(Co-)Evolution of Morphologies and Behaviours

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Artificial Evolution

- In general: *Artificial evolution* is the controlled micromanipulation of genetic information from one generation to the next
  1. Variational step: choice and/or transplantation of genes
  2. Selection step: survival and continued reproduction in a protected environment

Artificial Evolution in CS

- Most related to
  - Virtual creatures
  - Virtual environment/world
  - Genetic algorithms
  - Simulation of evolution and behaviours

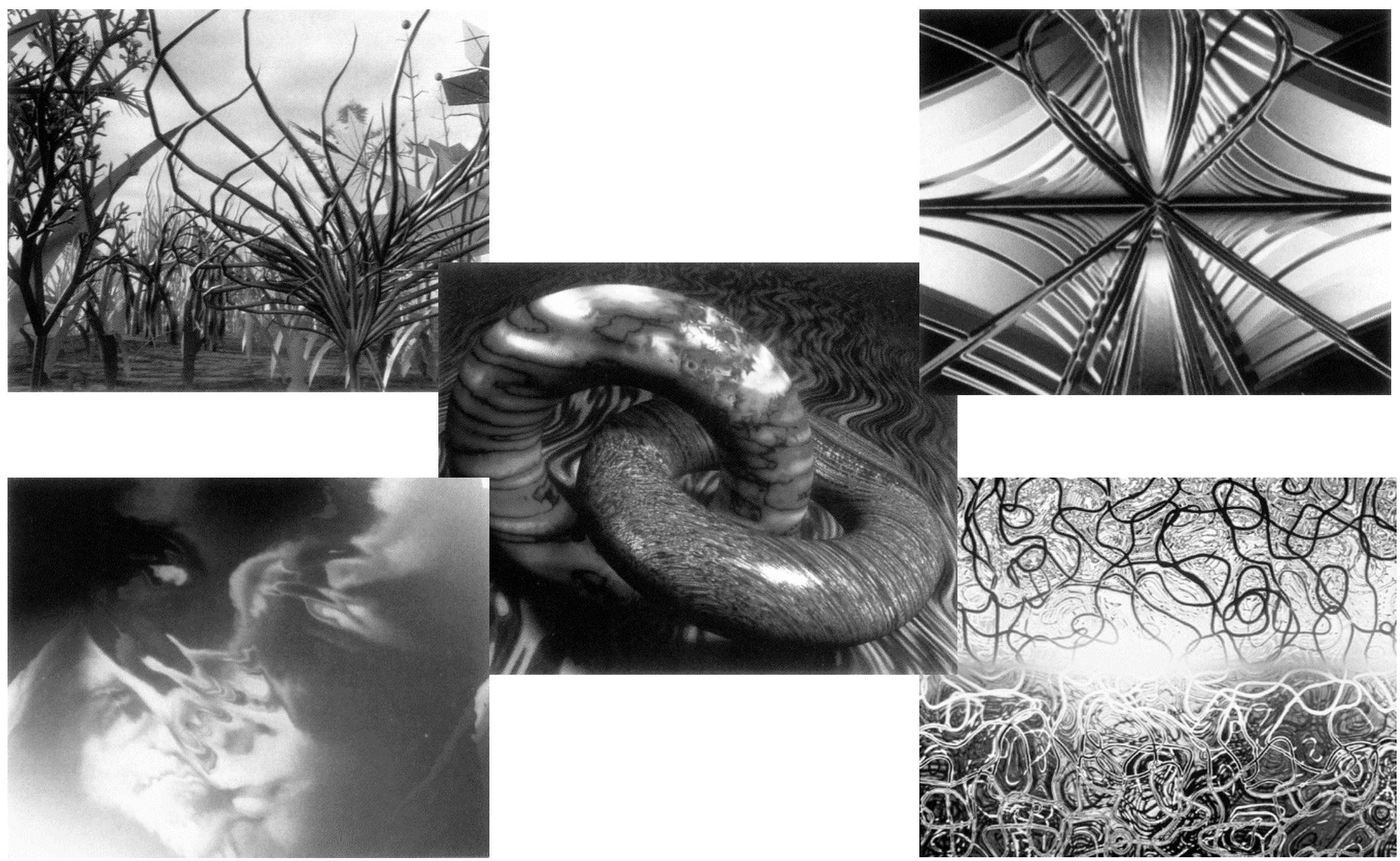
Karl Sims

- Early work: Evolution in computer graphics
- Evolving virtual creates which can swim, walk, jump, …
- Co-evolving 3D virtual creatures in competition

Evolution in Computer Graphics

- Genetic Algorithms
- Use Lisp symbolic expressions as the genotypes
- Unlimited length in genotypes parameters and expression rules

Some Evolved Graphics



Evolving Virtual Creatures

- Representation of the creatures
  - Morphology
  - Control
- Evolution
- Simulation

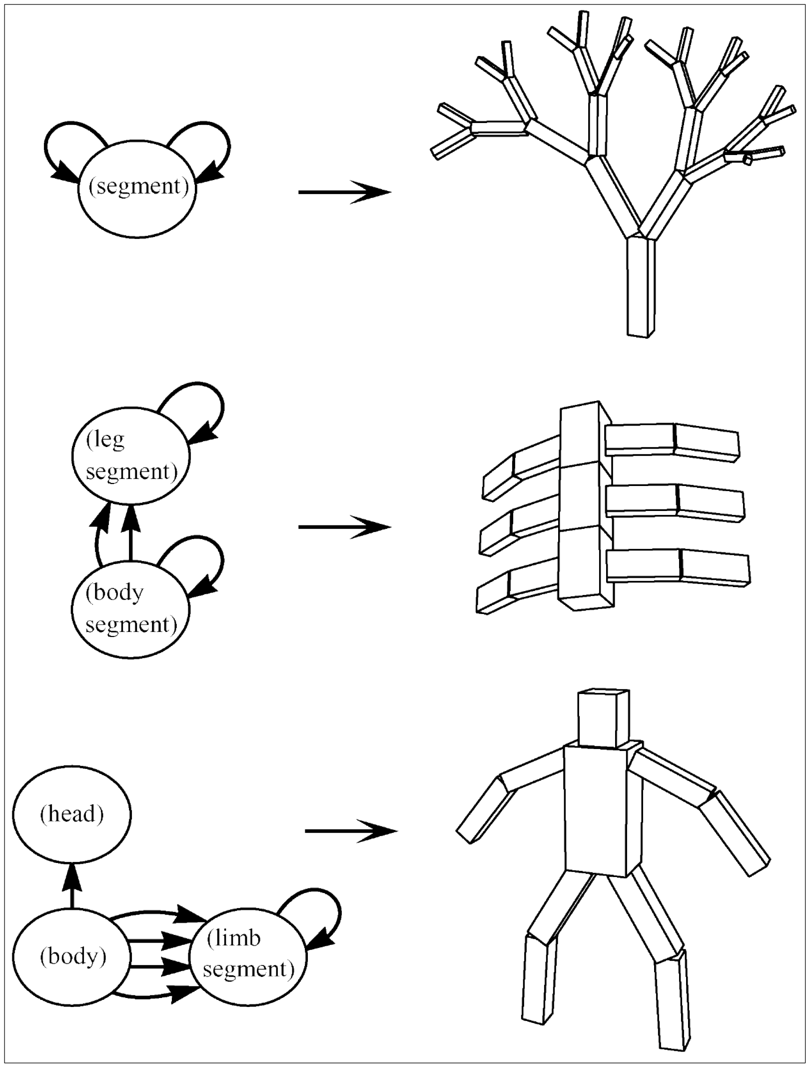
Morphology

- Phenotype: Hierarchy of 3D parts
- Genotype: Directed graph
  - Nodes indicate the corresponding rigid part; links indicate how the rigid parts are connected
  - The virtual creature is developed from the defined *root-node*, following all the connections
  - The connections can be recursive and duplicated!

Information Stored

- Nodes:
  - Dimensions (rigid shape, size, …)
  - Joint-type (rigid, revolute, twist, …)
  - Recursive-limit
  - Local neurons
- Connections:
  - Position, orientation, scale, reflection
  - Terminal-only (for hand-like rigid)

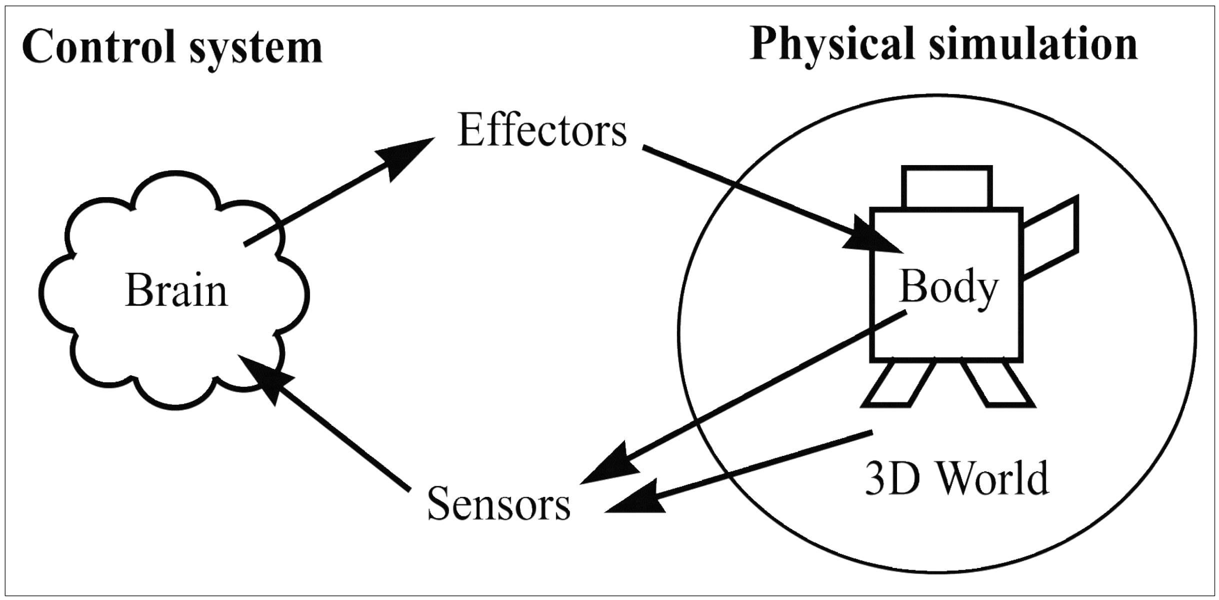
Example of Morphology



- The parameters are omitted
- The labels “body”, “leg” do not actually exist in the genetic expression

Control

- Sensors → "Brain" → Joints



Control

- Sensors
  - Spread in each part of the body
- Sensor types:
  - Joint angle sensors
  - Contact sensors
  - Photo-sensors

Control

- Neurons:
  - Internal neural nodes: enable arbitrary behaviours
  - Different neural nodes can perform diverse functions*: sum, product, divide, sum-threshold, greater-than, sign-of, min, sigmoid, …

