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# Lecture 7

Theory of intelligence:  
Design principles of autonomous agents

# Today's program

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1. Live panel discussion with Rodney Brooks
2. Theory of intelligence: Design principles for autonomous systems

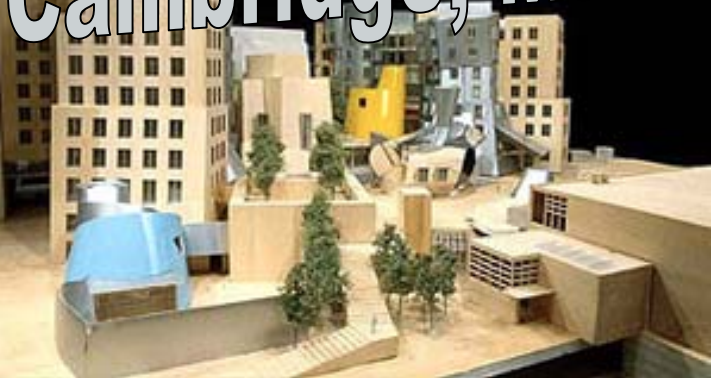
# Today: AI Visionary Rodney Brooks, MIT



Moderator: Britta Glatzeder

Participants: Yasuo Kuniyoshi and Rolf Pfeifer

Cambridge, Mass



03.15  
MIT CSAIL

H.323-standard:  
audio, video, data co

# “AI today - and tomorrow”

## Panel in the global virtual lecture hall



*Britta Glatzeder*  
*Moderator*  
*Univ. of Munich*  
*and*  
*Univ. of Zurich*

*from MUNICH*



*Yasuo Kuniyoshi*  
*Univ. of Tokyo*

*from TOKYO*

*Rodney Brooks*  
*AI visionary*  
*Director CSAIL*  
*MIT*

*from BOSTON*



*Rolf Pfeifer*  
*Univ. of Zurich*  
*and*  
*Univ. of Tokyo*

*from TOKYO*



# Welcome

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hello:

- Beijing
- Warsaw
- Lodz (new partner)
- Zurich
- Boston, MIT: Rodney Brooks
- Munich: Britta Glatzeder

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# Lecture 7

Theory of intelligence:  
Design principles of autonomous agents

Library robot  
(Tsukuba Univ.  
Japan)

*instructions via  
Internet  
digital camera  
mechanical arm  
laser system*

*select book  
flip through pages  
photograph and  
transmit contents*

ROBOLIBRARIAN



ALL THE NEWS WITHOUT FEAR OR FAVOR

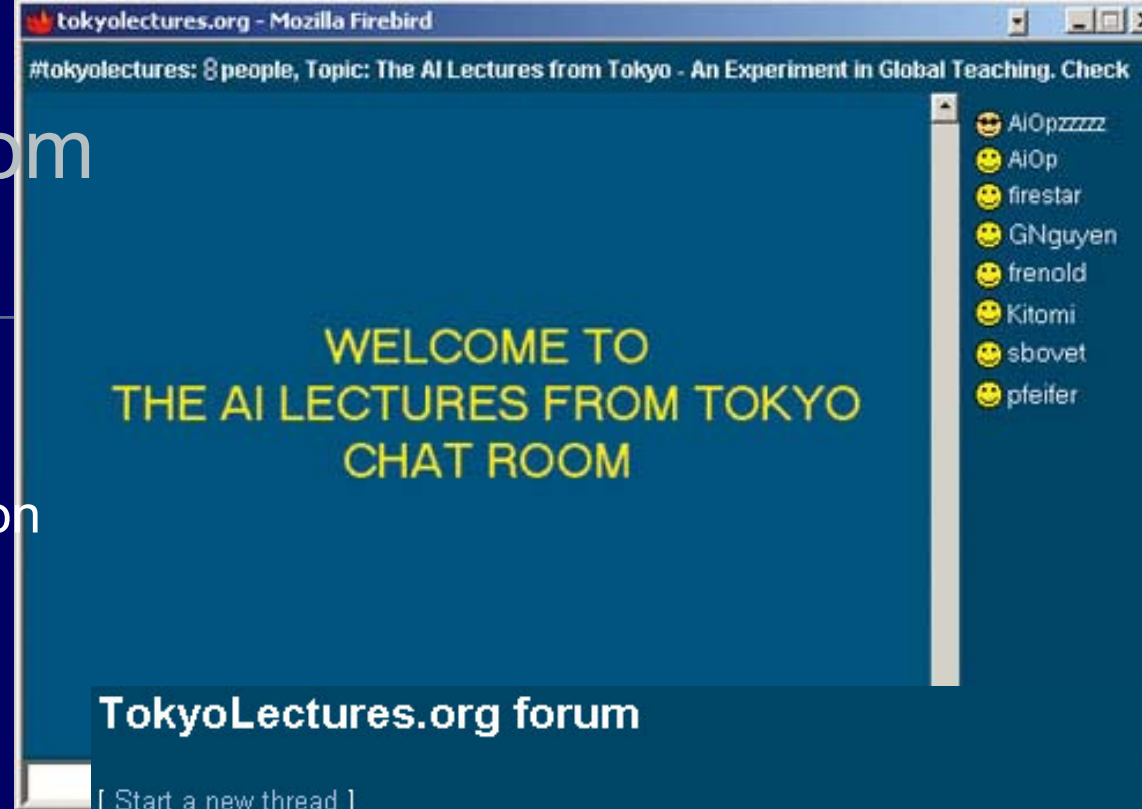
TSUKUBA,  
via the Inte  
searchers,  
between si  
graph and

