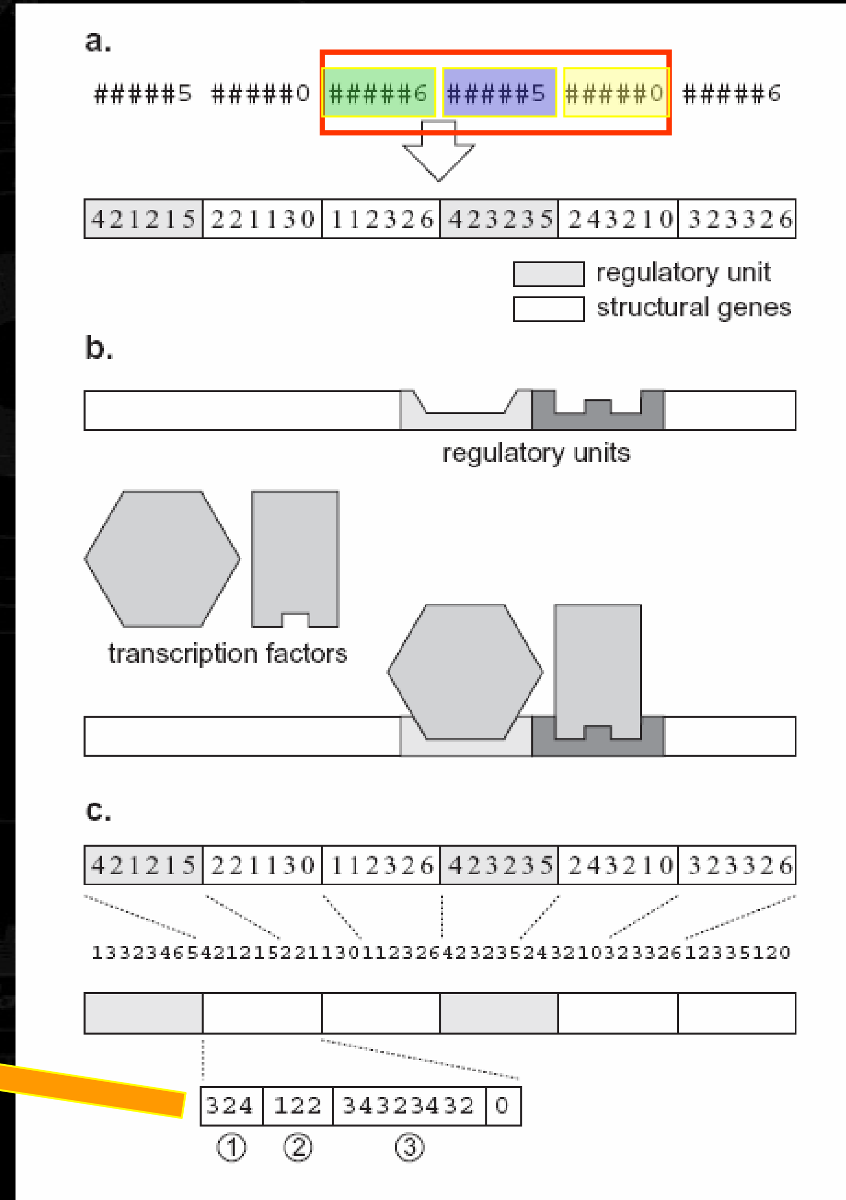
AES: Basic Mechanisms

0: end-of-gene marker
5: end-of-regulator-region
6: end-of-structural-region

Positions marked by # are filled with 1,2,3,4 corresponding to bases A,T,G,C

Regulatory genes (RG) are activated if:

- concentration of TF is high enough
- there is geometric affinity between RG and TF



ENCODING
1: {TF, receptor, CAM}
2: {diffusion of TF and range of CAM}
3: {geometric properties of gene}

AES: Fitness and Selection

- Structure of organism is not predefined in genome
- Fitness function:
  - Number of cells of final organism
  - Measure of T-shapedness

Philogenetic Development Using AES

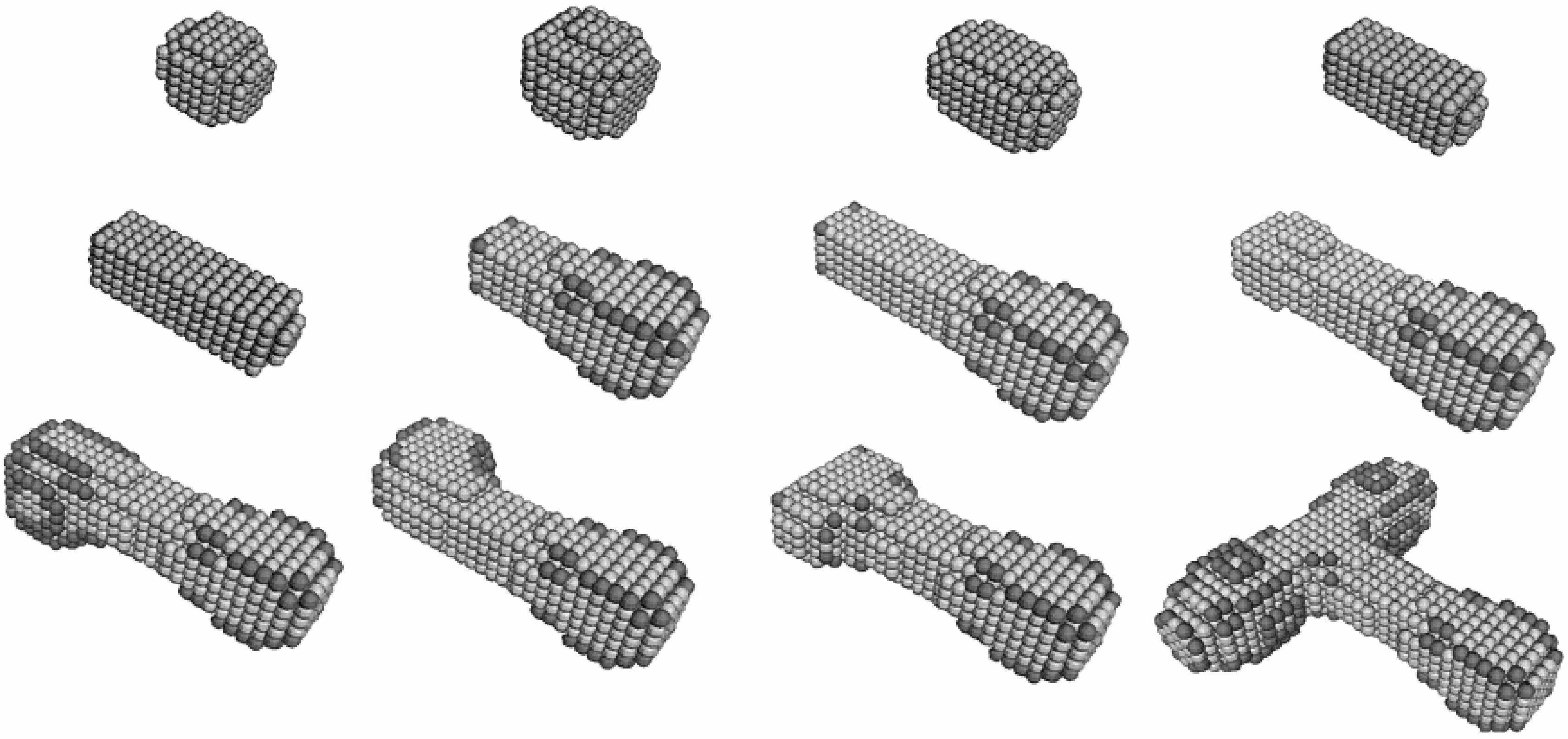


Figure 6.13: *Phylogenetic development of an organism using the Artificial Evolutionary System. The goal was to evolve T-shapes. The shapes of the best individuals are shown after every six generations. The final shape had emerged after 72 generations.*

Other Examples

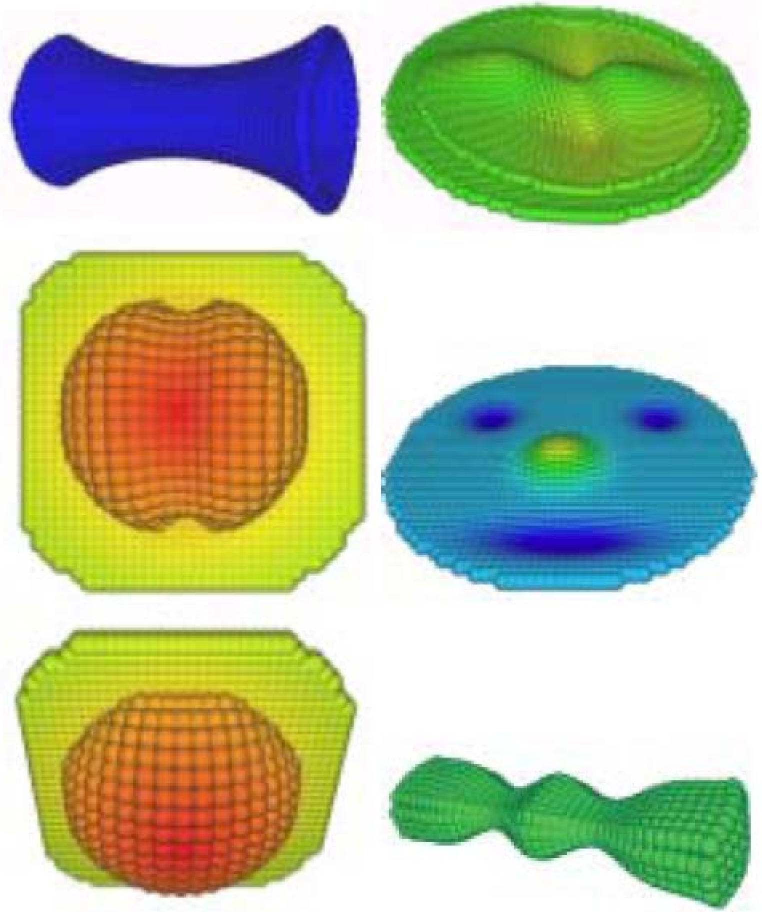


Figure 6: Creation of shapes by morphogenetic mechanisms. Different shapes can be controlled by the cells becoming different through cell differentiation

