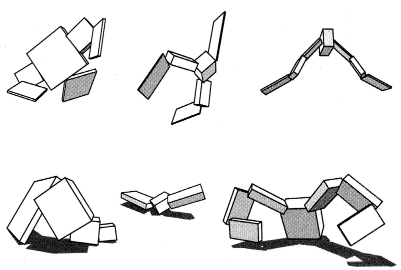
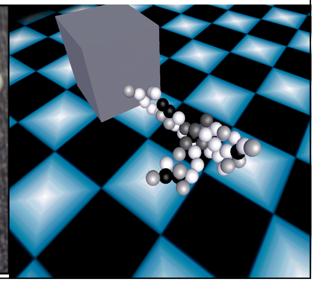
Neural Networks
25 May 2012

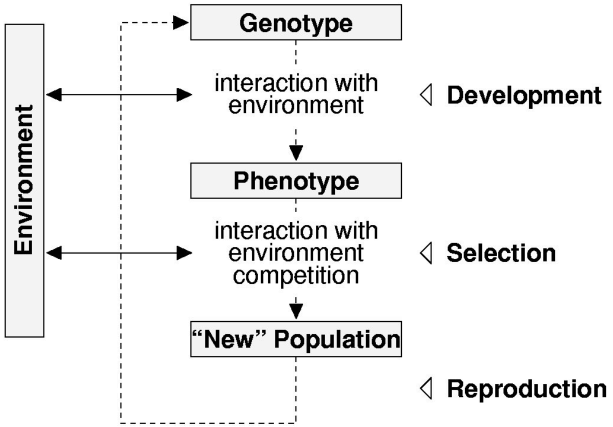
- morphological computation
- co-evolution of brain and body
- DAC: Distributed Adaptive Control

Co-evolution of "brain and body"

- Sims's creatures
- Golem's 3D-printed crawlers
- Bongard's "block pushers"



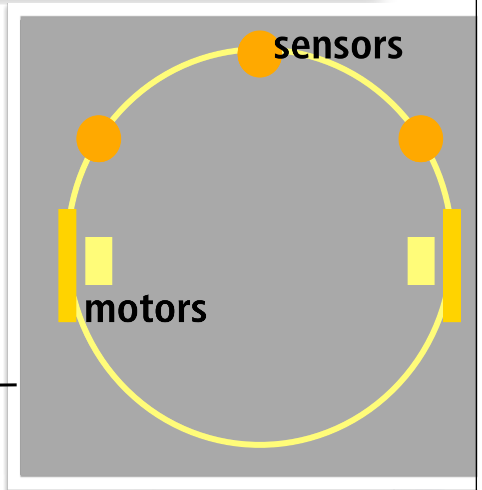




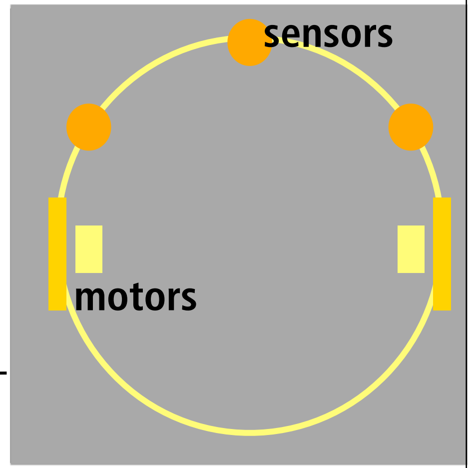
The "grand evolutionary scheme"

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

Evolving a neural controller

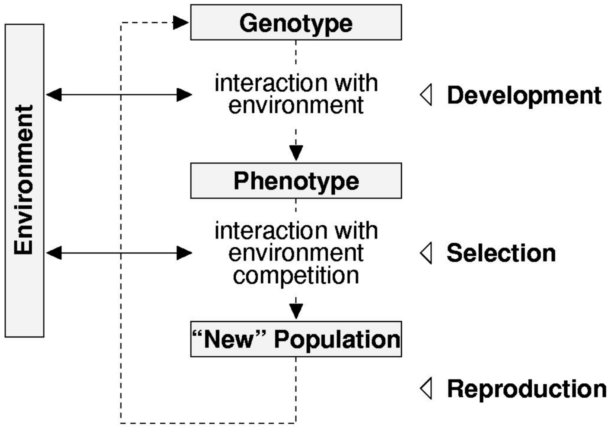


Encoding in genome



	1	2	3	4	5	6
initial genome	0011	0101	0010	0111	1010	1010
encoded weights	-.3	-.17	-.37	.03	.17	.17