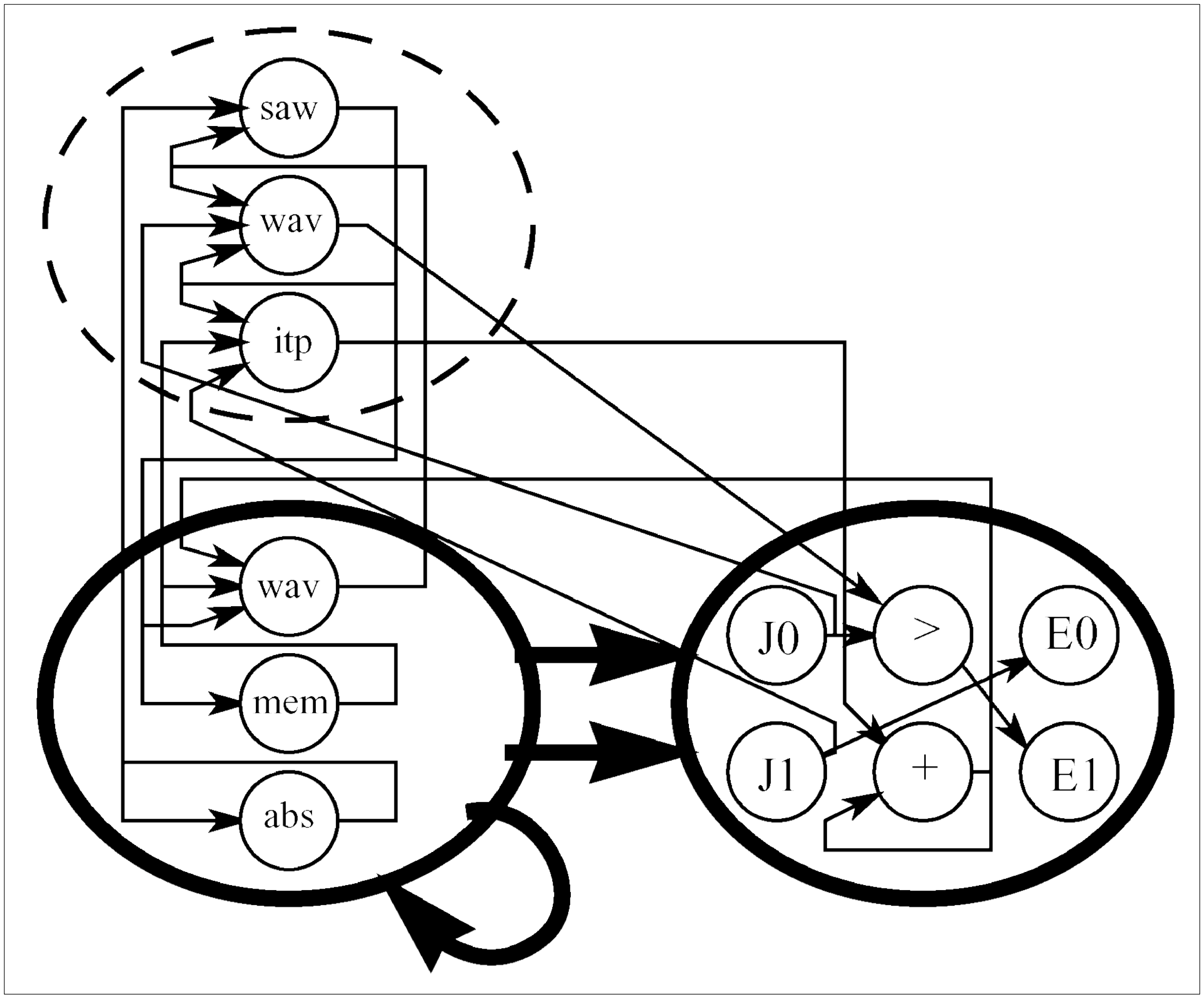
Control

- Effectors:
  - Receive the input from sensors and neural nodes, and then execute joint force, resulting the behaviour of the creature
  - One effector can receive positive or negative inputs so that it can do both “push” and “pull”*

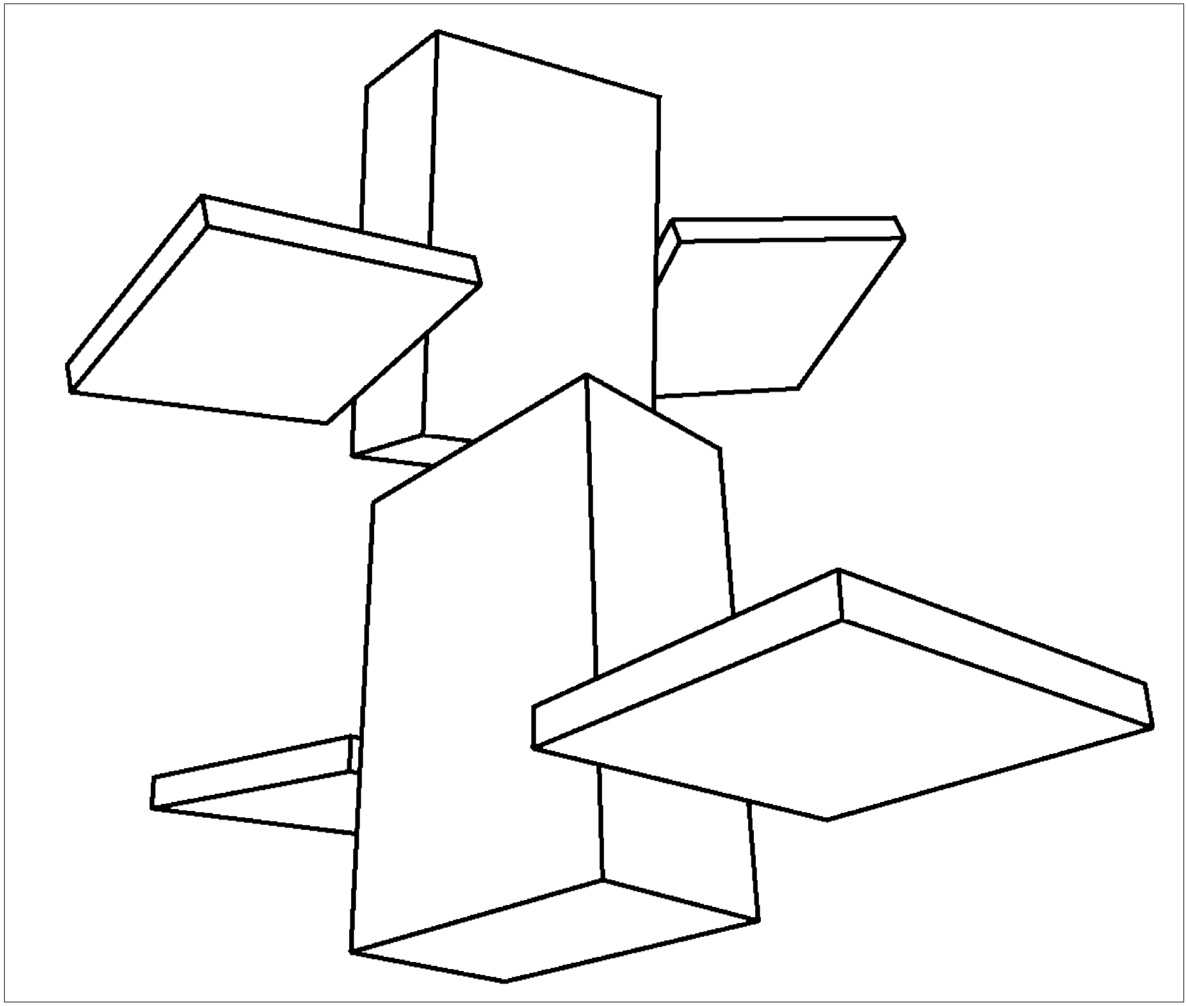
Comments on Control

* Some implementations of the control are not so biological realistic (diverse neural nodes, effectors that can “push” and “pull”), but they simplify the work

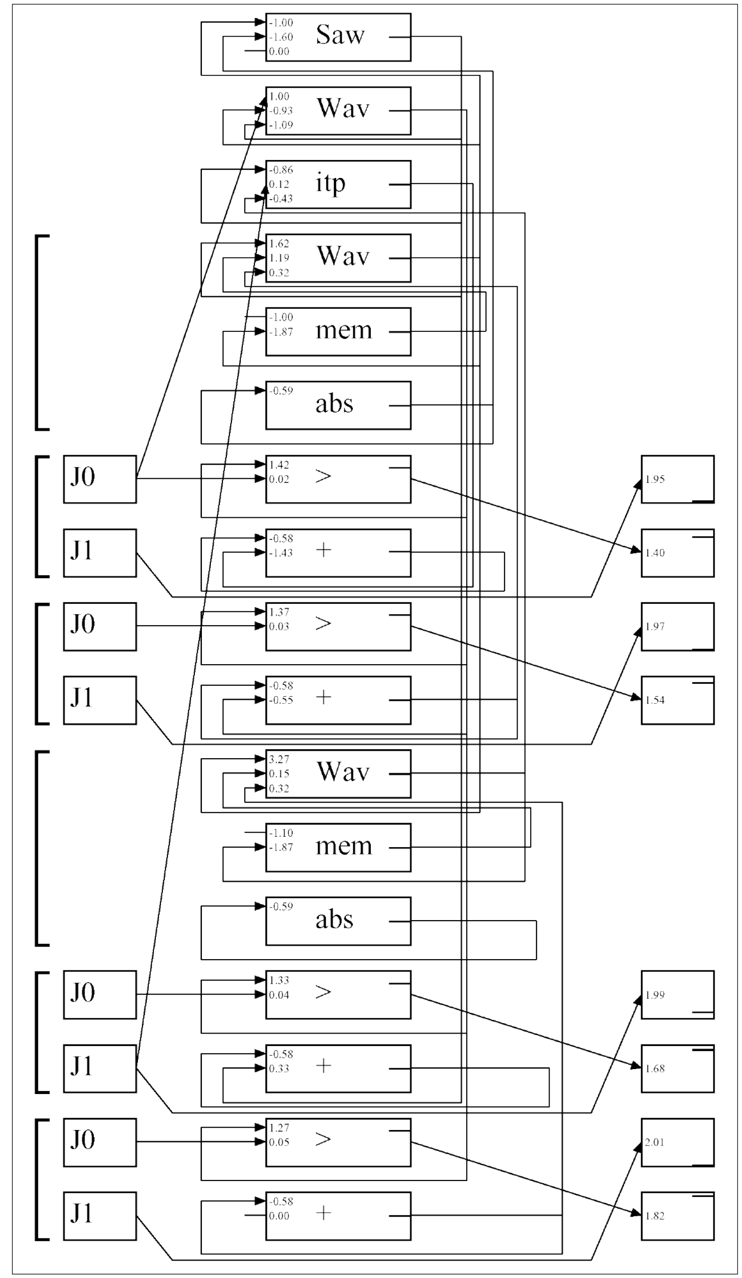
A Sample - Genotype



A Sample - Phenotype



A Sample – “Brain”