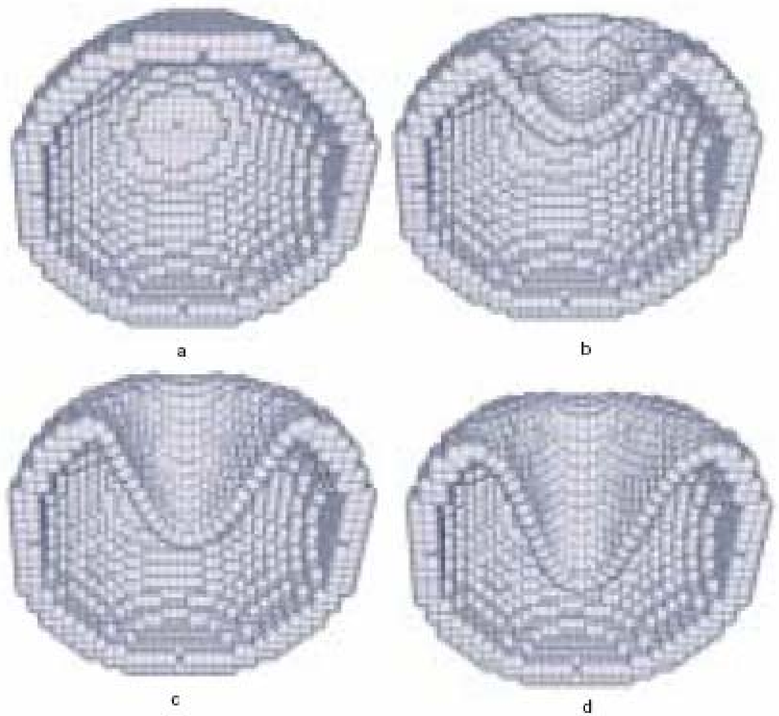
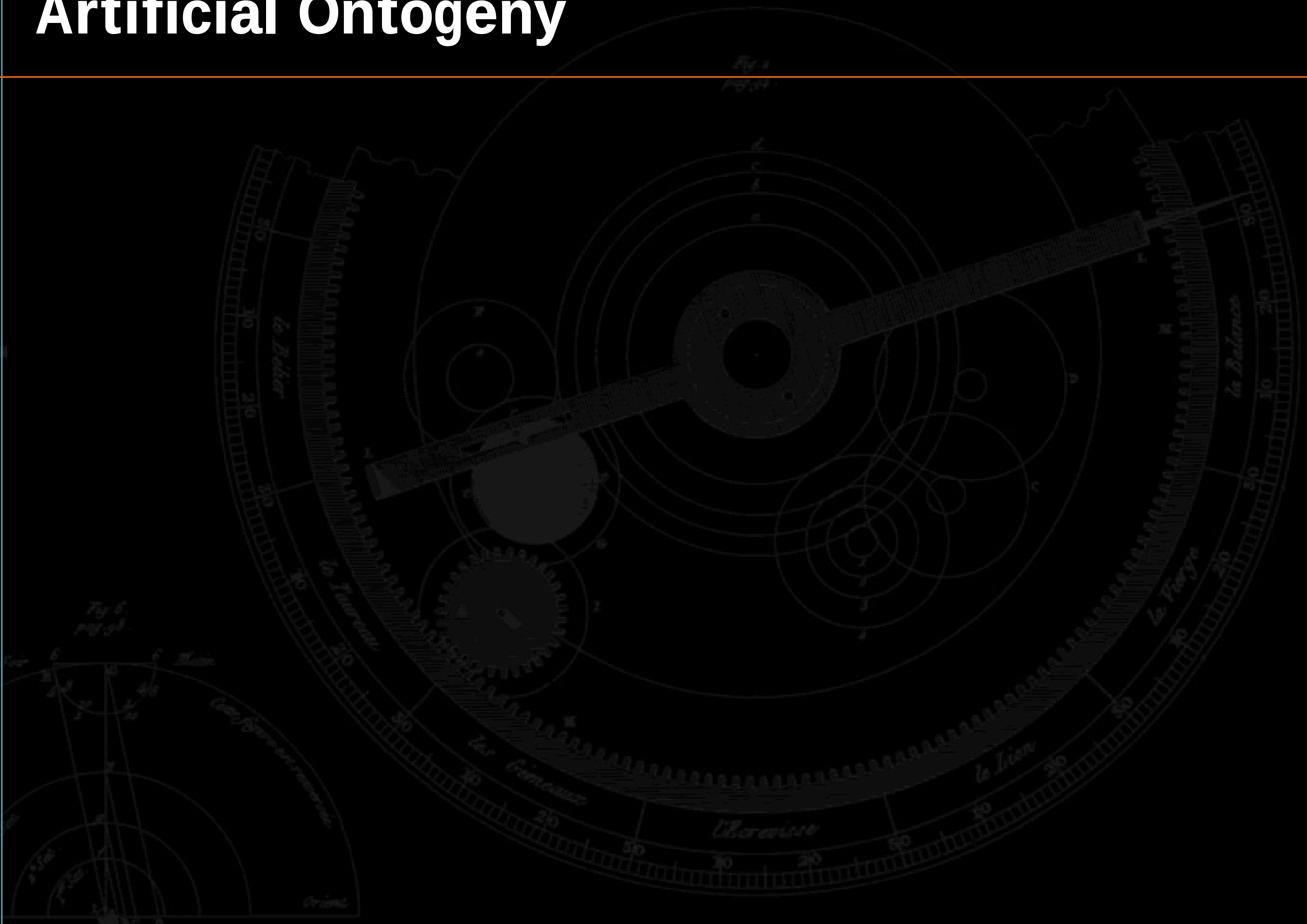


Figure 7: Four stages of simulated invagination. Cells were positioned spherically and the task was to evolve a mechanism able to invaginate a part of the sphere as illustrated in the above sequence of the dynamics of this developmental process.

AES: Lessons Learned

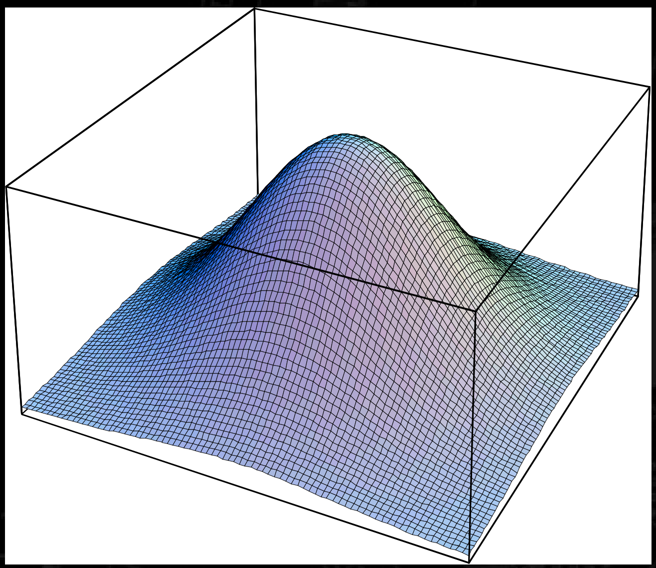
- Entire organism is grown without predefining its spatial structure in genome → makes length of genome independent of organism's size
- Example shows how biological insights can be abstracted and translated into a simulation model
- Nice example of how the genotype-phenotype mapping is influenced by interaction with the environment
- Search space is large: it is a real challenge to find appropriate constraints
- The organisms have only shape: what about behavior?

Artificial Ontogeny



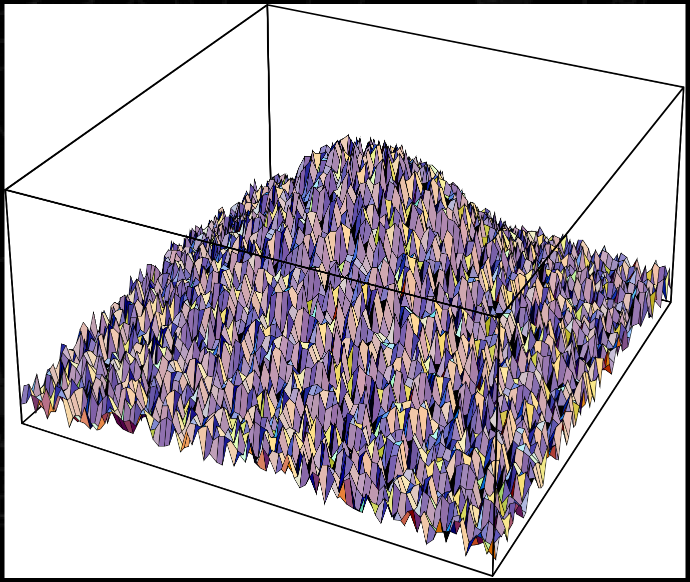
Evolution in the Real World

The difference between mathematical optimization and optimization in the real physical world



Ideal function in the mathematical world

Rugged hill in the experimental world



Evolvable Hardware

- New field at the intersection of reconfigurable hardware, automated physical design, evolutionary computation and autonomous systems
- Evolvable hardware = reconfigurable HW + reconfiguration mechanism (e.g. evolutionary algorithm)
- **Main objective:** new generation of hardware, self-configurable and evolvable, environment-aware, which can adaptively reconfigure to achieve optimal signal processing, survive and recover from faults and degradation, improve its performance over lifetime of operation

Evolvable Hardware – Why?