The "grand evolutionary scheme"



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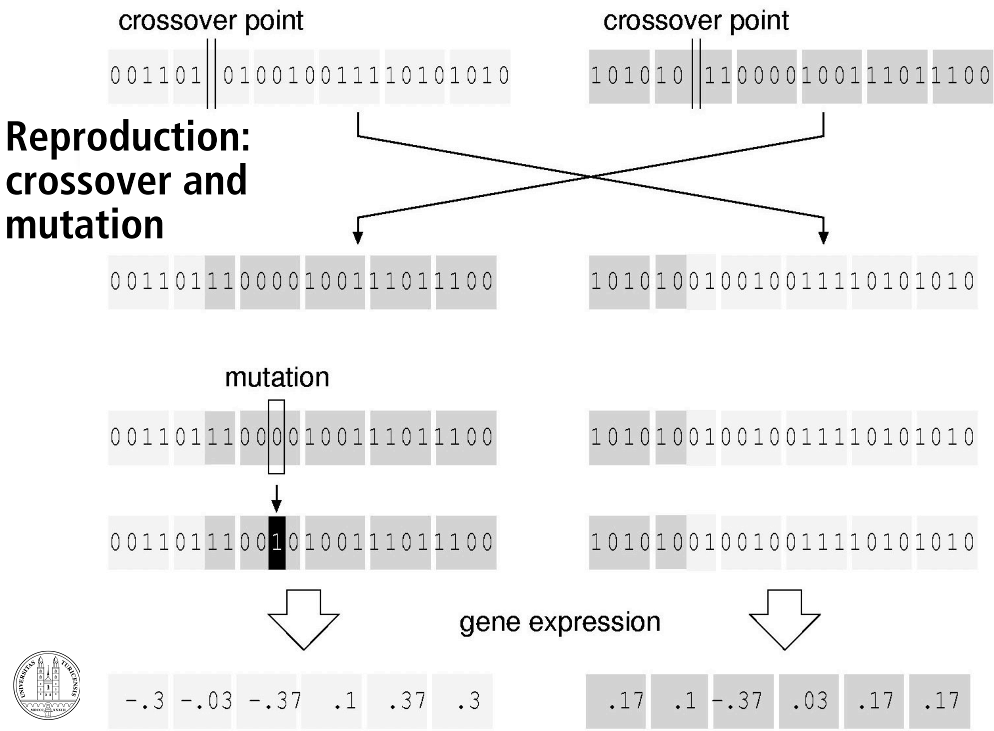
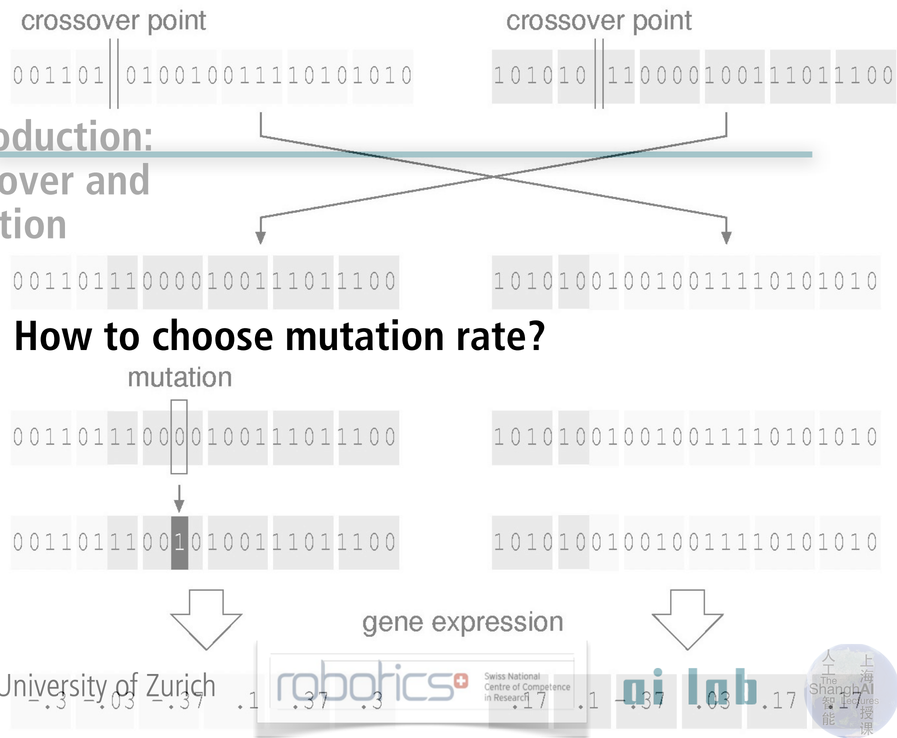
Fitness function and selection