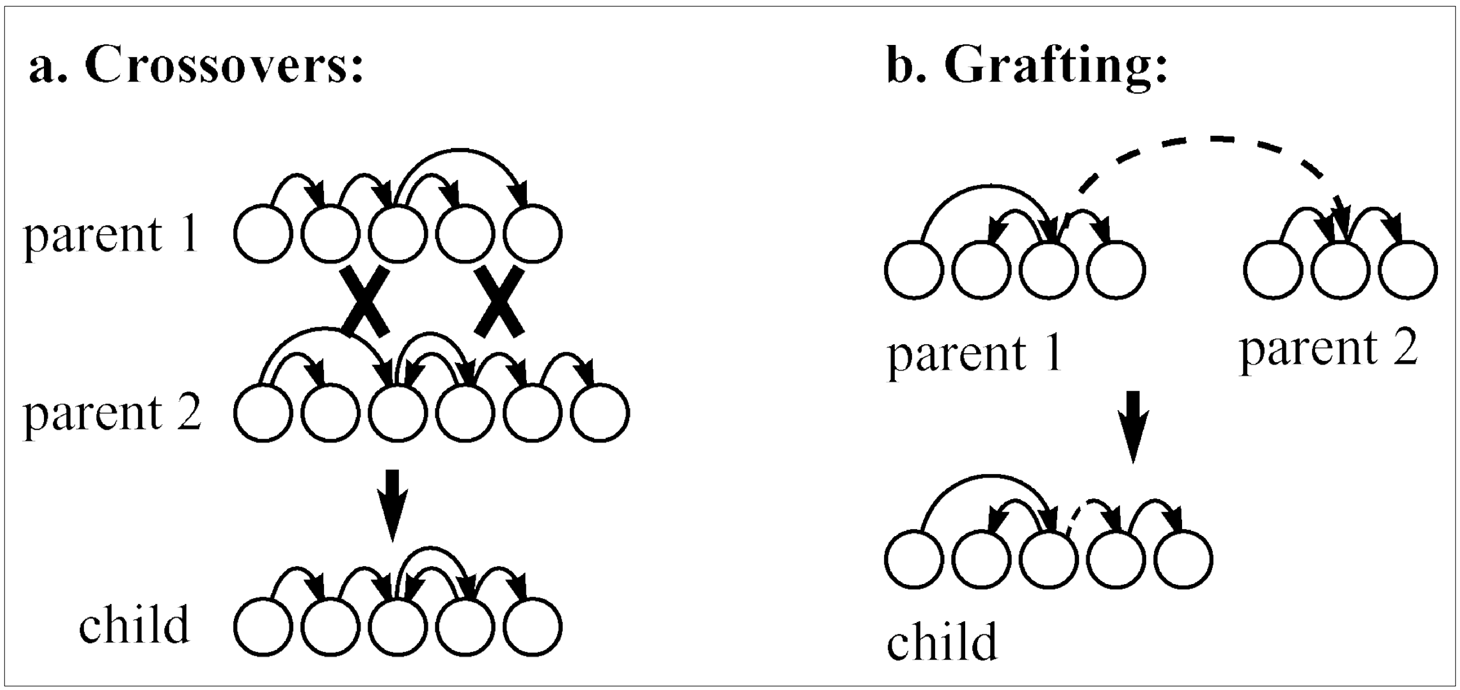


Evolution

- Mutation
  - The internal parameters of each node
  - A new random node is added
  - The parameter of each connection
  - New random connections added and old ones removed
  - Garbage collect

Evolution

- Mate



Simulation

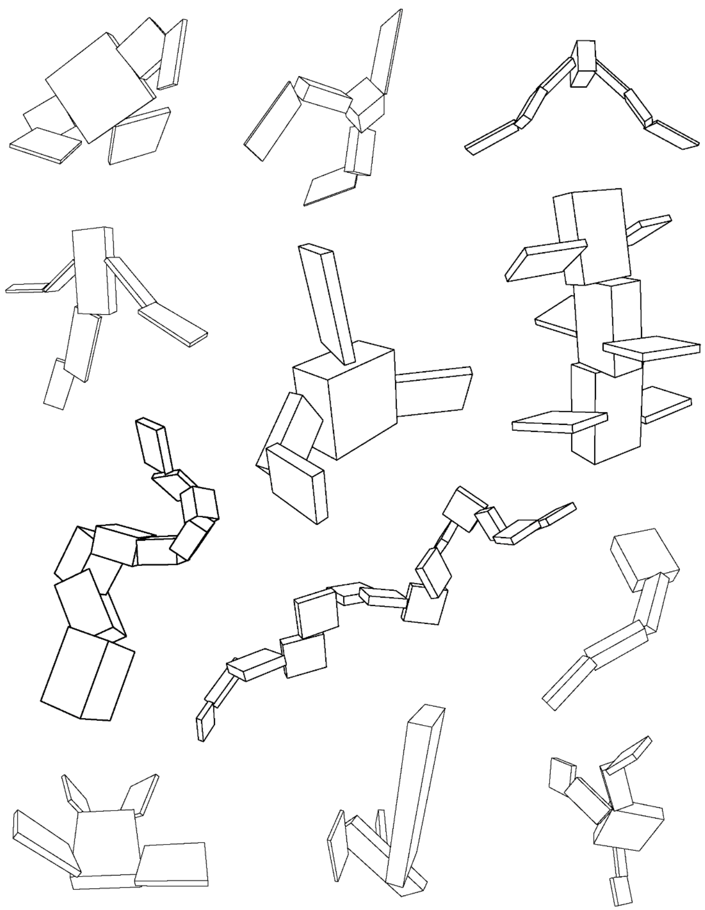
- Let the creature evolve in a virtual 3D world
- Body parts are represented by rectangular solids
- Velocities, forces, contacts and collisions are modelled
- When simulating underwater environments, viscosity is considered

Evolving towards Behaviours

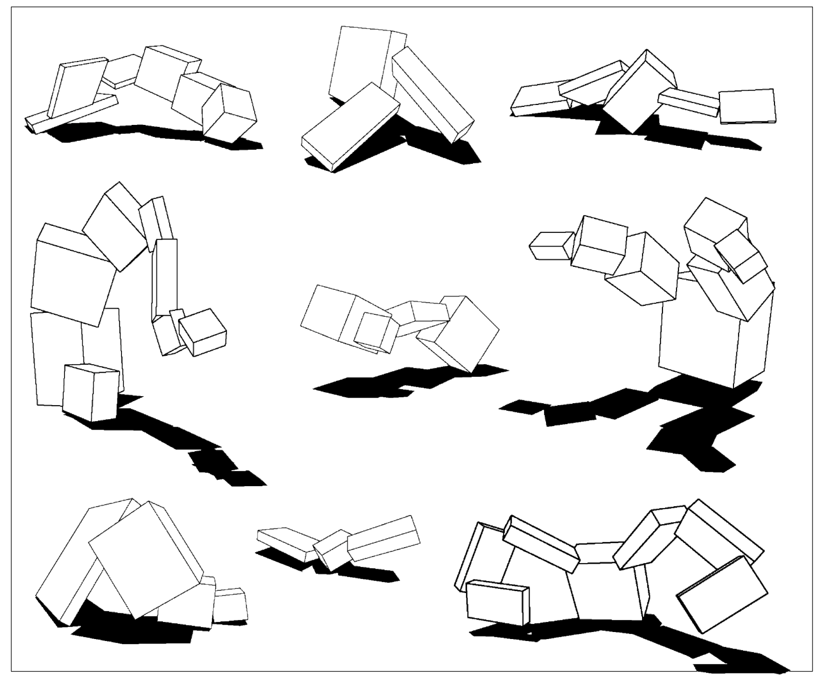
- Swimming
  - Turn off gravity; add viscosity
- Walking
  - Turn on gravity, turn off viscosity; add a ground plane with friction
- Jumping
- Following
  - Photosensors are enabled