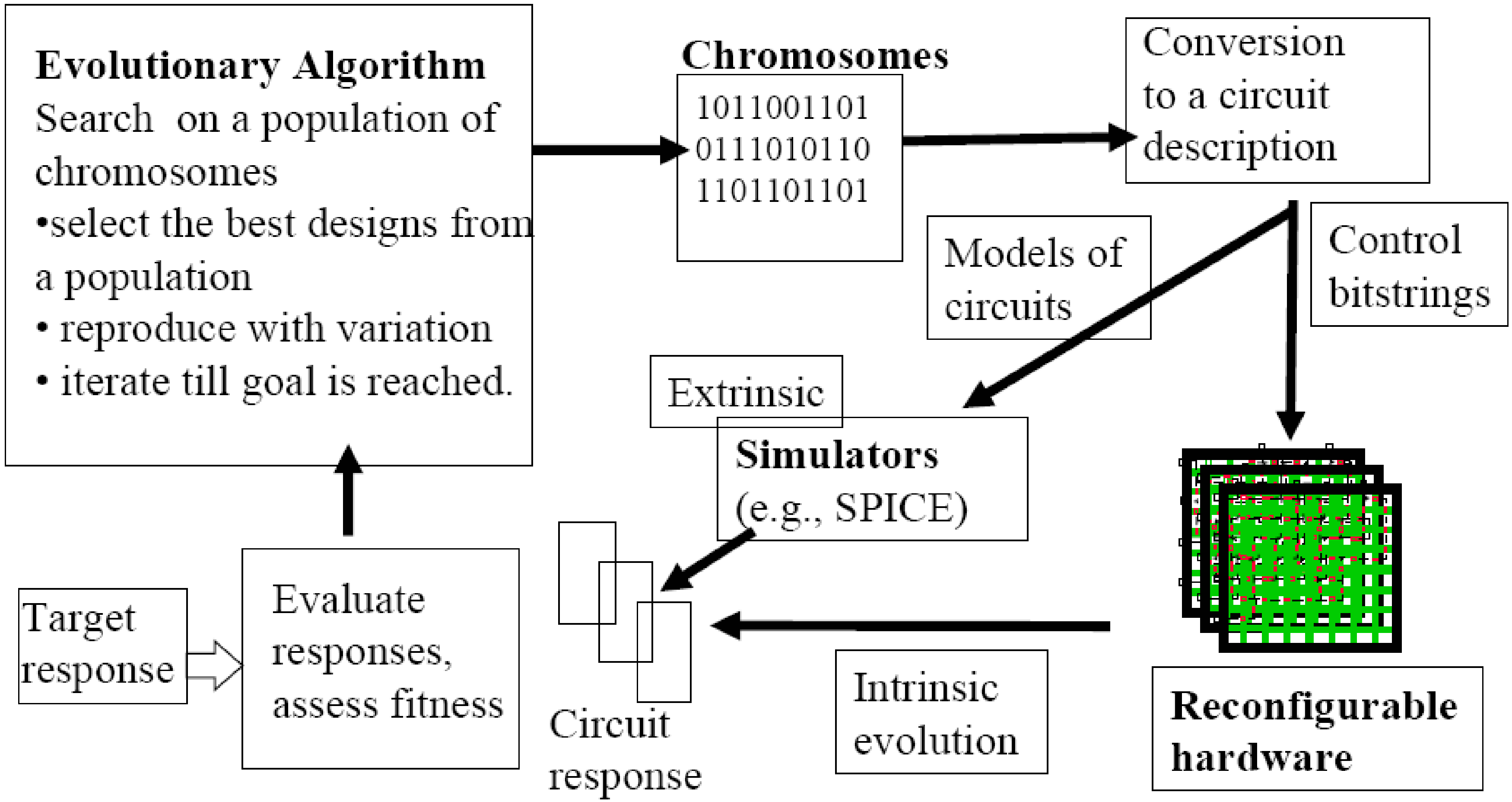
Evolution in hardware gives us unique opportunities

- Can exploit real-world physics that is often <u>difficult or impossible</u> to analyze or model in simulations – let's us drop simplifying constraints (evolution searches and exploits design spaces induced by physics or materials used to build the hardware!)
- Physical components have a size, shape and location, which are critical in determining the interactions between them. No longer artificial point-to-point interconnections as in simulations.
- Characteristics of the components and their interactions are <u>not exactly predictable or constant over time</u> (wear and tear)

Evolvable Hardware - Application Domains

- Jet engines
- Electronic circuits
- Antenna design
- Controller algorithms
- Optical systems
- Robotics
- ...

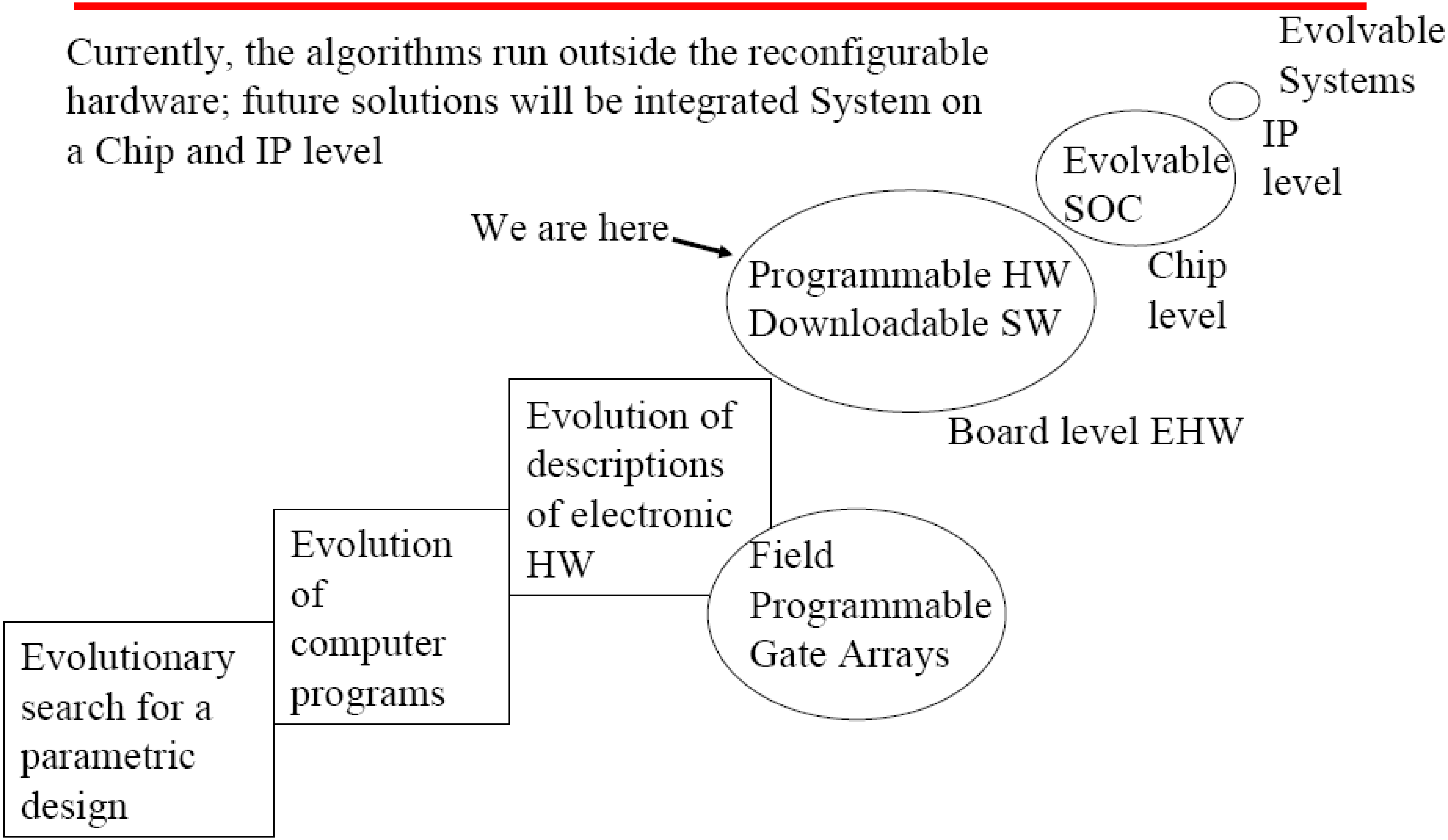
Evolving Electronic Circuits



Potential electronic designs/implementations compete;
the best ones are slightly modified to search for even more suitable solutions

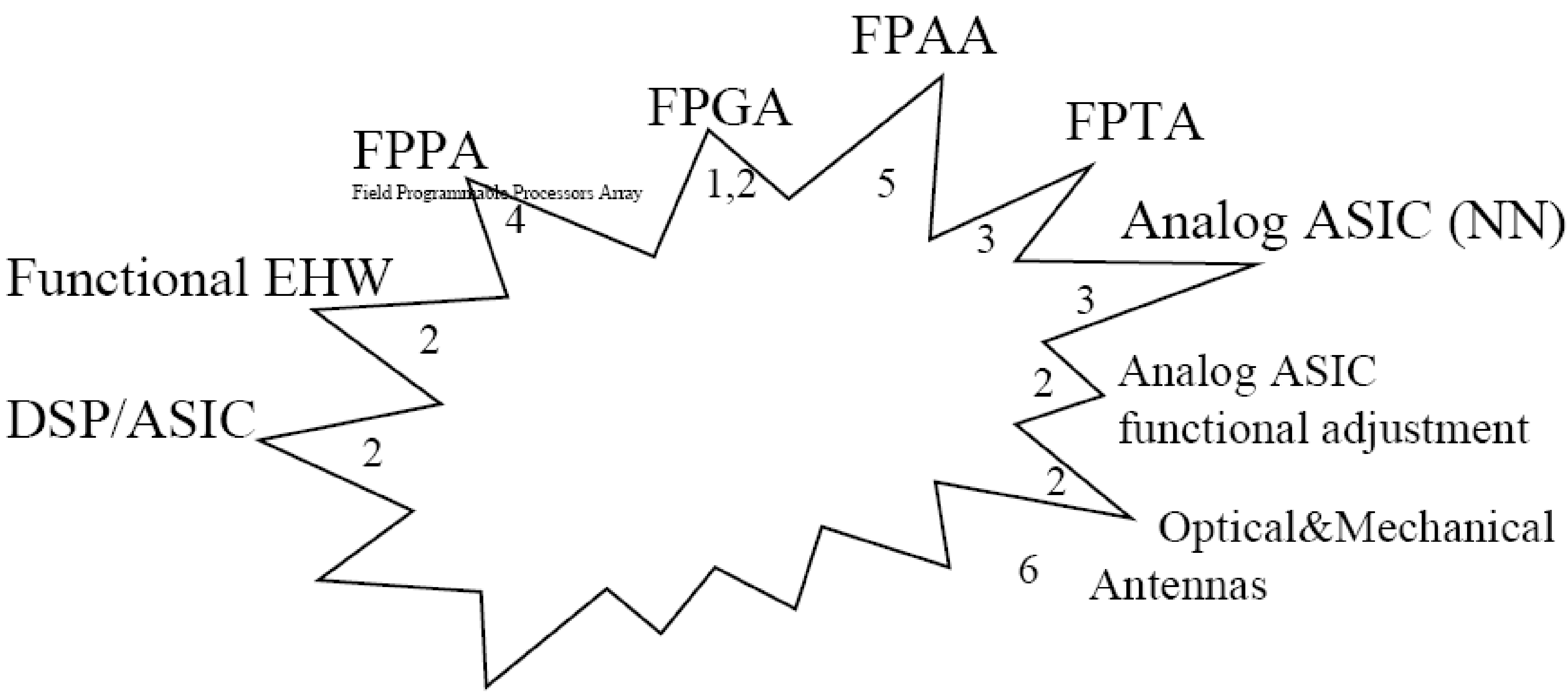
Evolution of EHW

Currently, the algorithms run outside the reconfigurable hardware; future solutions will be integrated System on a Chip and IP level



HW Platforms for EHW Experiments

First/ significant experiments on:...