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

Fitness function: two components
1. speed —> positive
2. collisions —> negative


crossover point
001101 010010011110101010
crossover point
101010 110000100111011100
Reproduction: crossover and mutation
001101110000100111011100
101010010010011110101010
mutation
001101110000100111011100
101010010010011110101010
001101110010100111011100
101010010010011110101010
gene expression
-.3 -.03 -.37 .1 .37 .3
.17 .1 -.37 .03 .17 .17

Reproduction: crossover and mutation



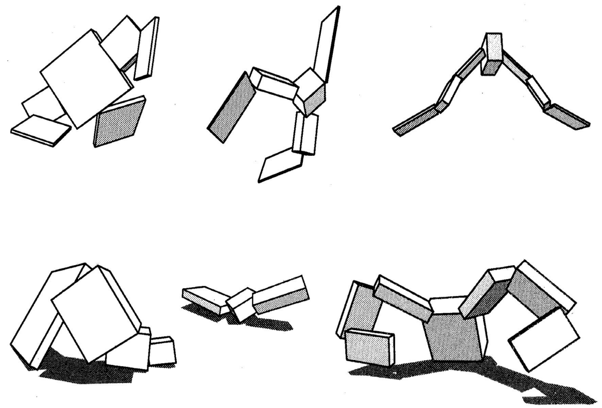
How to choose mutation rate?

Approaches to evolutionary robotics

- given robot → evolve control (neural network)
- embodied approach → co-evolution of morphology and control

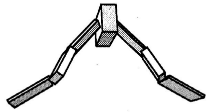
embodied approach:
1. parameterization —> Sims, Lipson and Pollack, Komosinski and Ulatowski
2. GRNs —> Eggenberger, Bongard

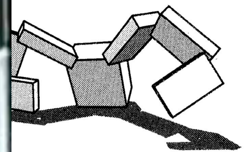
Evolving morphology and control: Karl Sims's creatures



Evolving morphology and control: Karl Sims’s creatures

Video “Karl Sims’s evolved





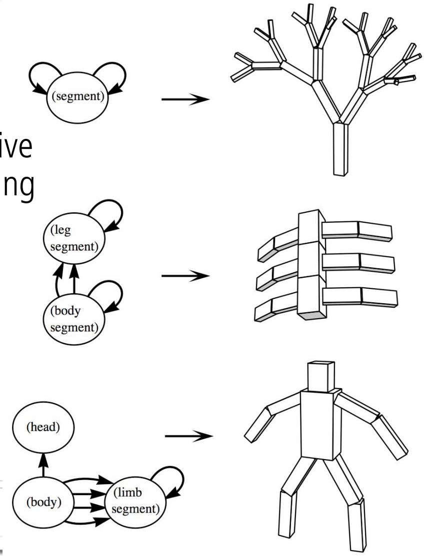
Parameterization of morphology

encoding in genome "genotype"

development

embodied agent "phenotype"

recursive encoding



Co-evolution of morphology and control

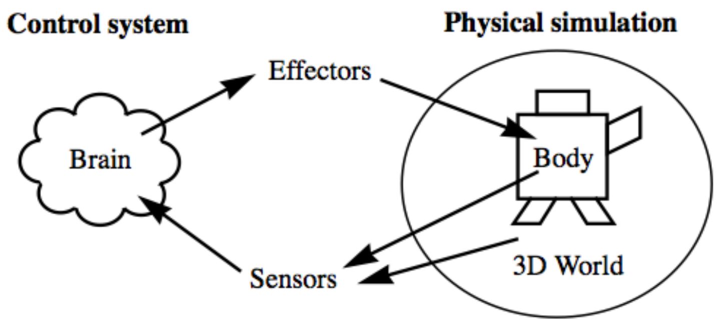


Figure 2: The cycle of effects between brain, body and world.