The Results

- Swimming

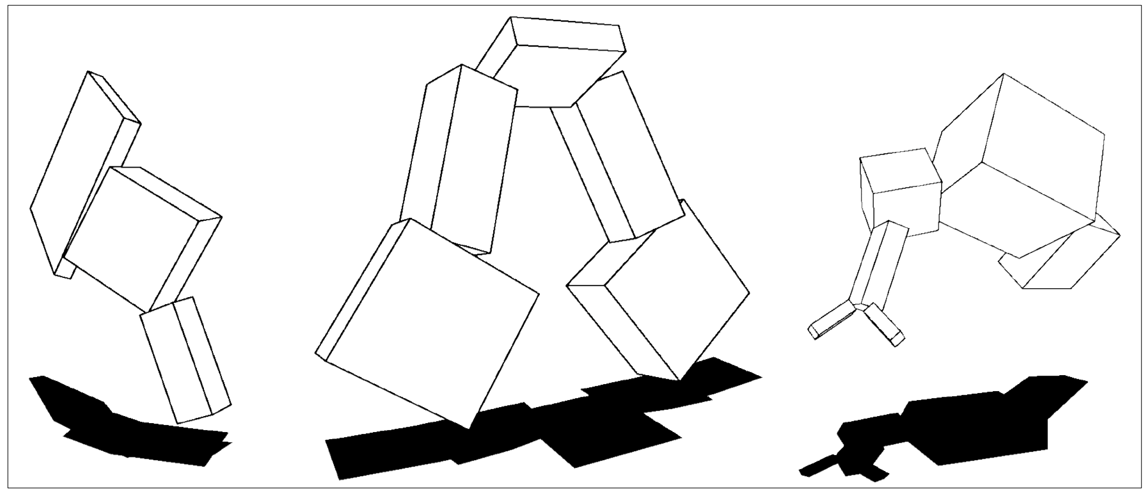


- Walking

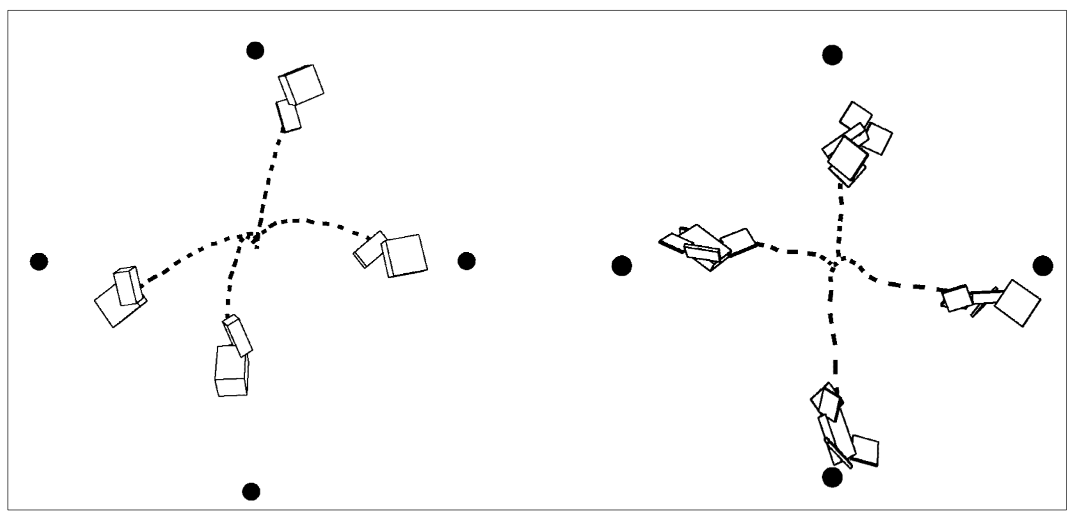


The Results

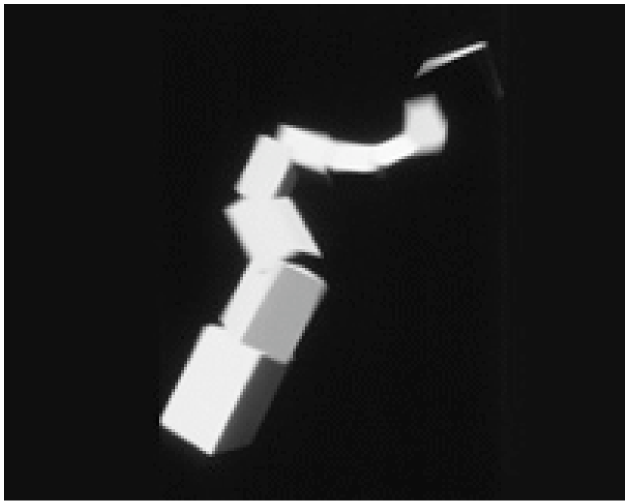
- Jumping

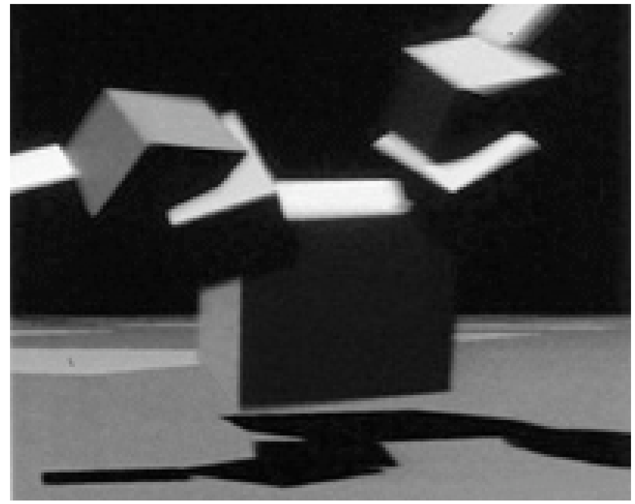


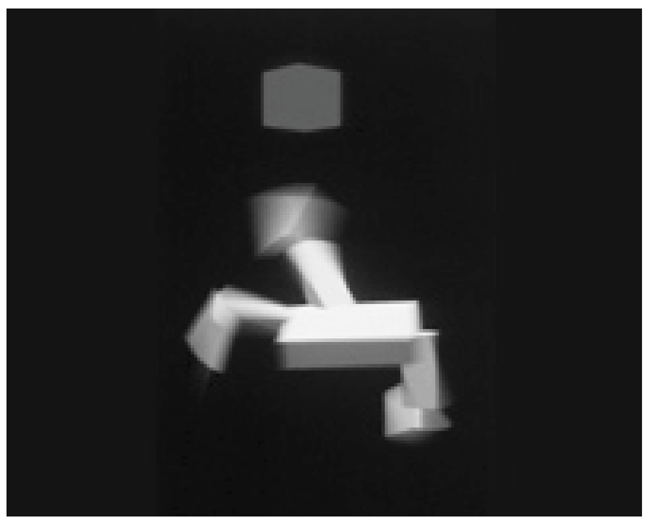
- Following



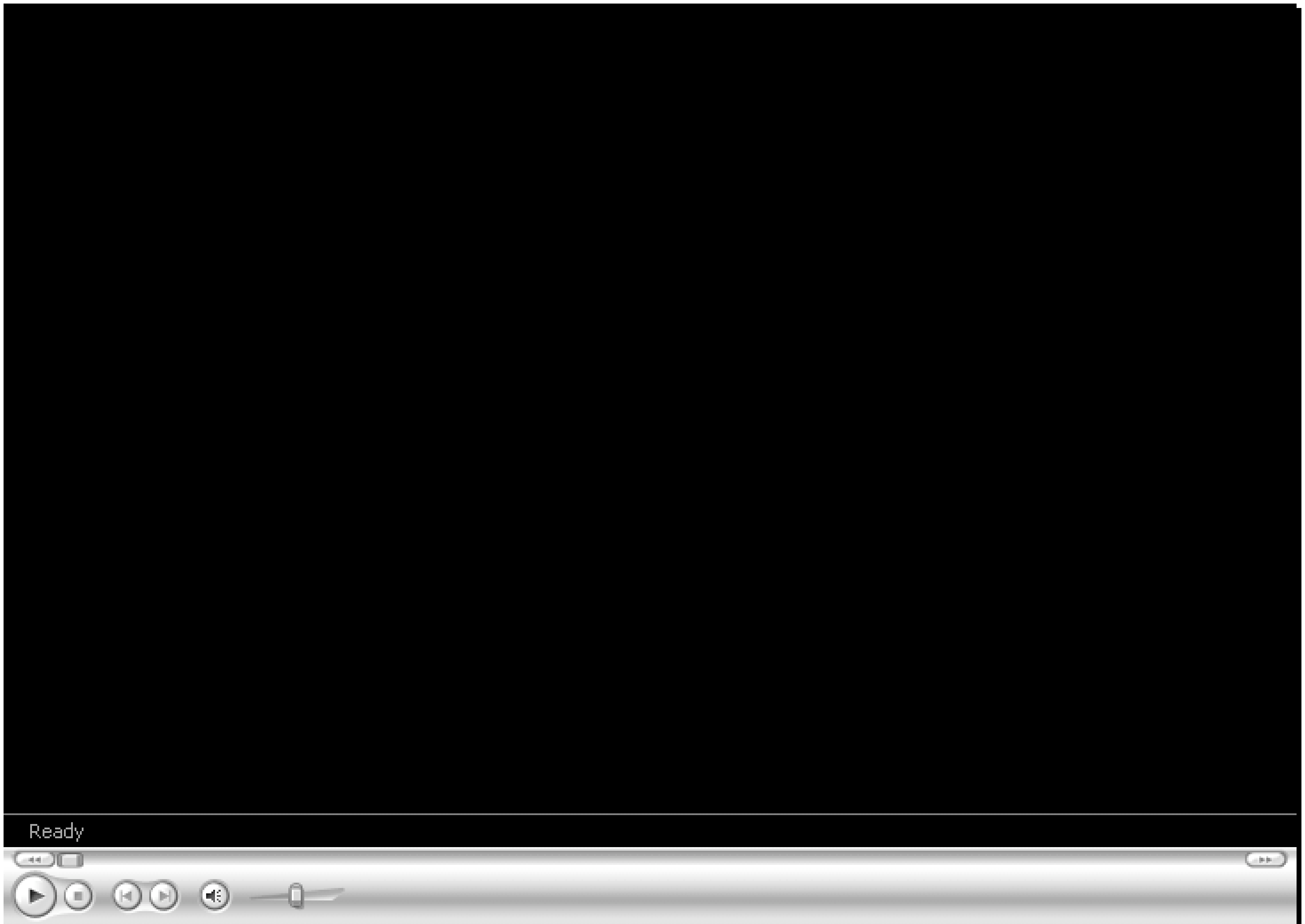
More Results





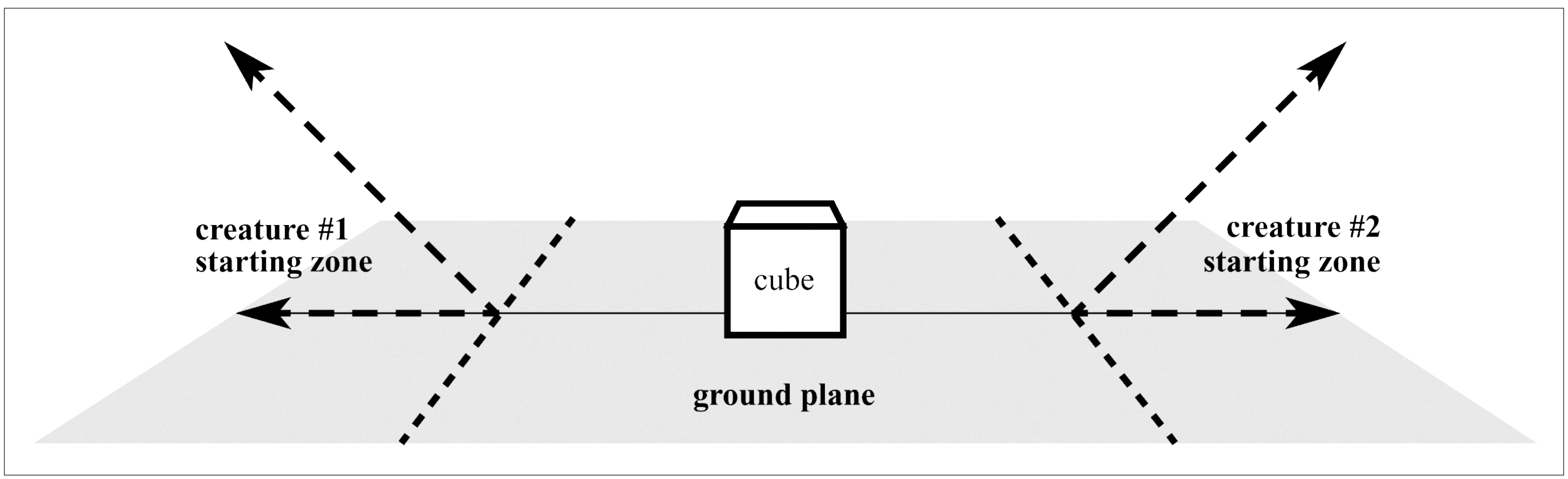


Result - Video



Co-evolution in Competition

- Design an arena for the virtual creatures to compete
  - A cube is placed in the centre of the ground plane
  - Two starting zones are assigned



Competition

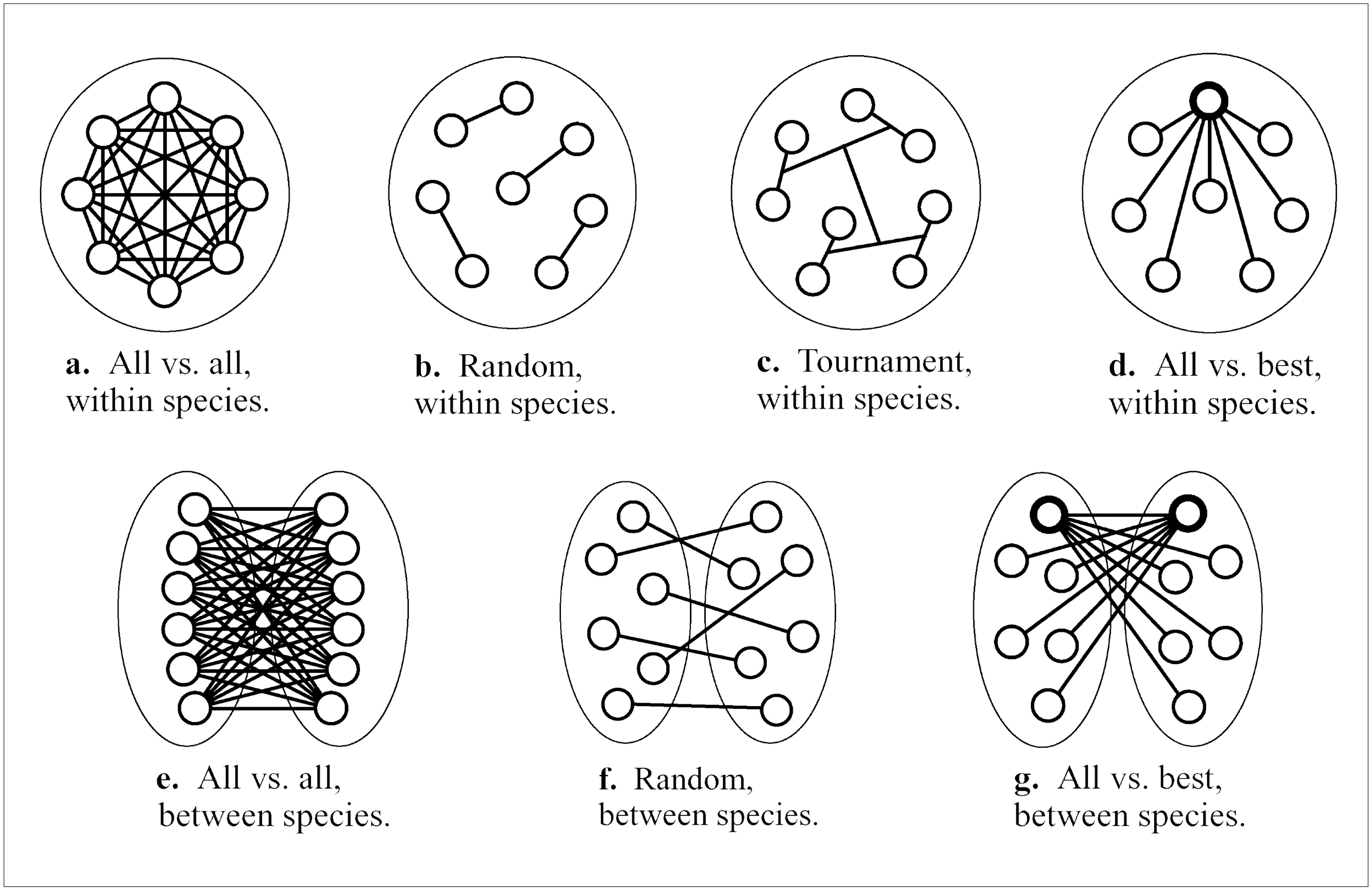
- Two creatures try to control the cube
- Start from the starting zone
- Winner: has the most control over the cube after a certain duration of simulated time