1 Thompson, U. Sussex, UK
2 Higuchi, ETL, Japan
3 Stoica, JPL
4 Marchal, CSEM, Switzerland
5 Zebulum, U. Sussex, UK (now at JPL)
6 Linden

FPGA

- Field Programmable Gate Array
- Contains large number of programmable (reconfigurable) components (cells or gates) and wires
- Switches can be configured in SW (through a configuration bit-string) to determine how the cells behave how they are interconnected (the specific arrangement is contained in a configuration memory)
- It is a physical circuit (not a simulation)
- **Question:** can the rich natural unconstrained dynamics of the silicon chip be exploited?

Evolution of Circuits

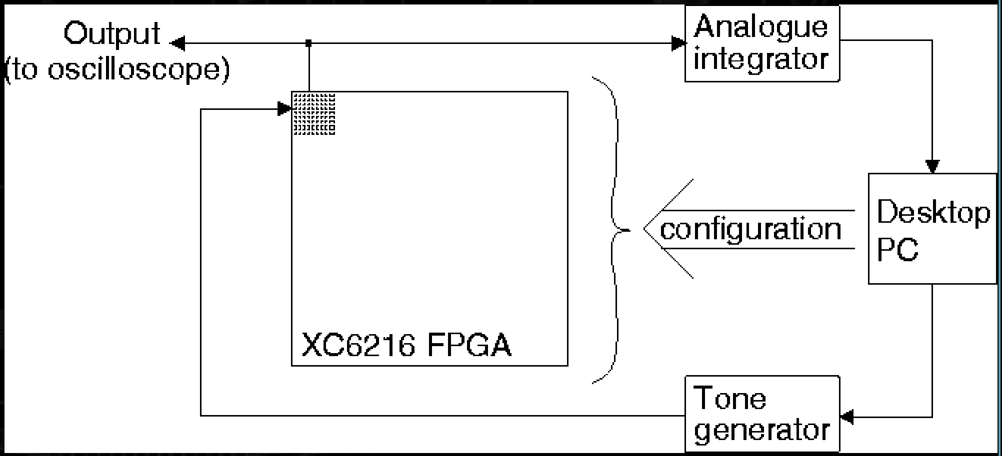
Goal: evolve a circuit to discriminate between square waves of 1kHz and 10kHz

Output Vout = +5V at one frequency; Vout = 0V at the other

Evolvable Hardware = Xilinx XC6216 FPGA

- 64x64 array of reconfigurable cells
- NEWS connectivity

Constrained to 10x10 corner

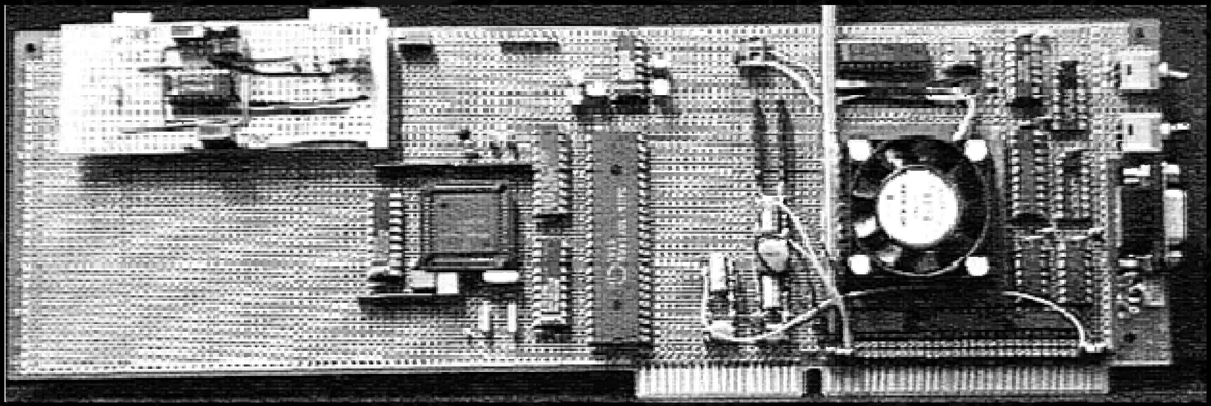


Thompson, 1996

Das Experiment

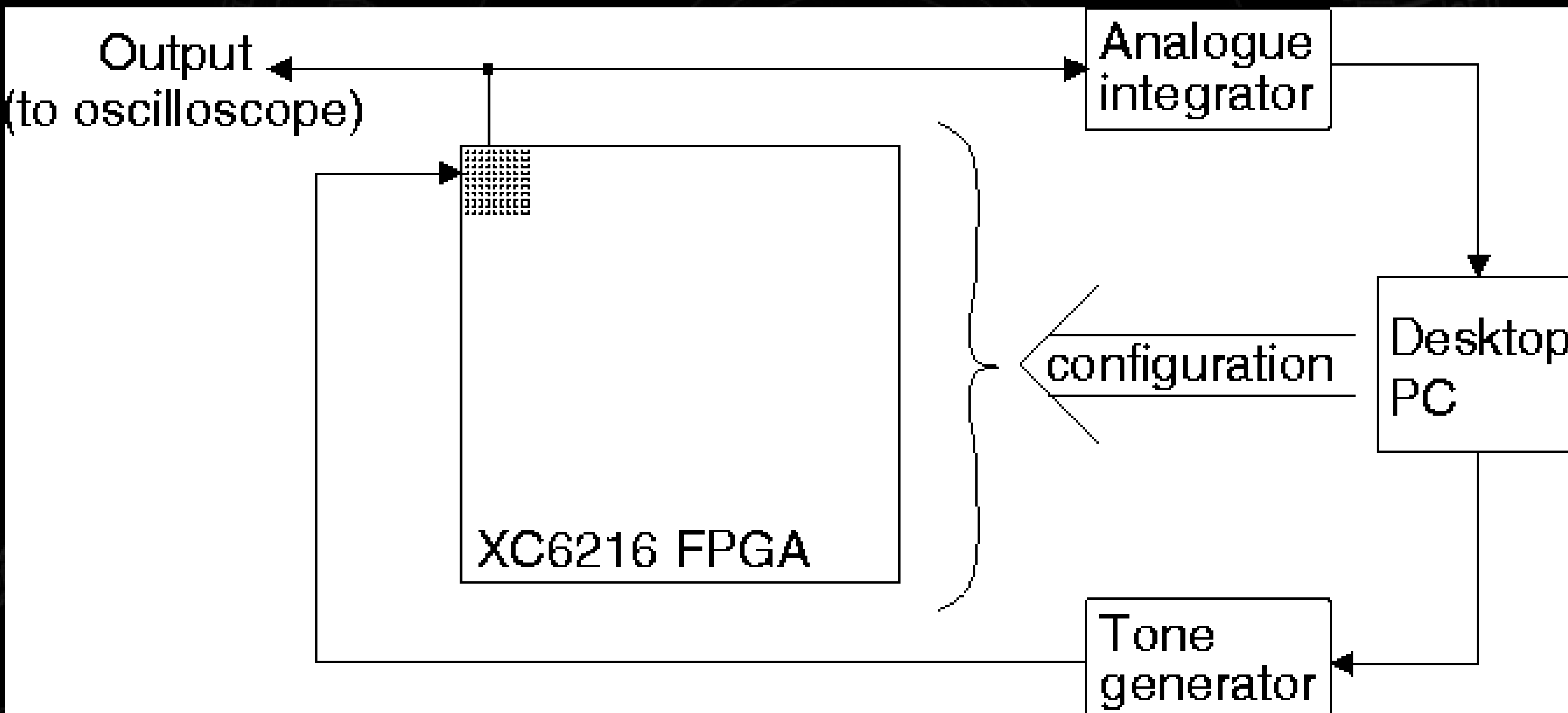
Note: Not an easy task!