Co-evolution of morphology and control

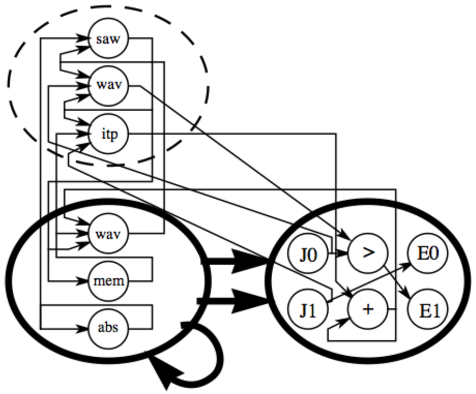
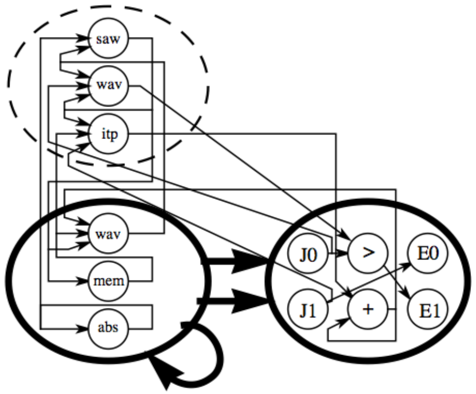


Figure 3: Example evolved nested graph genotype. The outer graph in bold describes a creature's morphology. The inner graph describes its neural circuitry. J0 and J1 are joint angle sensors, and E0 and E1 are effector outputs. The dashed node contains centralized neurons that are not associated with any part.

sum	cos
product	atan
divide	log
sum-threshold	expt
greater-than	sigmoid
sign-of	integrate
min	differentiate
max	smooth
abs	memory
if	oscillate-wave
interpolate	oscillate-saw
sin	

Neurons: have many functions (presumably more than biologically realistic): evolution can choose:
sum, product, divide, sum-threshold, greater-than, sign-of, min, max, abs, if, interpolate, sin, cos, atan, log, expt, sigmoid,integrate, differentiate, smooth, memory oscillate-wave, oscillate-saw

Genotype and phenotype



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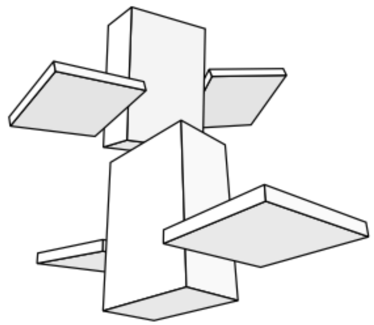
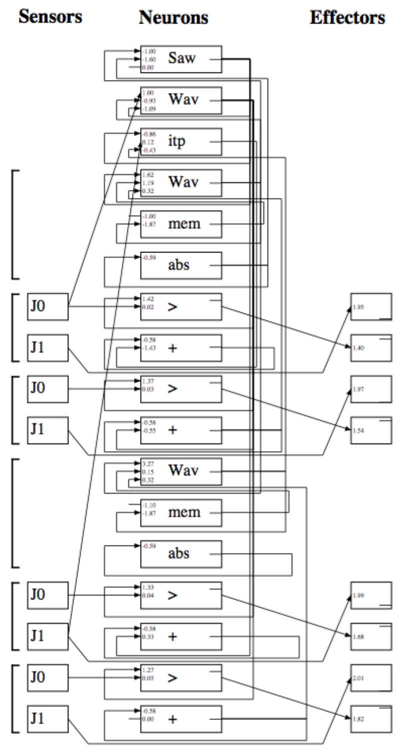


4a: The phenotype morphology generated genotype shown in figure 3.

Embedding of neural net



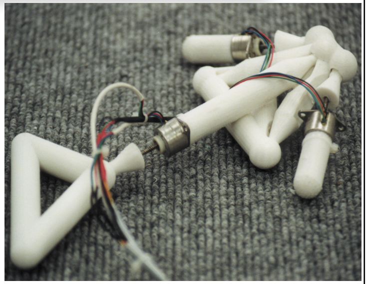
New version: Golem (Lipson and Pollack)

representation of morphology in genome

- **robot: bars, actuators, neurons**
- **bars: length, diameter, stiffness, joint type**
- **actuators: type, range**
- **neurons: thresholds, synaptic strengths**

(recursive encoding)

limitations?