Fitness

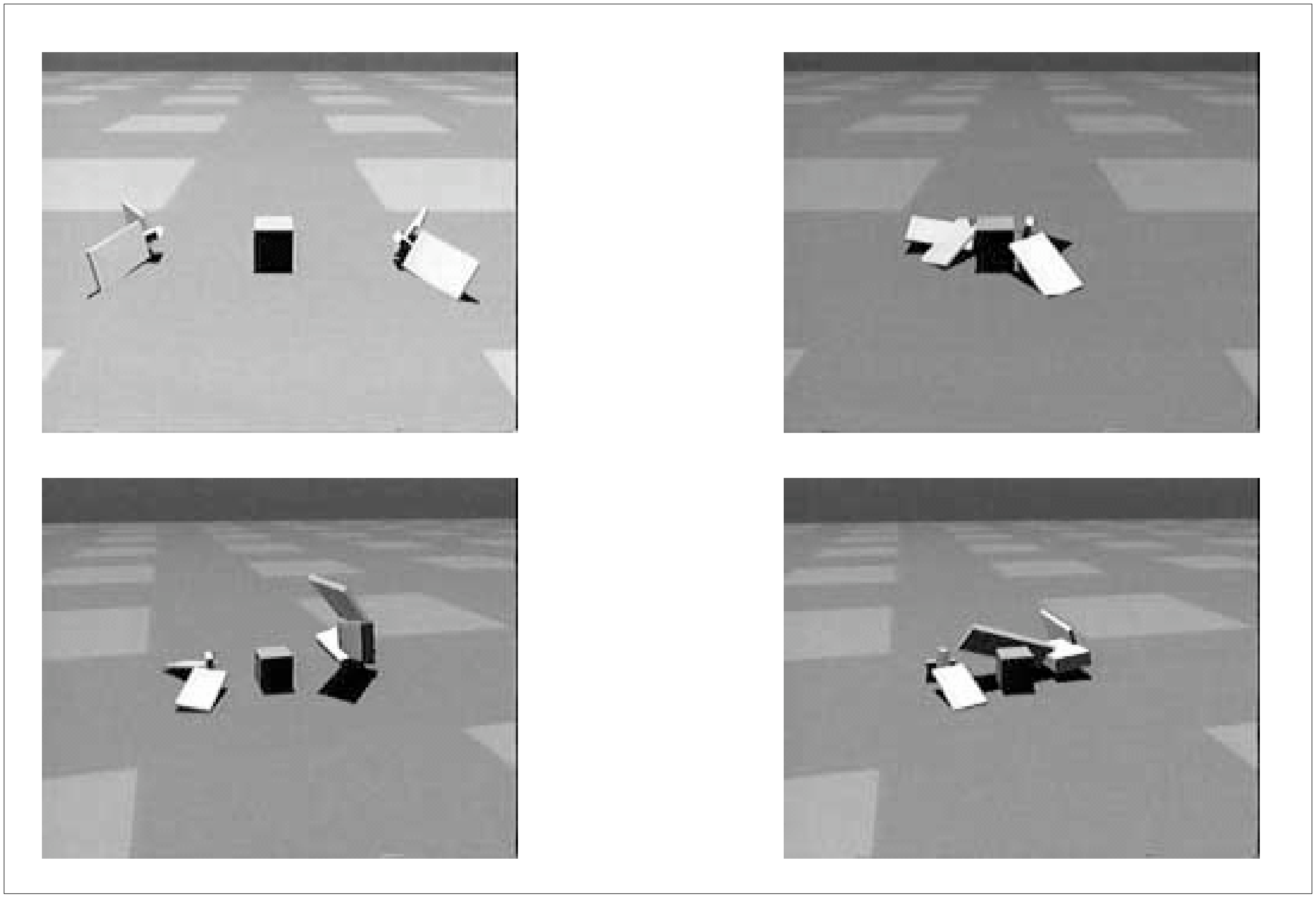
- The margin of victory: relative fitness value
- One creature being closer, or its opponent being further both cause higher score

$$f_1 = 1.0 + \frac{d_2 - d_1}{d_1 + d_2} \qquad f_2 = 1.0 + \frac{d_1 - d_2}{d_1 + d_2}$$

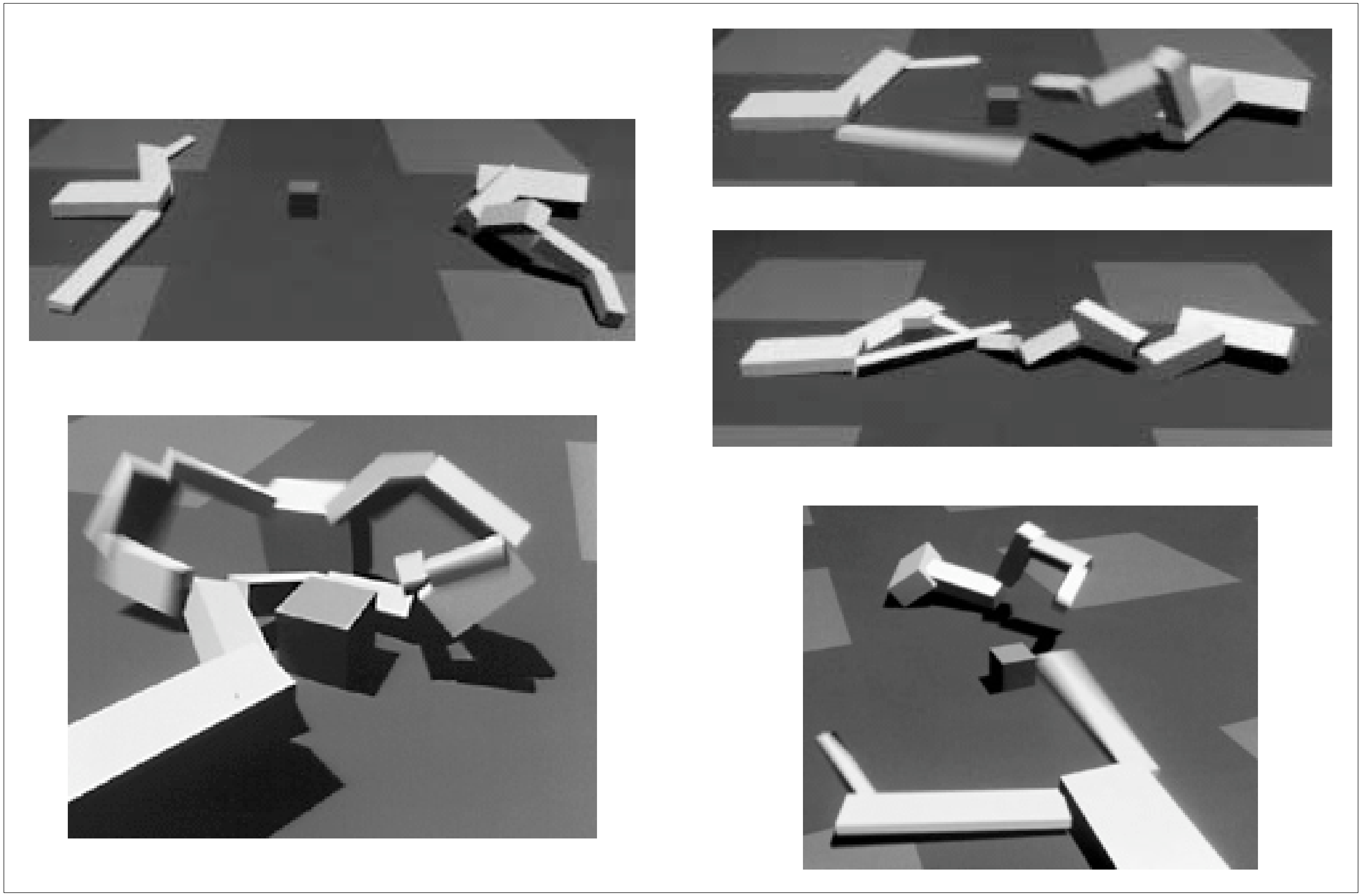
Competition Patterns



Results - Simple



Results -Complicated



From Virtuality to Reality

- The Golem project …

Golem

- Introduction
- Automatic Design
- Simulator
- Automatic Fabrication
- Results
- Future Direction

Introduction

- Golem Project
  - (Genetically Organized Lifelike Electro Mechanics)
  - http://demo.cs.brandeis.edu/golem/
- Motivation
  - To have robotically designed and robotically fabricated robots.