The Japan Times

Tuesday, 9 Dec. 2003

# Join the chat room and the forum

- discuss current topics
- post interesting information
- meet others around the world
- click on “community” on tokyolectures web site



tokyolectures.org - Mozilla Firebird

#tokyolectures: 8 people, Topic: The AI Lectures from Tokyo - An Experiment in Global Teaching. Check

WELCOME TO  
THE AI LECTURES FROM TOKYO  
CHAT ROOM

AiOpzzzz  
AiOp  
frestar  
GNguyen  
frenold  
Kitomi  
sbovet  
pfeifer

### TokyoLectures.org forum

[ Start a new thread ]

Due to technical difficulties, you may see two thread lists. Please forgive me, this is a temporary state and I am working on it...

### Threads with unread messages

[ previous ] - [ next ]

Subject	Author	Date	Count
Simulation	Janusz Matkowski	09 Dec 2003 22:47:49	1 / 1
Solution files	Wolfgang Lang	08 Dec 2003 09:25:05	1 / 1
Problems with Format	Benjamin Cordes	03 Dec 2003 21:41:43	5 / 5
Lecture 5: Redundancy principle in DAC architecture?	Hans Walter Kramer	03 Dec 2003 14:04:40	3 / 3
Phylogenetic perspective and evolution	Angelo Vaccaro	01 Dec 2003 23:46:30	4 / 5
Lecture 7: discussion with Rodney Brooks	Britta Glatzeder	30 Nov 2003 18:03:15	3 / 4

# Questions from last week?

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# Today's topics

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- Frame-of-reference: Presents (Tokyo and Zurich)
- Global Webots Communication Workshop (Simon Bovet)
- Artificial evolution/morphogenesis: concluding remarks
- Special assignment: Warsaw students
- Design principles for autonomous (intelligent) systems
  - overview
  - time perspectives
  - illustrations
- Case study: Walking
- Merry Christmas!