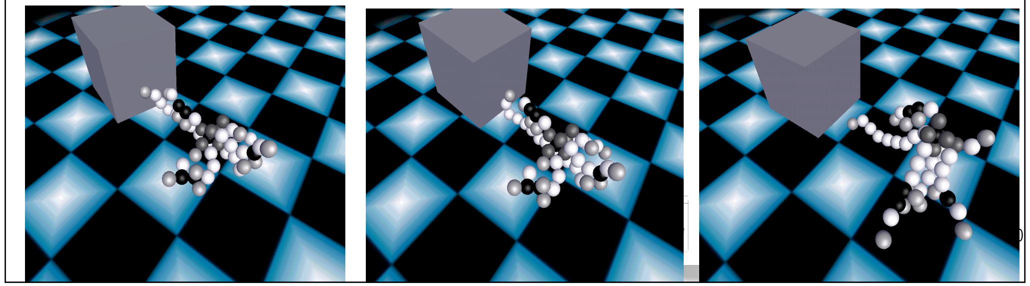


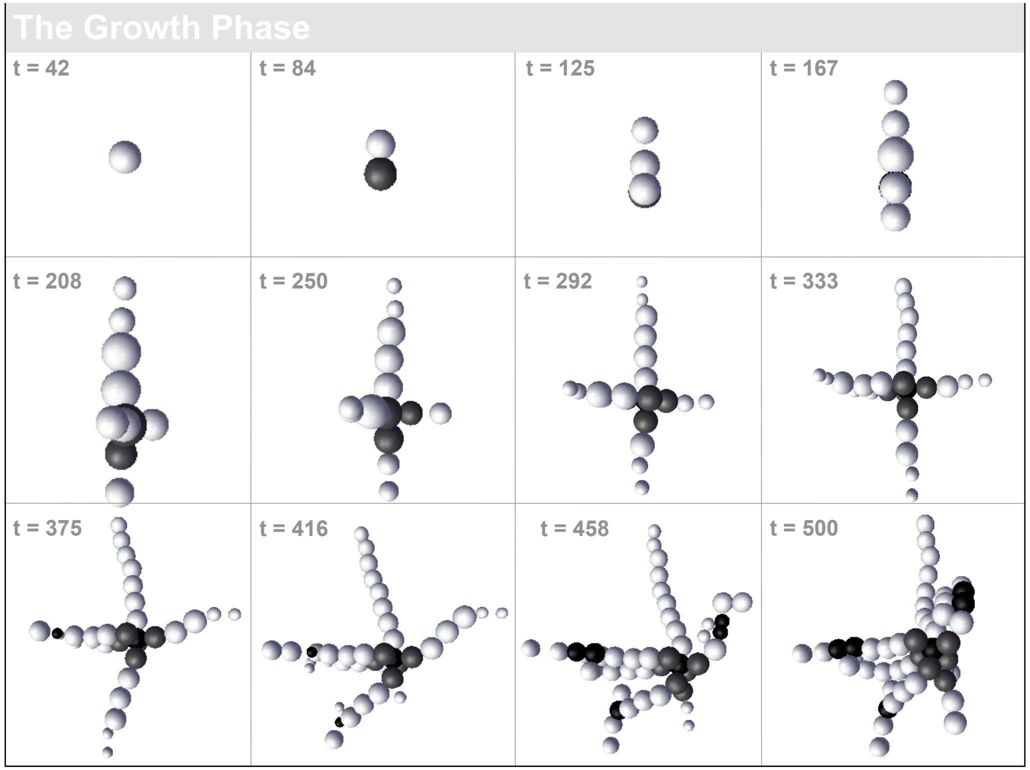
New version: Golem
(Lipson and Pollack)

Videos from Golem project evolved and 3D-printed "creatures"

Genetic Regulatory Networks (GRNs): Bongard's "block pushers"

- development (morphogenesis) embedded into evolutionary process, based on GRNs
- testing of phenotypes in physically realistic simulation