The evolved circuit needs to discriminate between <u>input periods five orders of magnitude</u> longer than the propagation time of each cell and this <u>without the aid of a clock</u>



Thompson, 1996

Das Experiment

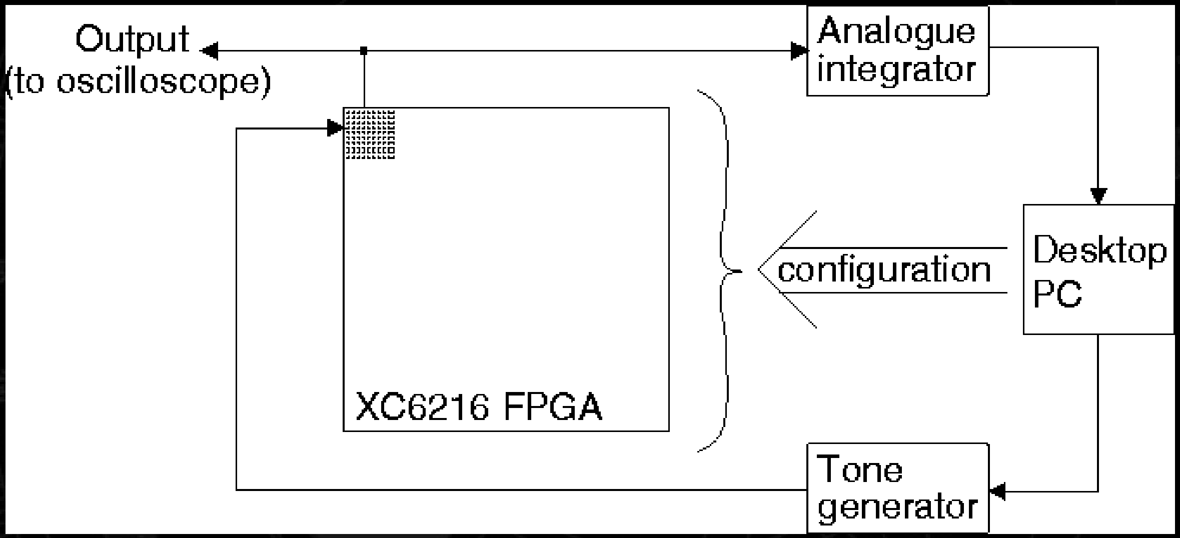


Genetic Algorithm

- Each cell has an 18-bit gene (encoding the cell's parameters); the genes are grouped into a linear bit-string genotype 1800 bits long
- Genetic Algorithm (GA) parameters
  - Population size = 50 (randomly generated)
  - Elitism (single fittest individual survives)
  - Fittest individual expected twice the offspring as the median-ranked individual
  - Mutation rate = 2.7 mutations/genotype

Thompson, 1996

Fitness Evaluation



- Five 500ms bursts of 1kHz square wave, five 500ms bursts of 10kHz square wave (random order, no gap)
- Reset integrator at beginning of each test tone
- Integrate output voltage over each test tone duration

Thompson, 1996

Fitness Evaluation

i_t = integrator value at end of test tone t

S_1 = set of five 1kHz test tones

S_{10}= set of five 10kHz test tones

$$\text{fitness} = \frac{1}{10}\left|\left(k_1 \sum_{t \in S_1} i_t\right) - \left(k_2 \sum_{t \in S_{10}} i_t\right)\right|$$

$$\text{where}\left\{k_1 = 1/30730.746, k_2 = 1/30527.973\right\}$$

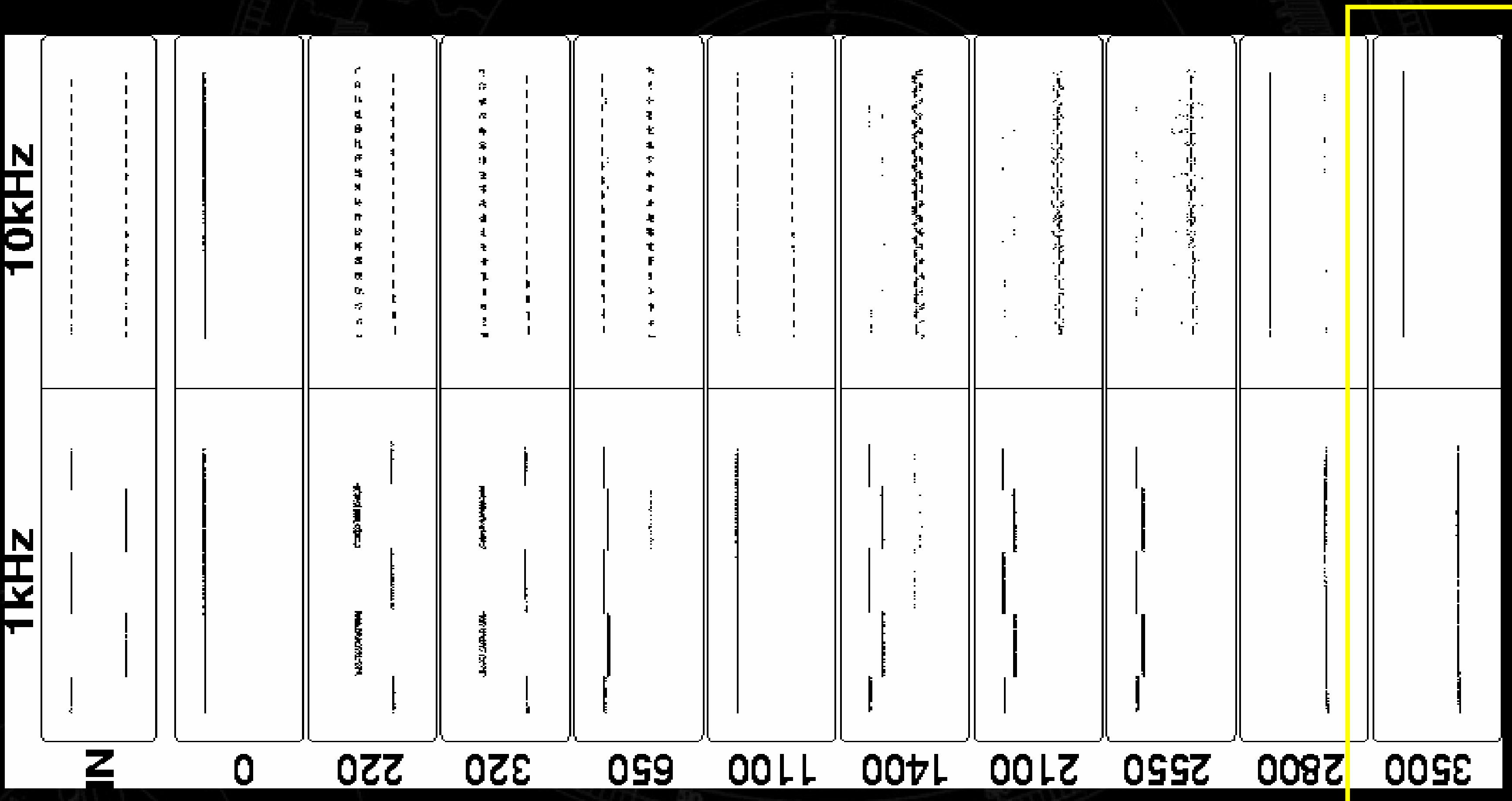
Maximizes difference between the average output voltage during the two input test tones

Constants determined such that circuits that directly map input to output get zero fitness