# Frame-of-reference (F-O-R)

Presents offered by Karakuri Ningyo

Tokyo and Zurich



*first Tokyo, then switch to Zurich*

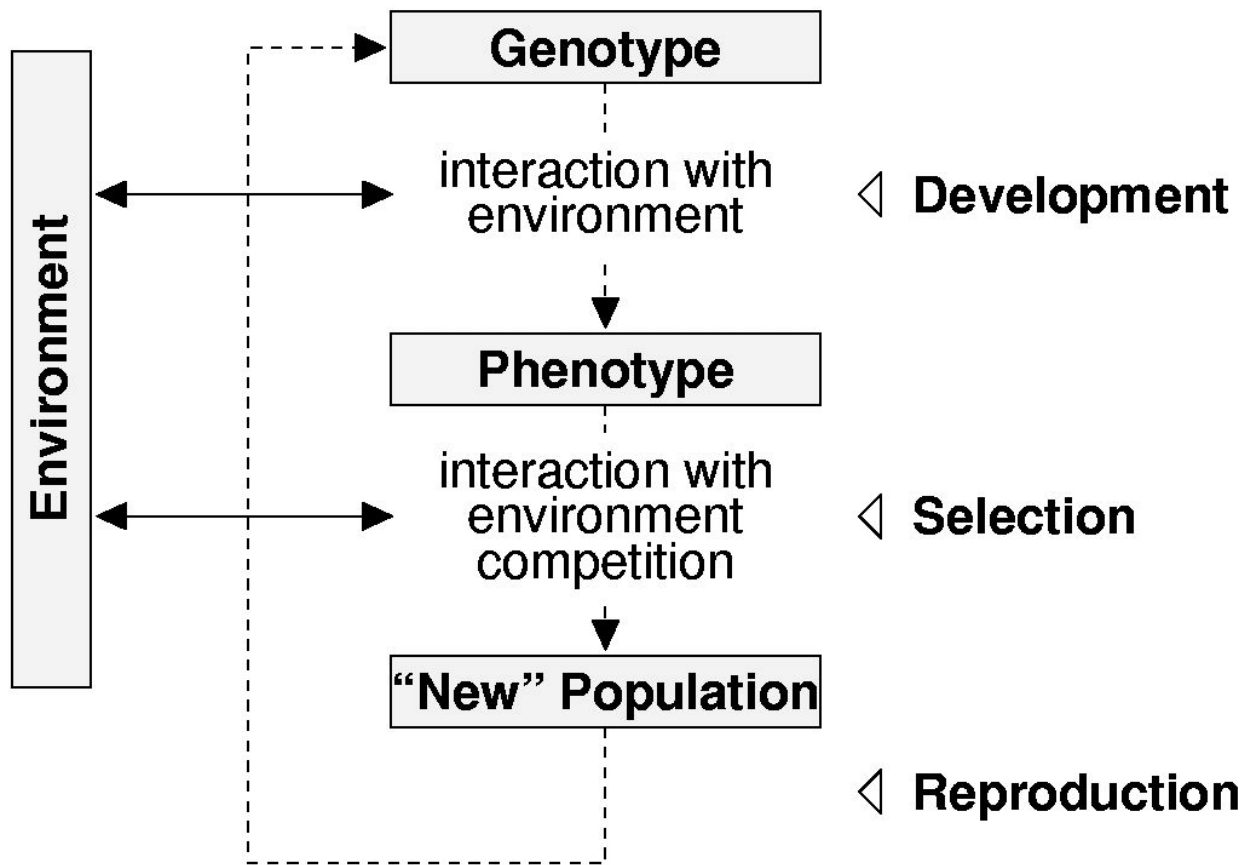
# Global Webots Communication Workshop

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Simon Bovet, Zurich (responsible for academic aspects of lectures)

*switch to Zurich*

# “Grand” evolutionary scheme

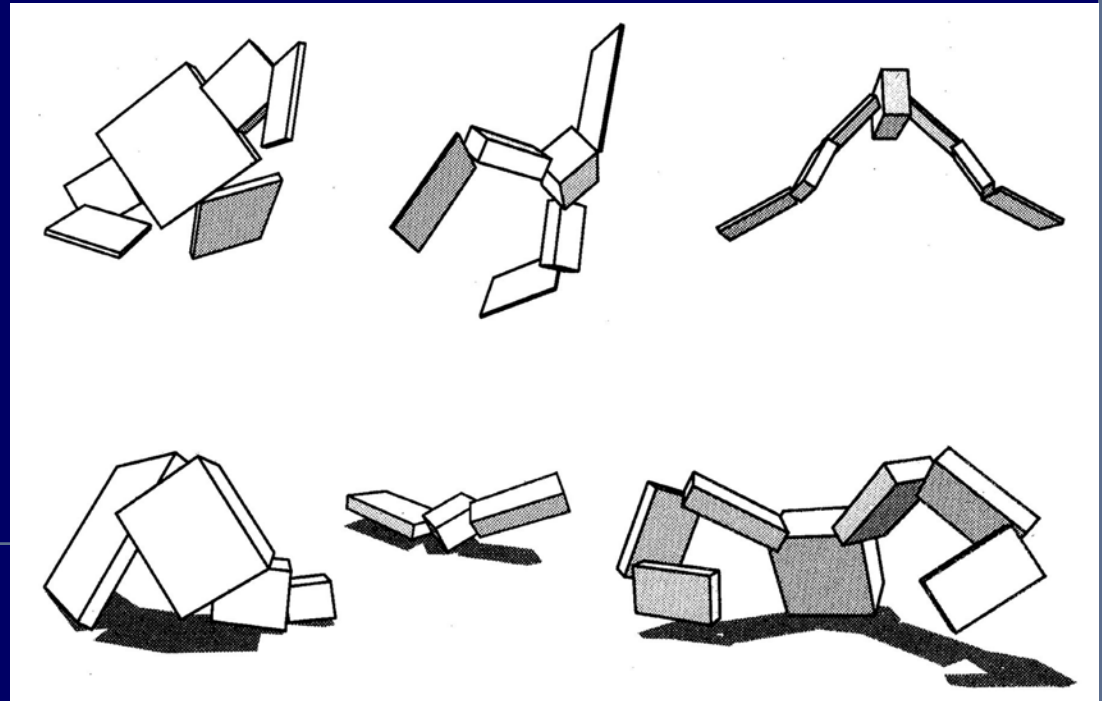


encoding	development	selection	reproduction
<ul style="list-style-type: none"> <li>• binary</li> <li>• many-character</li> <li>• real-valued</li> </ul>	<ul style="list-style-type: none"> <li>• no development (phenotype = genotype)</li> <li>• development with and without interaction with the environment</li> </ul>	<ul style="list-style-type: none"> <li>• “roulette wheel”</li> <li>• elitism</li> <li>• rank selection</li> <li>• tournament</li> <li>• truncation</li> <li>• steady-state</li> </ul>	<ul style="list-style-type: none"> <li>• mutation</li> <li>• crossover</li> </ul>