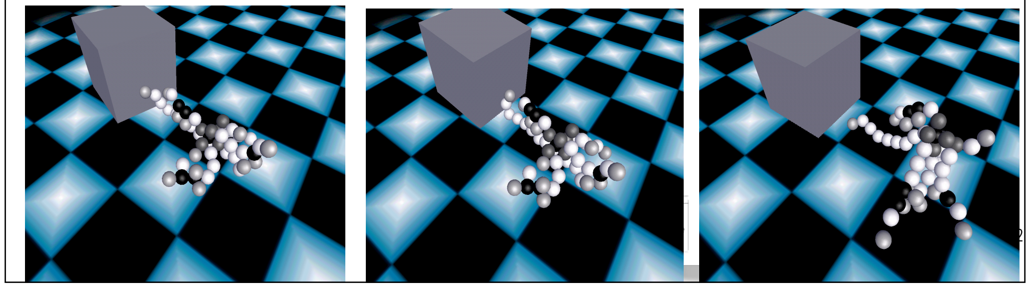


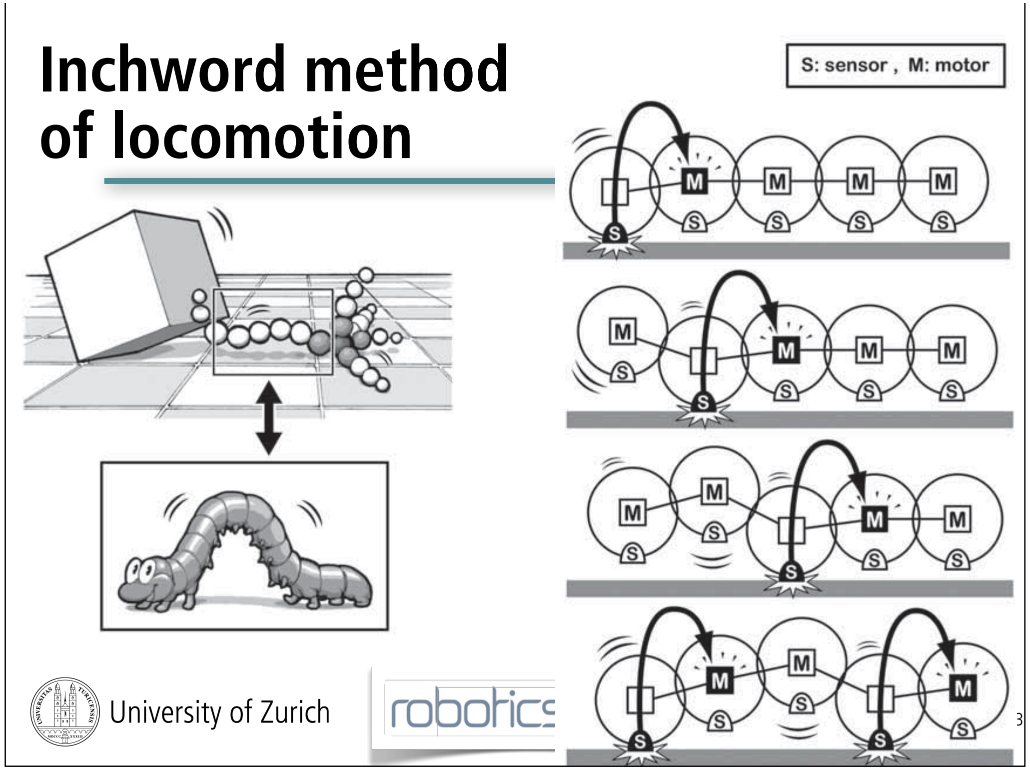

The Growth Phase
t = 42
t = 84
t = 125
t = 167
t = 208
t = 250
t = 292
t = 333
t = 375
t = 416
t = 458
t = 500

Evolution of a “block pusher” (“Artificial Ontogeny”)

- development (morphogenesis) embedded
-

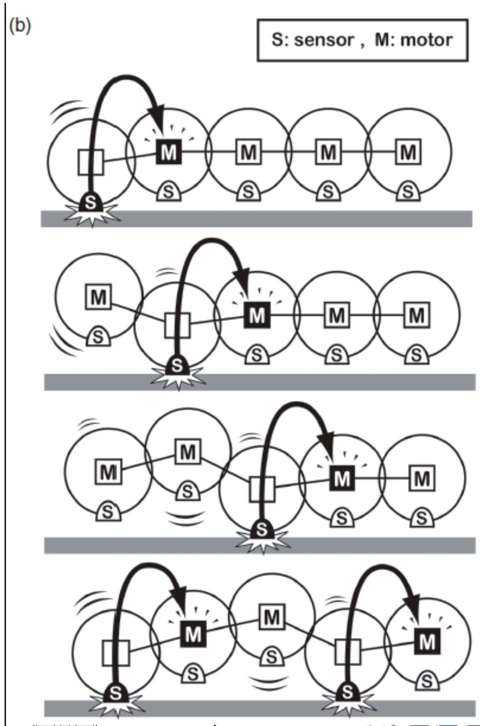
Video “Evolution of block pushers”