Thompson, 1996

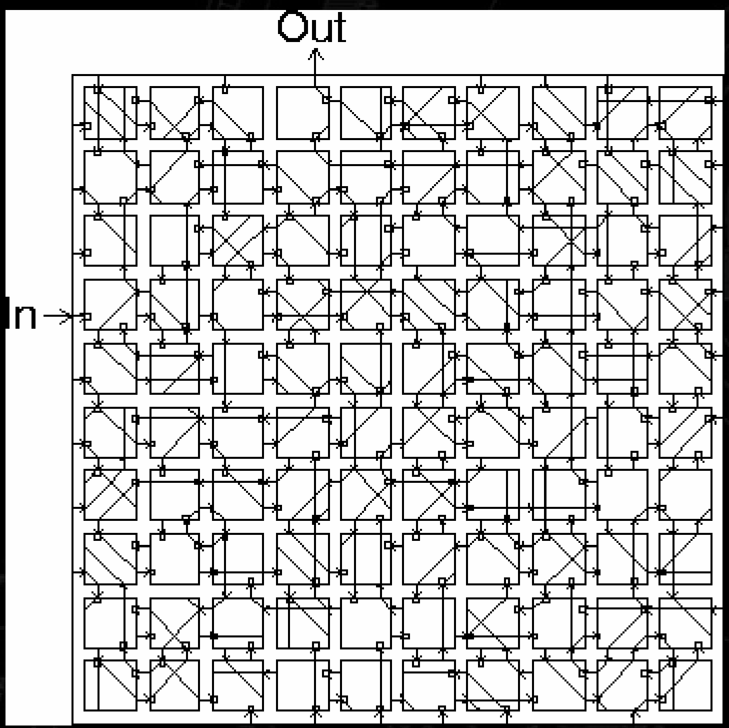
Results

3500 generations

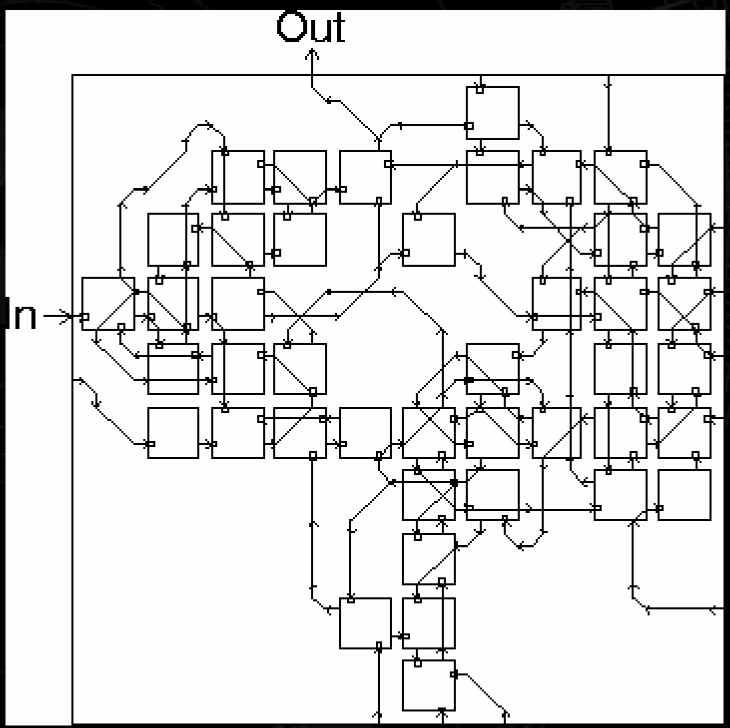


Thompson, 1996

Resulting Circuit



Full evolved circuit



Pruned circuit

Thompson, 1996

Functional Circuit

Random “unused” cells were clamped to random constant values

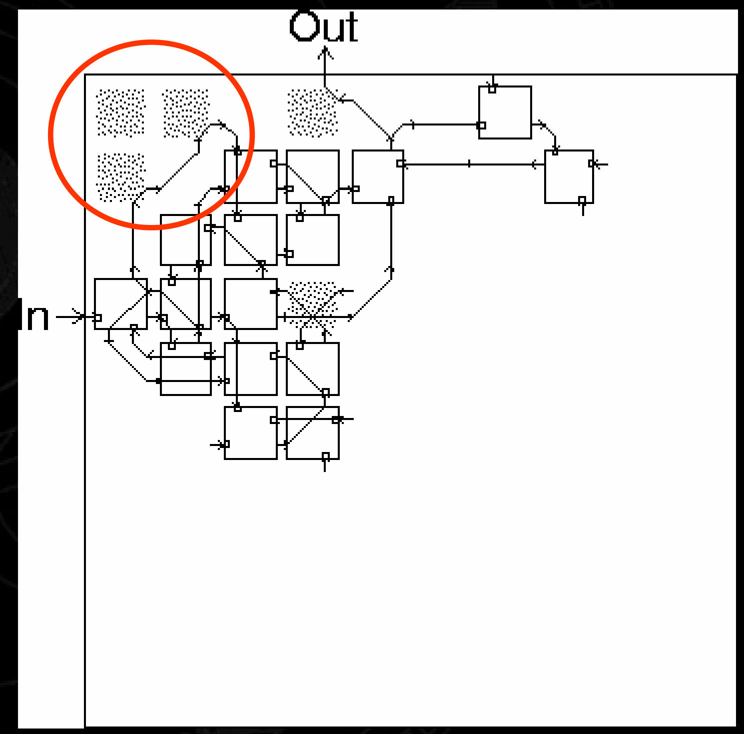
Fitness was re-evaluated

- Cell unclamped if performance degraded
- Cell left clamped otherwise

Iterated to build a maximal set of clamped cells without altering fitness

Grey cells *cannot* be clamped even though there is no path to the output!

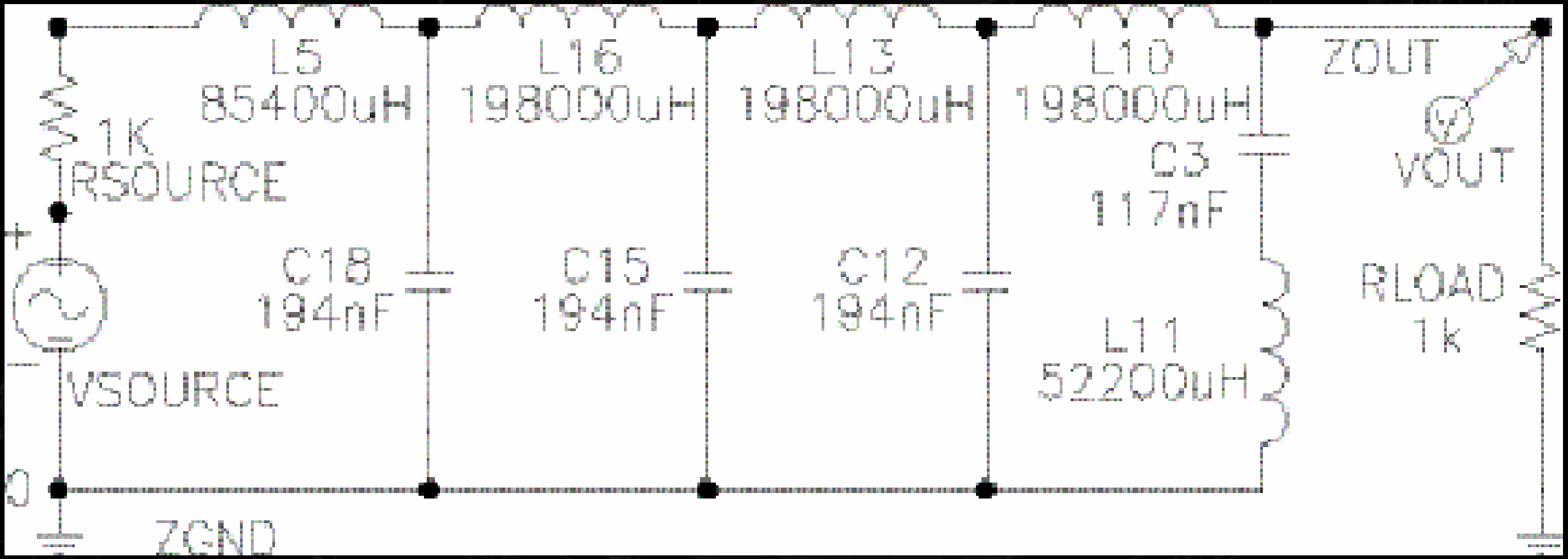
Conclusion: gray cells are not connected BUT interact with the rest of the circuit by other means (e.g. electromagnetic coupling); evolution has exploited these couplings in a clever way!



Thompson, 1996

Evolving Circuits

This evolved circuit infringes on a 1925 patent!



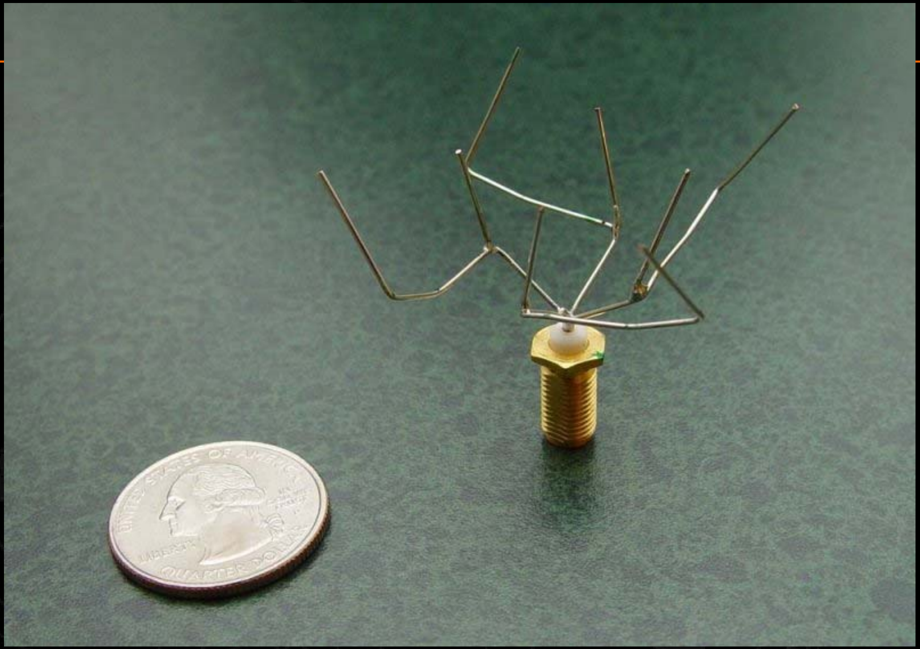
Evolving an Antenna

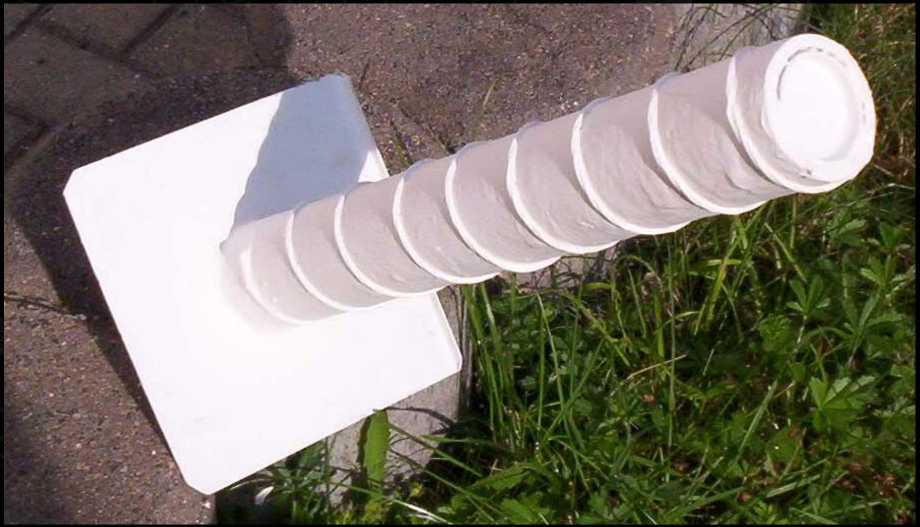
The problem (Altshuler and Linden 1998) is to determine the *x-y-z* coordinates of the 3-dimensional position of the ends (*X1*, *Y1*, *Z1*, *X2*, *Y2*, *Z2*,… , *X7*, *Y7*, *Z7*) of 7 straight wires so that the resulting 7-wire antenna satisfies certain performance requirements

The first wire starts at feed point (0, 0, 0) in the middle of the ground plane

The antenna must fit inside the 0.5λ cube

Evolving an Antenna

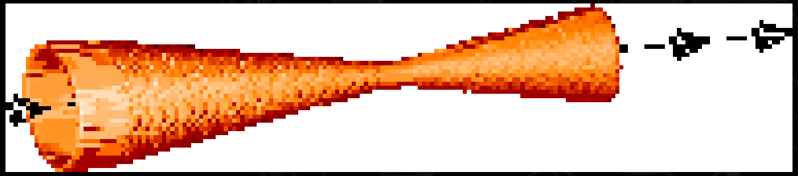




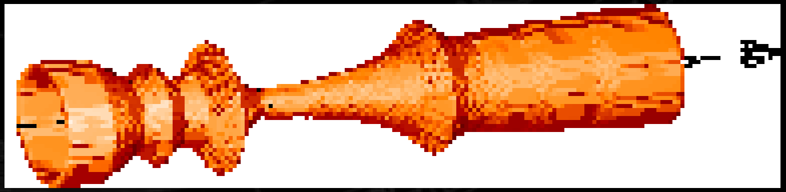
not evolved!