Introduction cont…

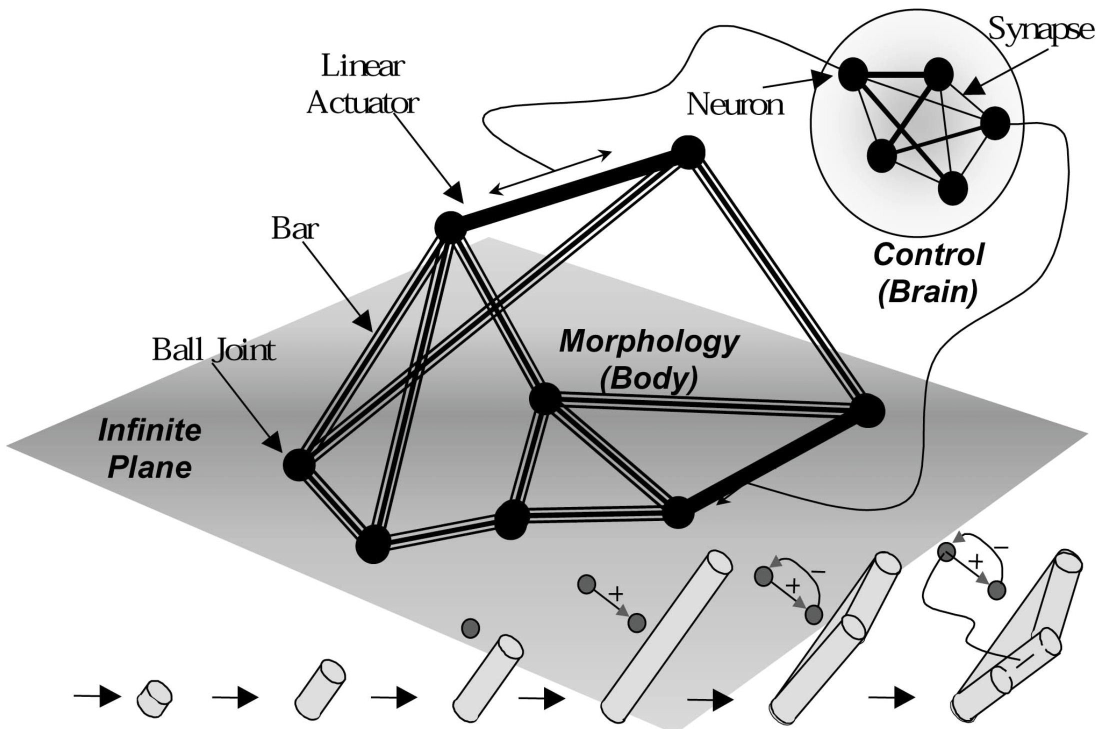
- Differentiation between Karl Sims work and Golem
  - Complexity of behaviour
  - Methods for fitness evaluation
  - End result
    - Simulated vs Physical

Automatic Design

- Basic Design
  - Use only elementary building blocks and operators in the design and fabrication process
  - Structural (Morphology) building blocks
    - Bars and actuators
  - Control building blocks
    - Neurons and synapses

Automatic Design

- Schematic illustration of an evolvable robot



Automatic Design cont…

- Robot Representation

Robot:=(vertices)(bars)(neurons)(actuators)

Vertex:=(x,y,z)

Bar:=(vertex 1 index, vertex 2 index, relaxed length, stiffness)

Neuron:=(threshold, synapse coefficients of connections to all neurons)

Actuator:=(bar index, neuron index, bar range)

Automatic Design cont…

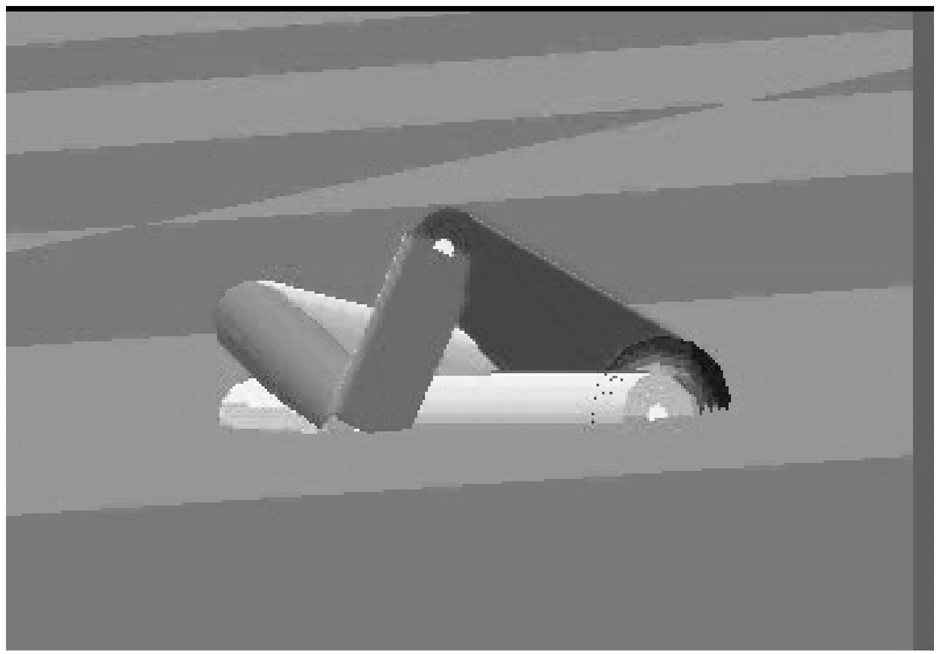
- Evolution Procedure
  - Start population of 200 machines
    - Zero bars and zero neurons
  - Fitness determined by locomotive ability
    - Net distance that the centre of mass moved on an infinite plane in a fixed duration
  - 300 600 generations typical

Automatic Design cont…

- Notes on Evolution
  - Body (morphology) and brain (control) evolve simultaneously
  - At minimum, neural network generating varying output must connect to an actuator for any motion to occur
    - Can take tens of generations

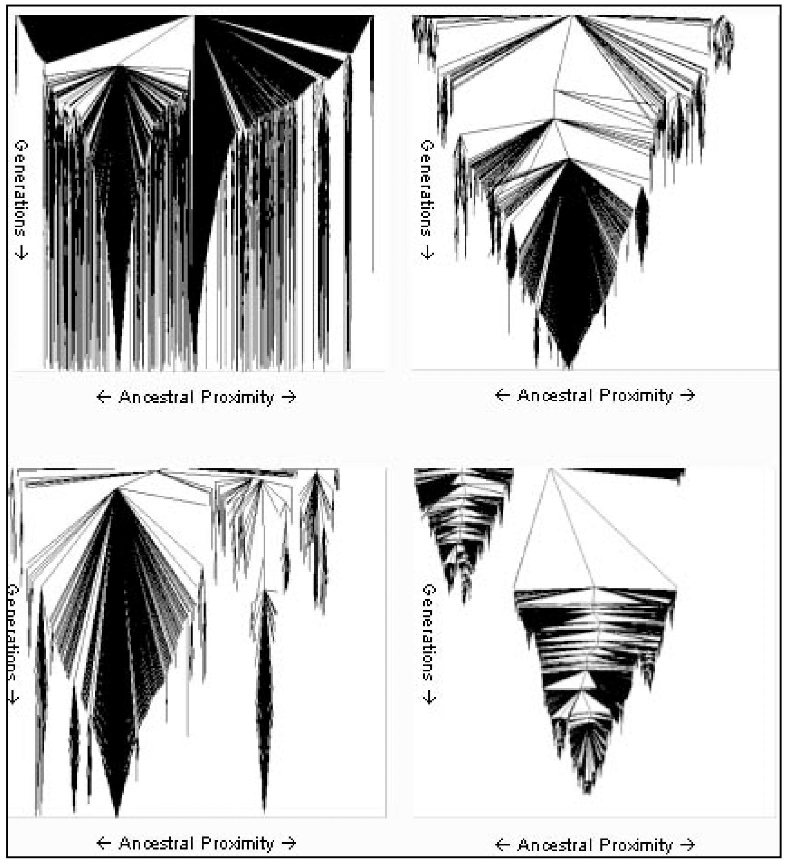
Automatic Design cont…

- Typical evolution process:



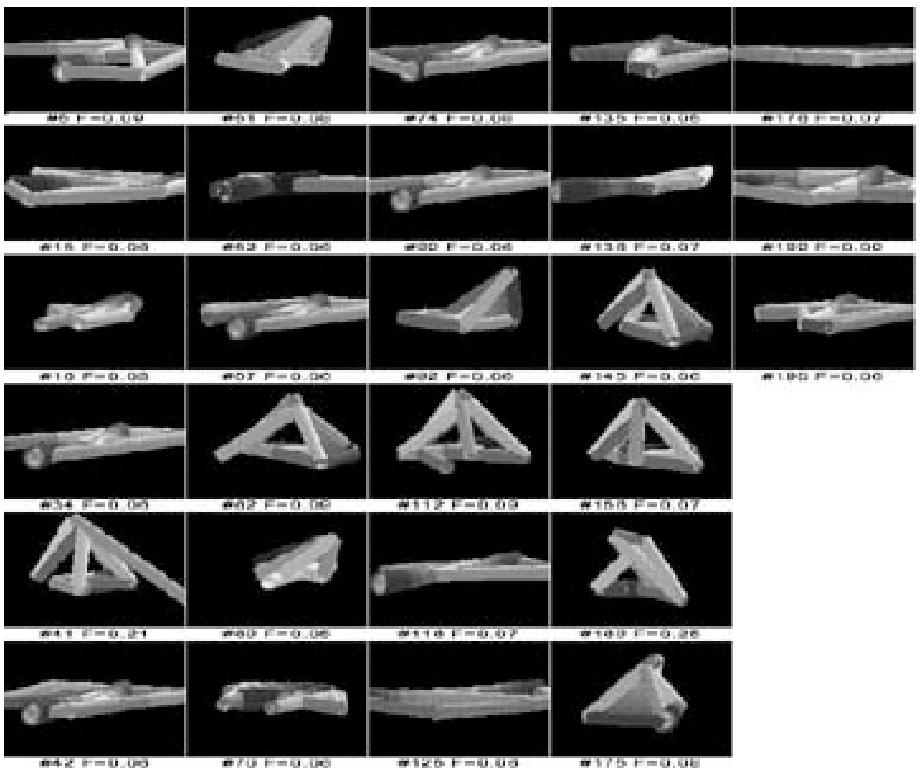
Automatic Design cont…

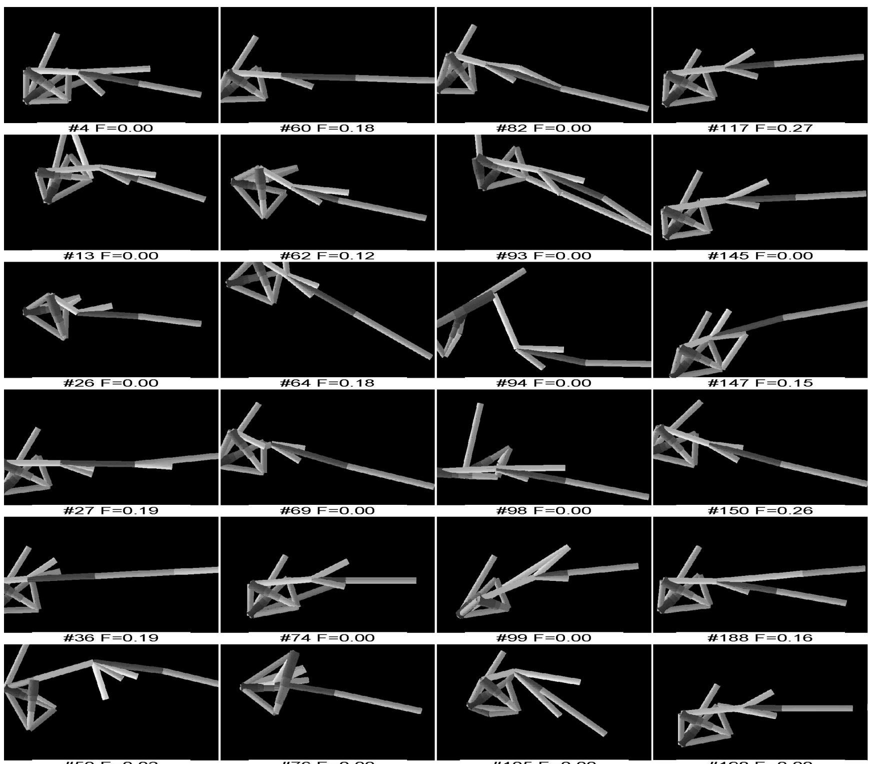
- Various Evolutionary Patterns



Automatic Design cont…

- Two samples of entire generations



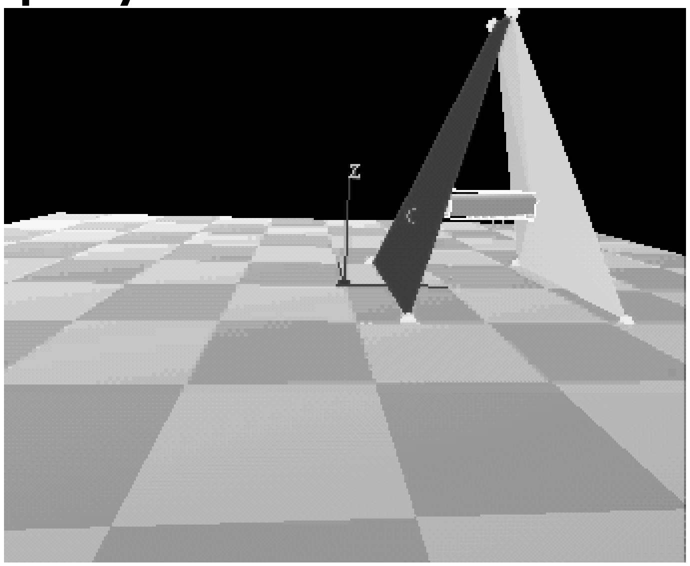


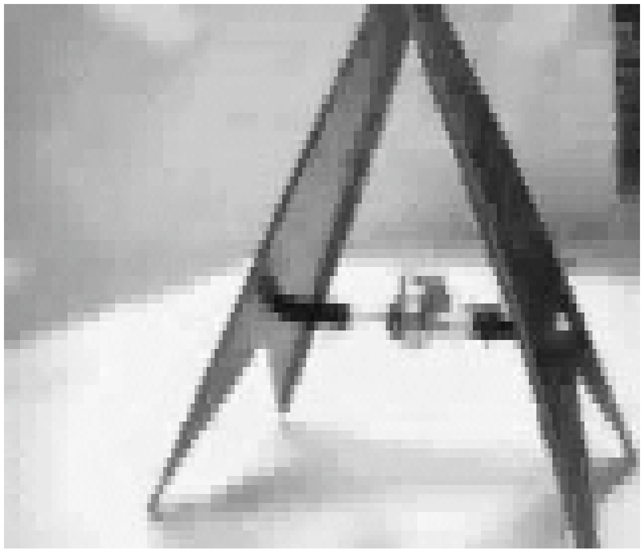
Simulation

- The mechanics and the neural network are simulated concurrently
- Supports low-momentum motion like crawling and walking but not jumping
- Modelled material properties correspond to that of the rapid prototyping process

Simulation

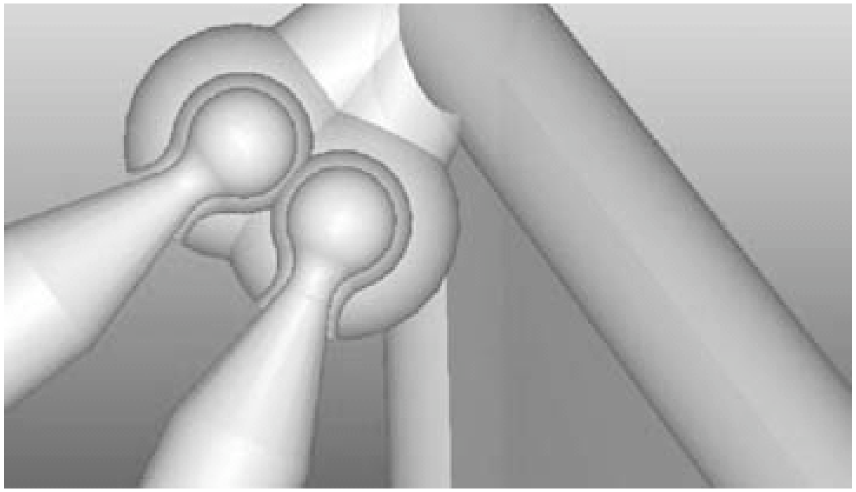
- Comparison of simulation to physical model

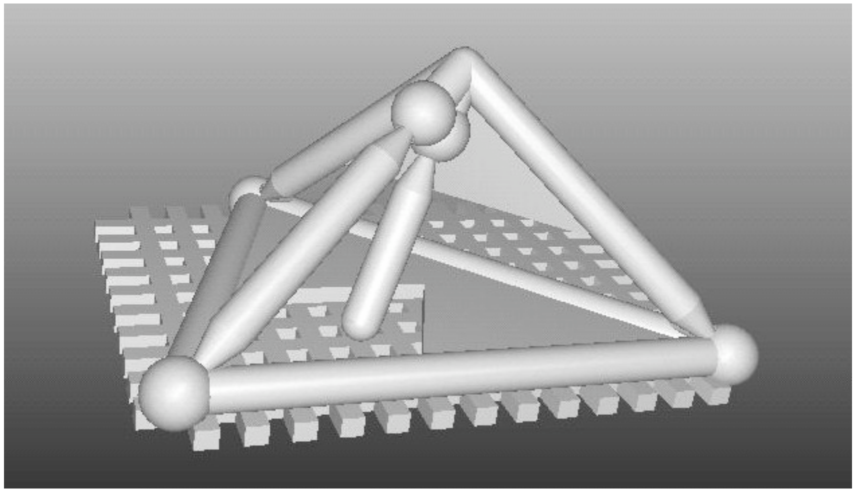




Automatic Fabrication

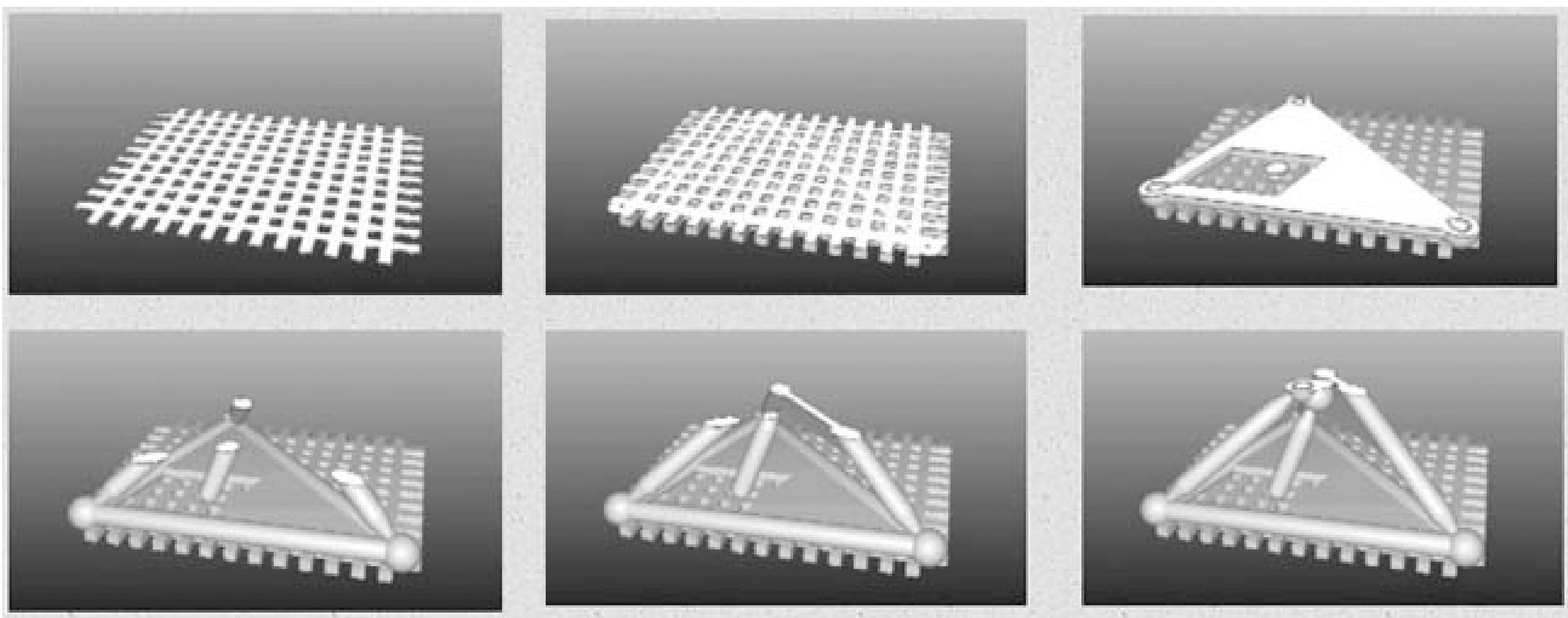
- Robots are automatically expanded into solid computer models





Automatic Fabrication

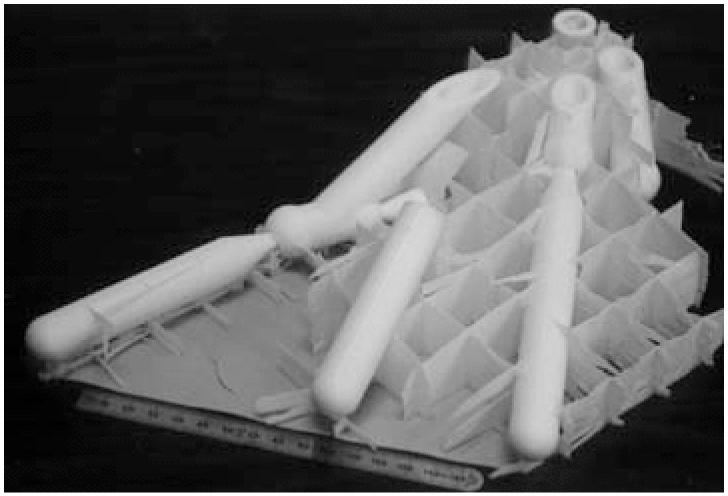
- Solid bodies created

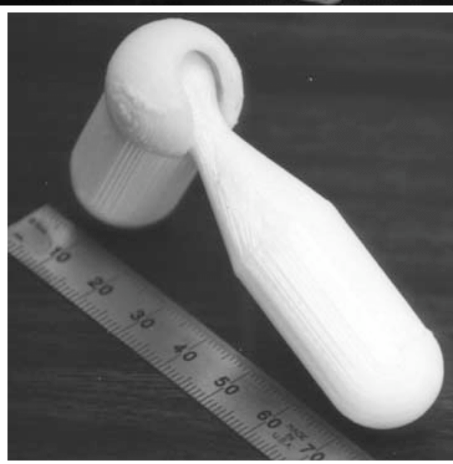


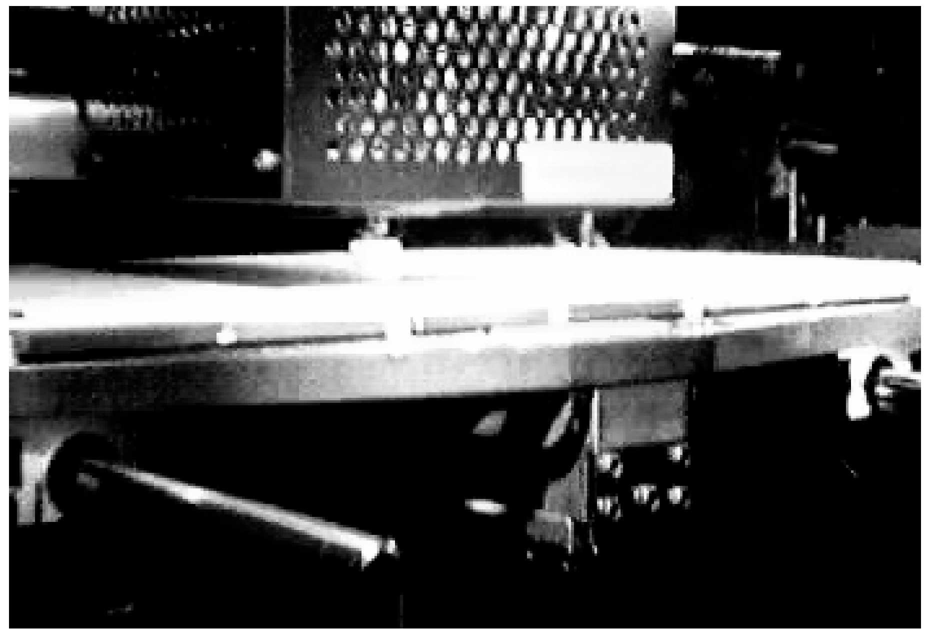
Automatic Fabrication

- Notes
  - Robots assembled as one unit
  - Humans snap in motors and connect microcontrollers
    - Extent of human input
  - Evolved neural network is executed on microcontroller to activate motors