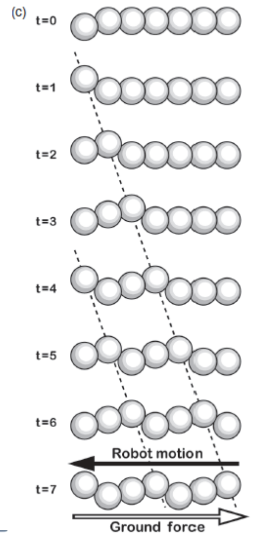




Emergence of locomotion:The block pusher. (*a*) the actual block pusher. (*b*) The inchwormlike locomotion of the block pusher.A sensor, S, in one cell is connected to a motor,M, in a neighboring cell.Whenever S touches the ground, it will actuate the motor M, which subsequently will lift up the cell containing S. This reflex propagates through the entire creature and causes the locomotion behavior. (*c*) The pattern of motion is reminiscent of how an inchworm moves: waves travel along the animal’s body in order to move it forward.

Emergence of locomotion through local reflexes

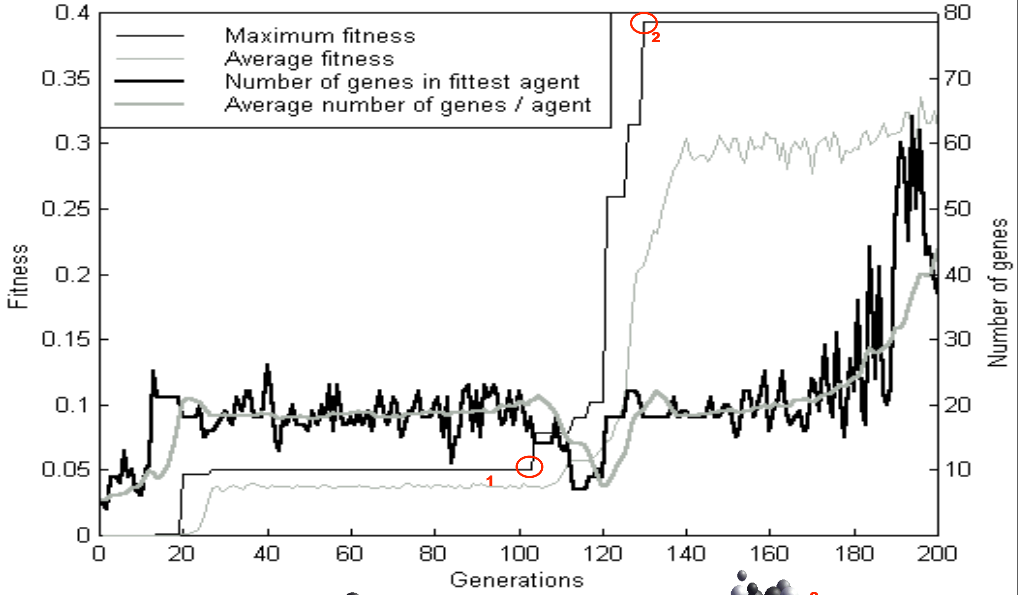


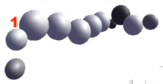


from “How the body …”

Observations on Bongard's "block pushers"

- size of organism
- no direct relation between length of genome and fitness of phenotype
- means of locomotion: no global neuronal coordination
- specialization of cells (black, dark gray, light gray, white)


Maximum fitness
Average fitness
Number of genes in fittest agent
Average number of genes / agent
Fitness
Number of genes
Generations
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
20
40
60
80
100
120
140
160
180
200
10
20
30
40
50
60
70
80
1
2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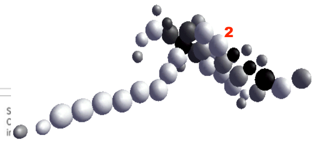
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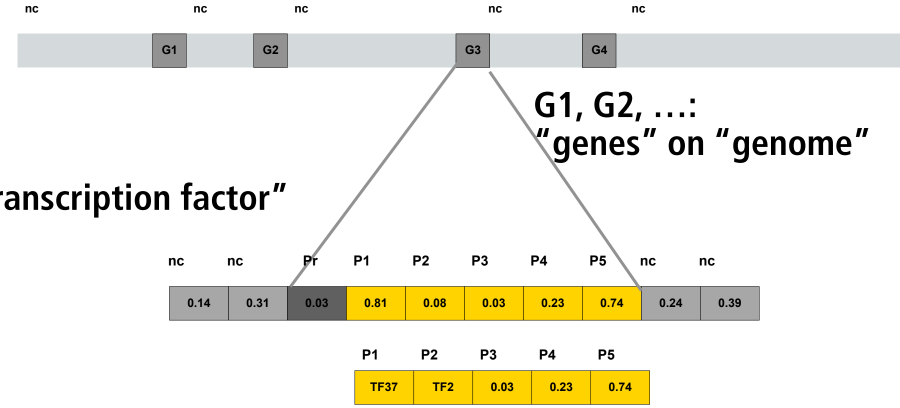
Representation of “gene”