Evolving a Nozzle

Task: to optimize the shape of a jet nozzle
Approach: random mutations to shape + selection

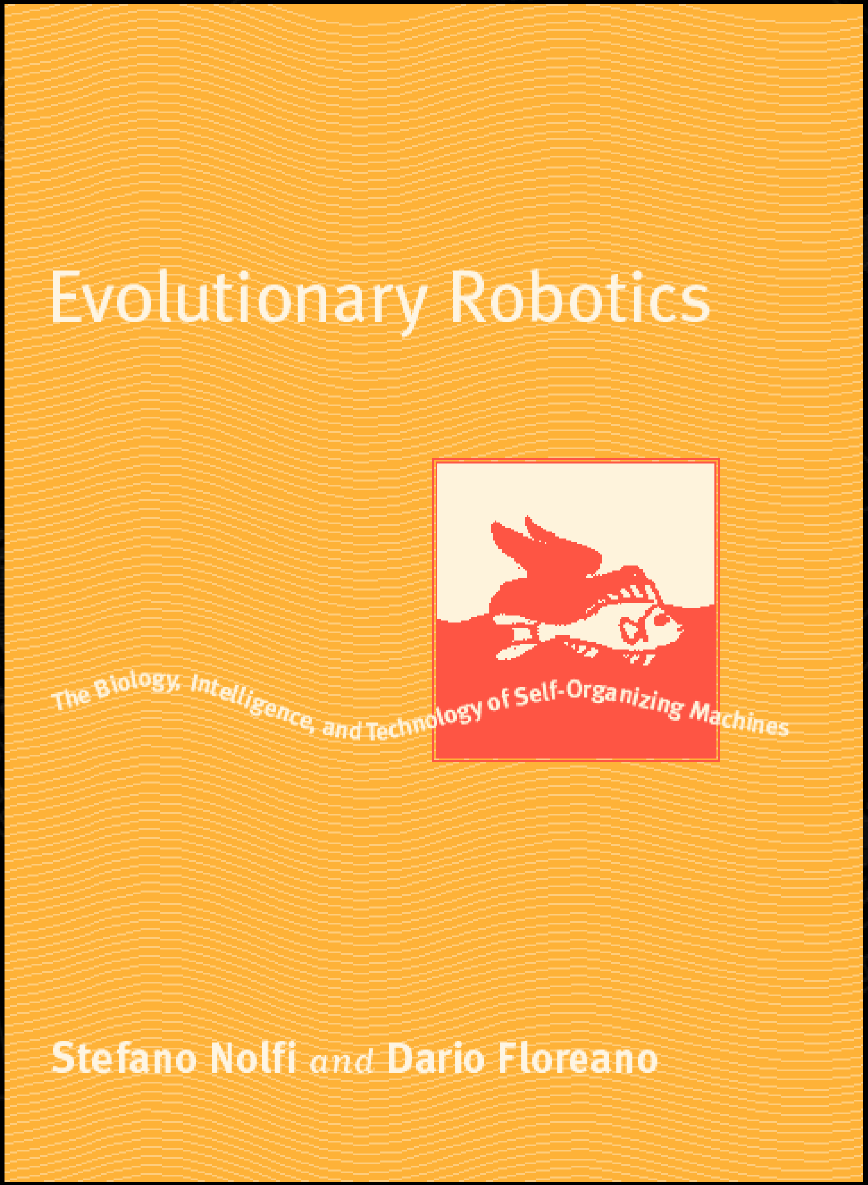


Initial shape



Final shape

Evolutionary Robotics



Evolutionary Robotics

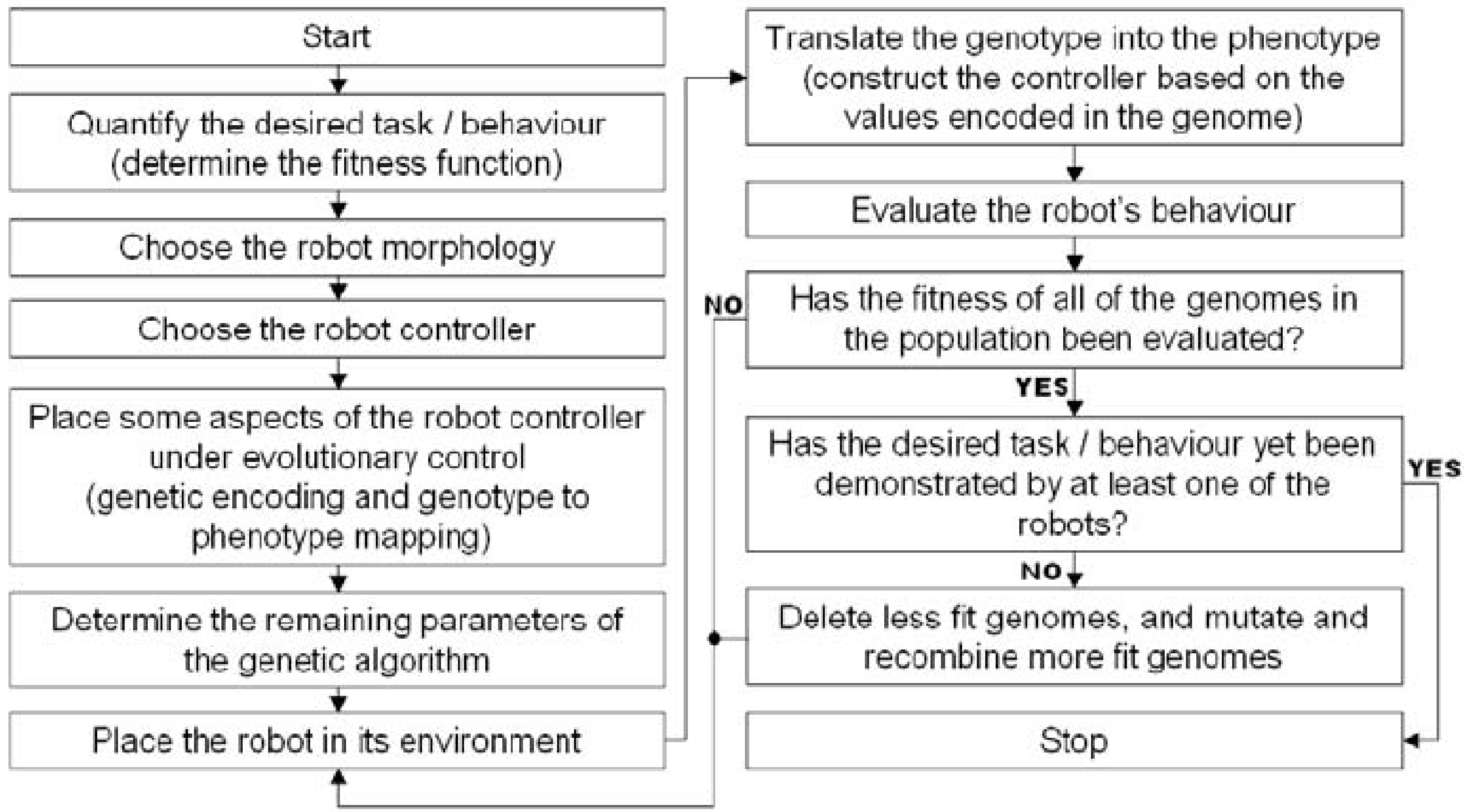


Figure 1-3: **Algorithmic flow of an evolutionary robotics experiment.**

Josh Bongard (2003)

Evolution of Spiking Neural Networks

http://lis.epfl.ch/research/projects/BioinspiredFlyingRobots/

Evolving Controller for Airship

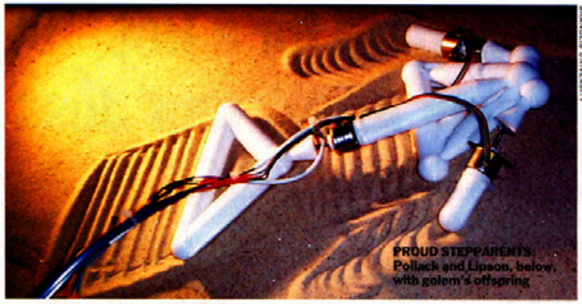
http://lis.epfl.ch/research/projects/BioinspiredFlyingRobots/

The GOLEM Project

MOVIE TIME!

Lipson, H. and Pollack, J. (2000) "Automatic design and manufacture of robotic lifeforms" *Nature* 406:974-978

TECHNOLOGY



BRANDEIS UNIVERSITY

PROUD STEPPARENTS: Pollack and Lipson, below, with golem's offspring

A Robot out of Cyberspace

A computer designs and builds its own buglike progeny, but it's not quite ready to rule the world

PICTURE A TODDLER PLAYING WITH Legos or Tinker Toys. Without any instruction, she tries putting them together. Finally, after a lot of trial and error, she assembles a little machine that actually does something. Much to her delight, it chugs along the floor like some fanciful arthropod out of *A Bug's Life*. As the precocious builder's parent, you would be proud—especially if you were told that what she did on her own has long eluded the world's most powerful computers.

JULIA MALAKIE—AP

Last week, when scientists at Brandeis University announced that one of their machines had finally designed and built a simple, toylike robot, the news immediately invited scary comparisons with such Hollywood rogue robots as *The Terminator* and *2001: A Space Odyssey's* psychopathic HAL. Some futurists, like Sun Microsystem's chief scientist Bill Joy, even warned that this might be one genie that shouldn't be let out of the bottle.

But if you look a little closer at the work of researchers Hod Lipson and Jordan Pollack, you'd see their robot creation isn't ready yet to rule the universe. Even compared with other robots, it's primitive: using only four basic parts—plastic cylinders and ball joints, simple circuitry and small motors, along with rules for friction and gravity—it designed little self-propelled crawlers, like the toddler's insect.

Other scientists have created similar robots in their computers, to say nothing of systems intelligent enough to play championship chess, but Pollack and Lipson took a giant step out of the virtual world. After they hooked their computer to a $50,000 commercial plastic model-making machine, it produced actual offspring, not just a model on a computer screen. The only human intervention was installing the robot's little motor and computer-programmed microchip ("neurons").