Automatic Fabrication







Results

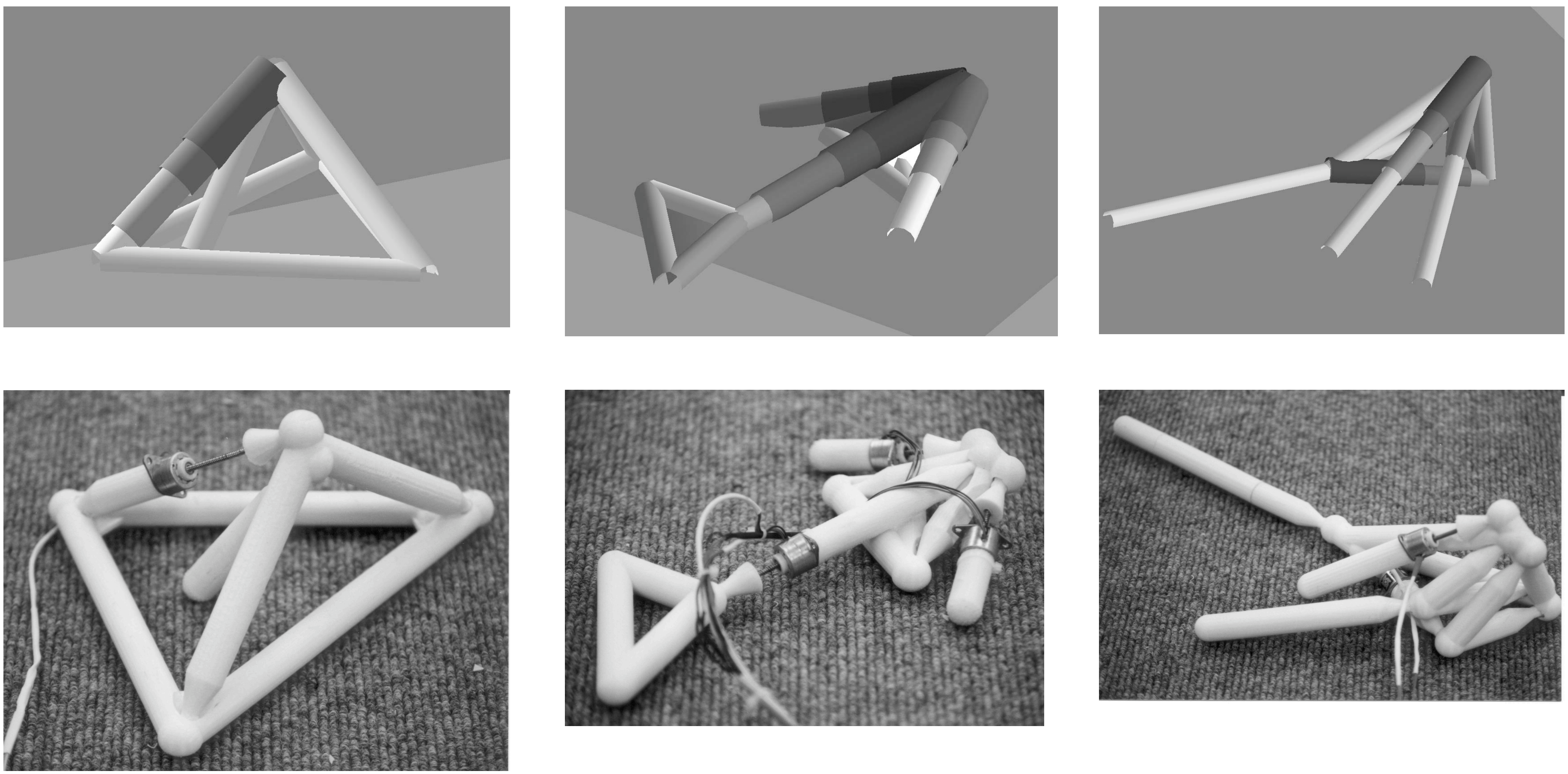
- Robots typically contained 20 building blocks
- Significant redundancy present in some robots
- Symmetry exhibited in some robots

Results cont…

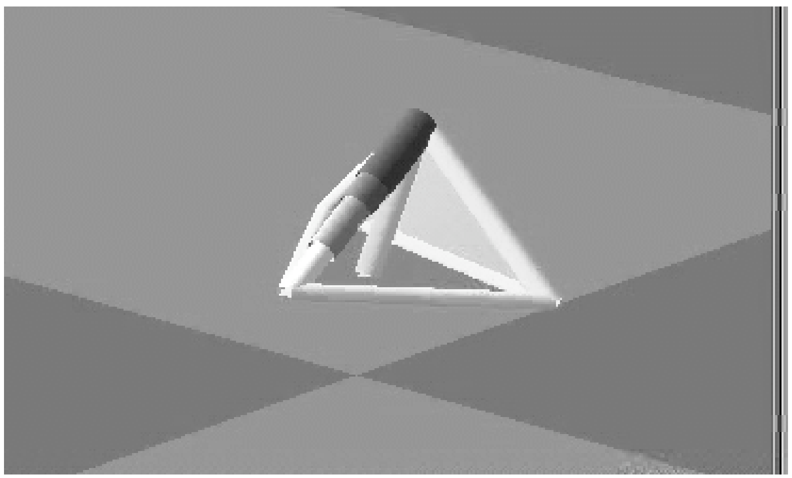
- Distance travelled over 12 cycles of neural control

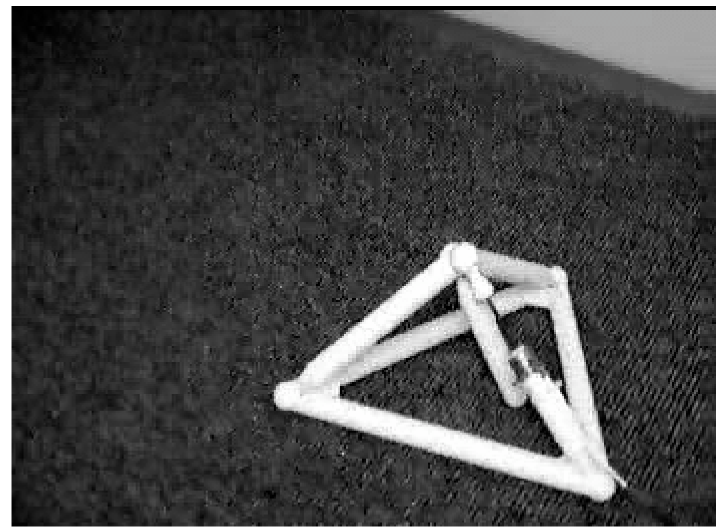
Machine	Virtual (cm)	Physical (cm)
Tetrahedron	38.5	38.4
Arrow	59.6	22.5
Pusher	85.1	23.4

Results cont…



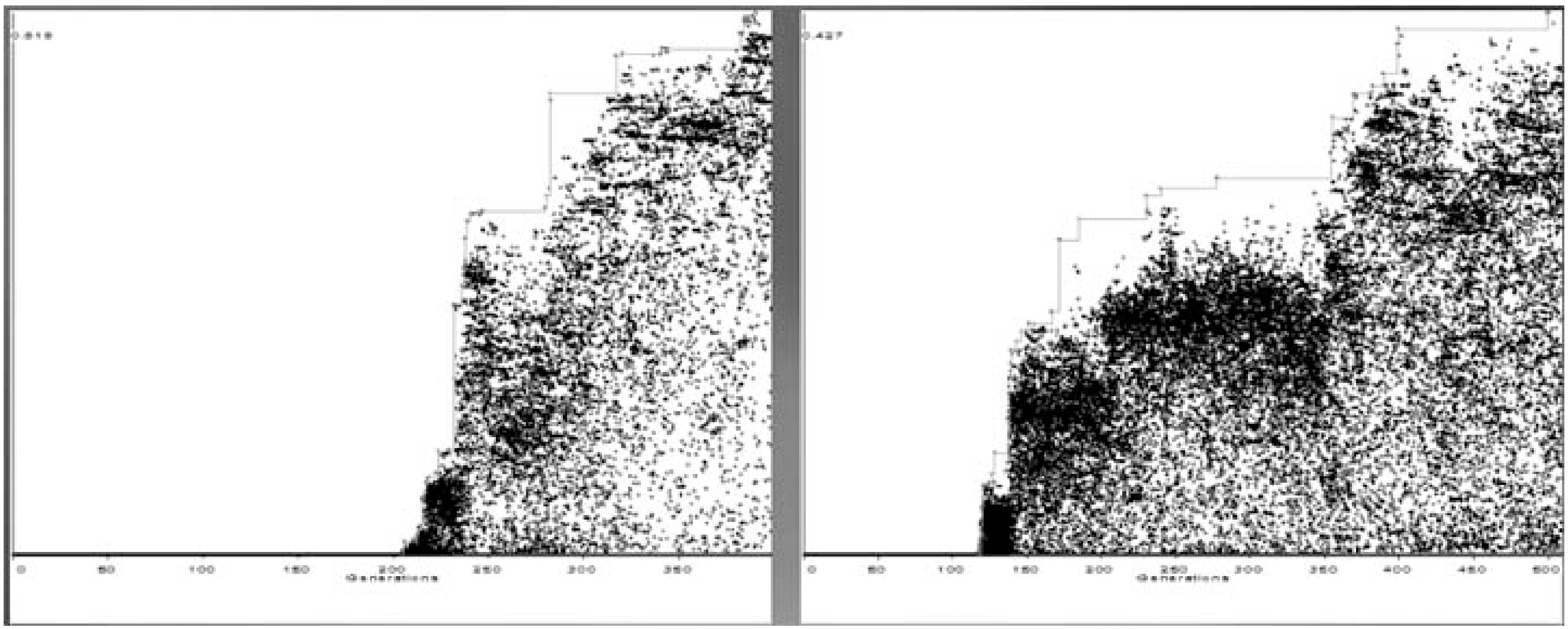
Results cont…





Future Direction

- Slowing fitness over time



Discussion