nc: “non-coding region”

TF: “transcription factor”



Representation of “gene”

Parameters of “gene”:

nc: non-coding region
TF: “transcription factor”
Pr: start of promotor region
P1:TF regulating expression of this gene
P2: TF emitted by gene when expressed
P3: quantity of TF emitted
P4, P5: lower and upper bound of concentration range between which gene is expressed
when expressed: gene emits one of 42TFs, 20 regulatory, 22 structural (morphology and neural network

For more detail, see, for example:

Bongard, J., and Pfeifer, R. (2003). Evolving complete agents using artificial ontogeny. In F. Hara, and R. Pfeifer (eds.). Morpho-functional machines: The new species. Designing embodied intelligence. Tokyo: Springer, 237-258.

TFs for growth process (examples)

TF0: splitting of cell
TF1, TF2: attachment of cell with angle
TF3: joint type
...
TF6: create neuron
TF7, TF 8: position of neuron in cell
TF9: delete neuron
TF10: create synapse
TF11: delete synapse
TF12: split synapse into two branches
…
TF40: produced by touch
TF41: produced by torque on hinge joint

For more detail, see:

Bongard, J. (2003). Incremental approaches to the combined evolution of a robot’s brain and body. Unpublished doctoral dissertation. University of Zurich.

Bongard's evolutionary scheme

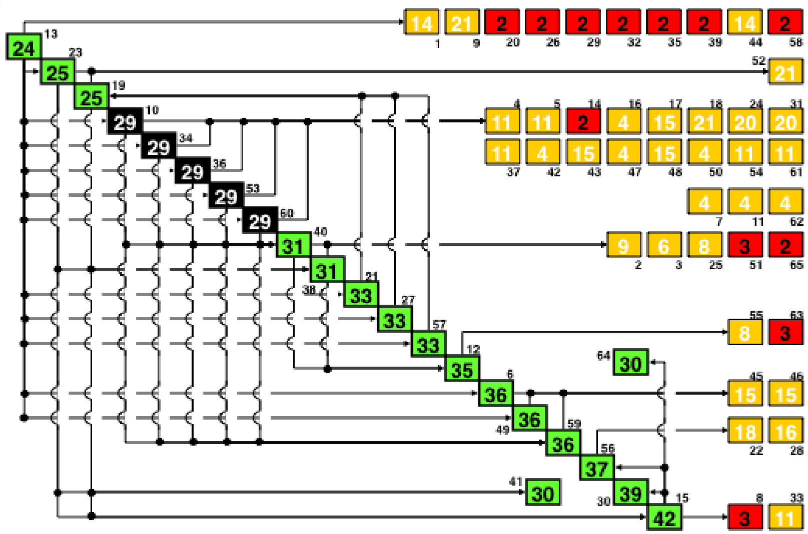
genotype:
parameters of genetic regulatory network

ontogenetic development:
"transcription factors"

phenotype selection:
physically realistic simulation

reproduction:
mutation and recombination

GRN for evolved creature (Josh Bongard)



yellow: structural genes for neural growth
red: structural genes for body morphology growth
green: regulatory genes
black: targeted for lesion experiments
number inside box: TF emitted by gene if expressed
number outside box: position of gene in genome
E.g.: genes 45, 46: regulated by TF 36 produced by genes 49 and 59.
In this model, there are many more genes for neural than for body growth.
As can be seen from the figure, this network doesn't contain any loops. Thus, there are no problems with stability. In real-world GRNs, the complexity is much higher, with many loops.

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parameters of genetic regulatory network

ontogenetic development:
“transcription factors”

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Thank you for your attention!