Through repeated design "generations" that the researchers likened to Darwinian evolution, their computer sought the "fittest" offspring—ones that could crawl the farthest in a given time. One creation shuffled along like a crab. Another left markings in the sand with its snakelike contractions. The best design turned out to be a pyramidal-shaped creature that pushed itself along with a shovel-like bar.

In their report in *Nature*, Lipson and Pollack admit their "primitive replicating robot" is far from the mythical medieval humanoid, or golem (after whom they've named their project). For one thing, it doesn't actually replicate—it can't make robots that make new robots—nor does it learn from its environment. But, as Rodney Brooks of the M.I.T. Artificial Intelligence Lab points out, it's a "long-awaited and necessary step" to creating machines that are truly lifelike. **—*By Frederic Golden***

TIME, SEPTEMBER 11, 2000 47

The New York Times

THURSDAY, AUGUST 31, 2000

Scientists Report They Have Made Robot That Makes Its Own Robots

By KENNETH CHANG

For the first time, computer scientists have created a robot that designs and builds other robots, almost entirely without human help.

In the short run, this advance could lead to a new industry of inexpensive robots customized for specific tasks. In the long run — decades at least — robots may one day be truly regarded as "artificial life," able to reproduce and evolve, building improved versions of themselves.

Such durable, adaptive robots, astronomers have suggested, could someday be sent into space to explore the galaxy or search for other life.

But the quest to create artificial life also revives concerns that computer scientists could eventually create a robotic species that would supplant biological life, including humans.

"Some things we probably can do we shouldn't do," said Bill Joy, chief scientist at Sun Microsystems, who wrote a recent article warning of the power of emerging technologies. "Just like we can kill things with DDT, but we shouldn't."

For now, the robotic manufacturing system — a computer hooked up to a machine that builds plastic models — in the laboratory of Dr. Jordan B. Pollack and Dr. Hod Lipson at Brandeis University in Waltham, Mass., cannot create anything nearly as complicated as itself. Instead, it produces eight-inch-long contraptions of plastic bars and ball joints.

When a motor and microchip are added, the automatons have one, and only one, ability: to crawl slowly. The fastest can scuttle along at a few inches a second.

"They look like toys," Dr. Pollack, a professor of computer science, said. But, he added, "They were not engineered by humans, and they were not manufactured by humans."

Brandeis University

The "Arrow" left a trail as it crawled across a bed of sand.

Dr. Pollack and Dr. Lipson, a research scientist, report their results in today's issue of the journal Nature.

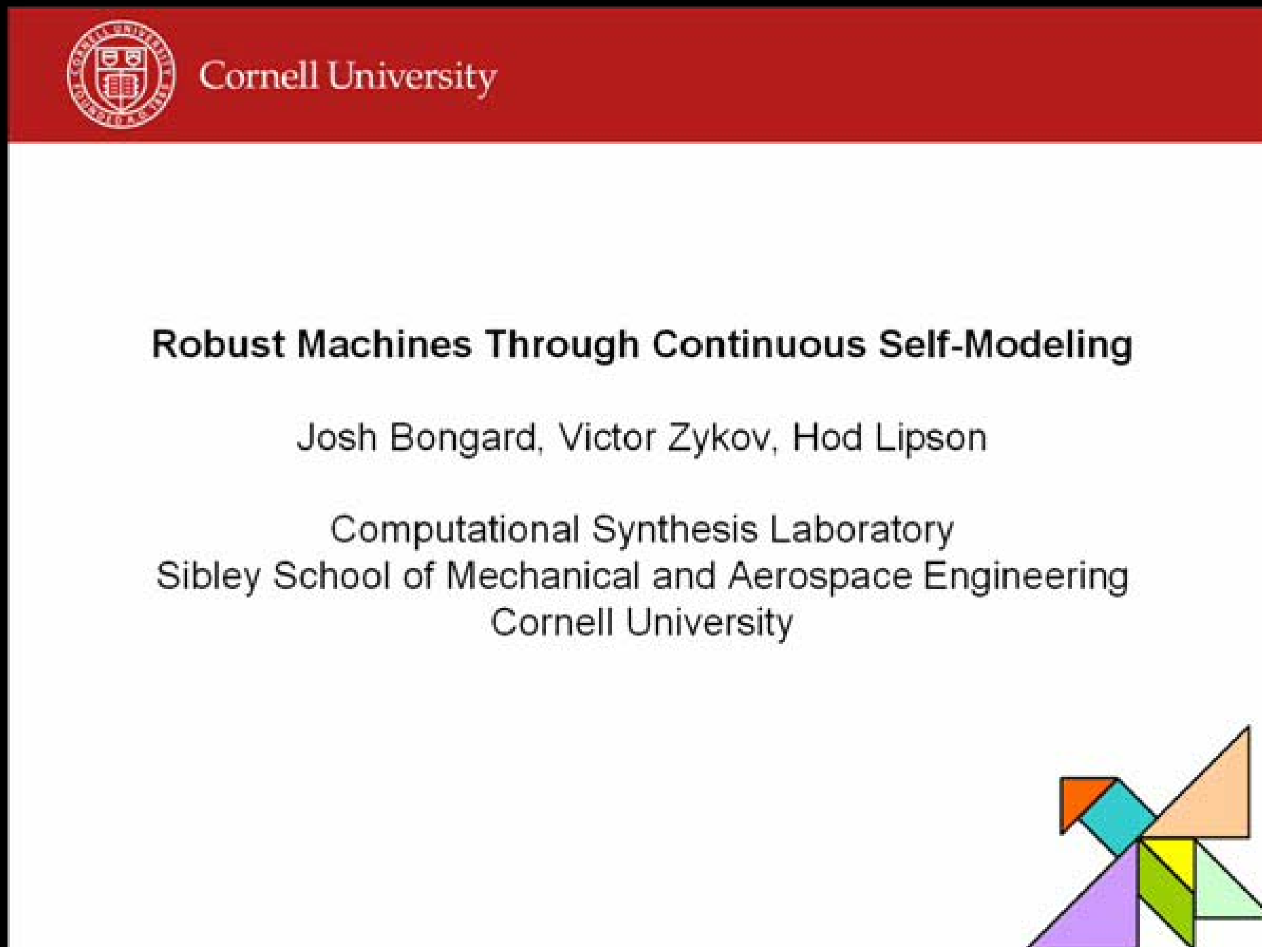
"This is the first example of pretty much 100 percent automated evolution of a machine," said Dr. Philip Husbands, a professor of artificial intelligence at the University of Sussex in England. "It's a rather primitive example, but it's the first step to something that could be quite significant."

In the future, the technique could

Continued on Page A18

Resilient Machines

Resilient Machines



Resilient Machines

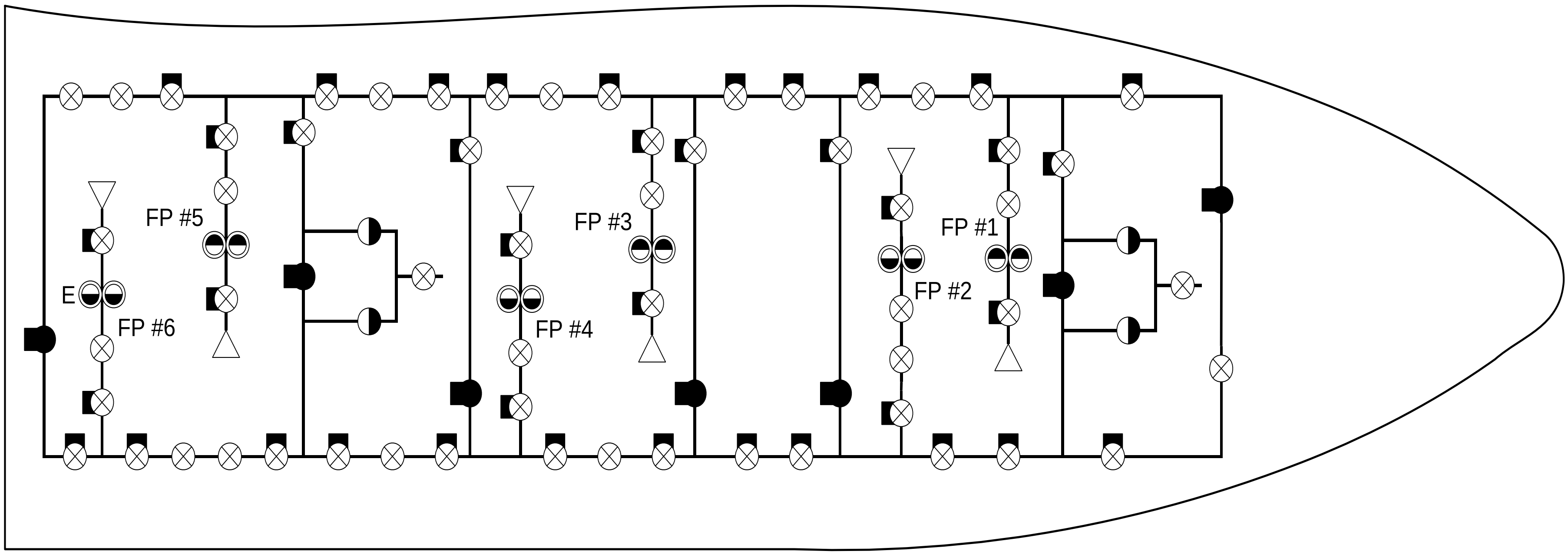
Evolutionary/Adaptive Testing

Identify failure modes in complex systems

Engineers can only test a small fraction of all possible configurations and damage scenarios

Possible to find small investments that will dramatically improve robustness? i.e., better design

Design Testing – Ship Systems



USS Arleigh Burke

Icosystem Corporation, 2004

Design Testing - Ship Systems

Objectives:

- Feasibility of evolutionary testing on a shipboard control system
- Modeling ship's firemain system with local valve controls
- Evolving *challenges*
  - Pipe rupture, e.g. from torpedo attack
  - Water demand, e.g. ballasting water

Problem Statement:

- Use *evolutionary computing* to search vast space of possible challenges
- Identify particularly problematic combinations of challenges
- Study effects of random vs. correlated challenges