# Evolving control and morphology **Video**

## Karl Sims's Creatures

*Karl Sims  
(last week)*



# Karl Sims's Creatures: Parameterization of morphology

*encoding in  
genome  
(genotype)*

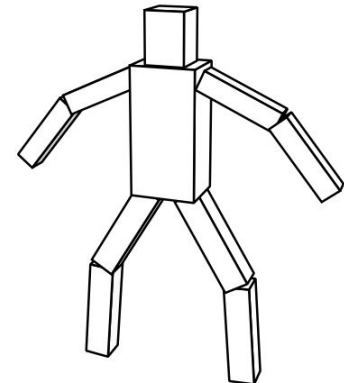
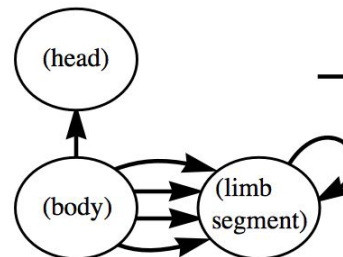
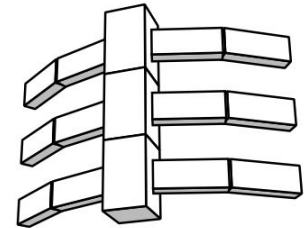
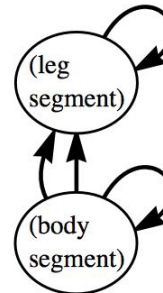
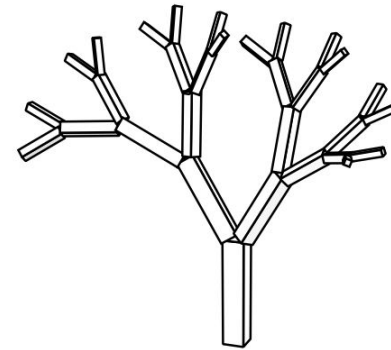
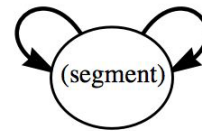


development



*“embodied  
agent”  
(phenotype)*

*(recursive encoding)*



# Karl Sims' Creatures: Parameterization of morphology

*encoding in  
genome  
(genotype)*

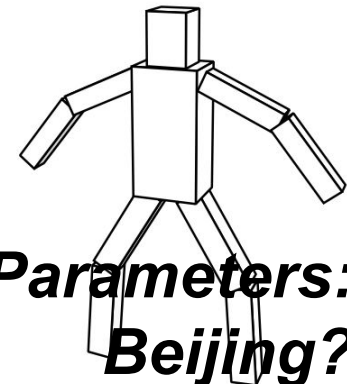
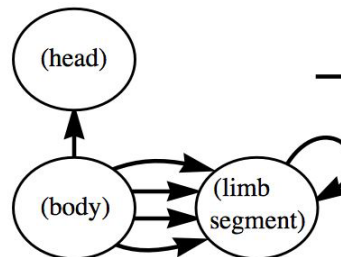
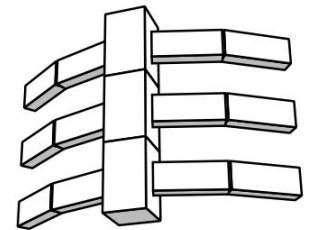
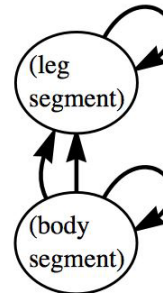
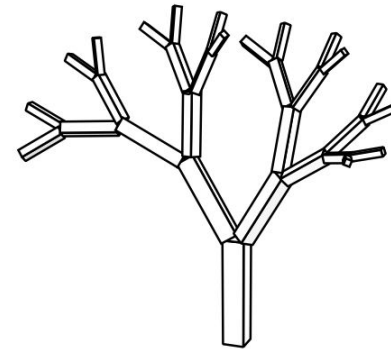
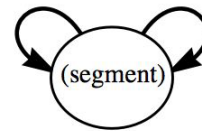


development



*“embodied  
agent”  
(phenotype)*

*(recursive encoding)*



**Parameters:  
Beijing?**

# Karl Sims' Creatures: Parameterization of morphology

*encoding in  
genome  
(genotype)*



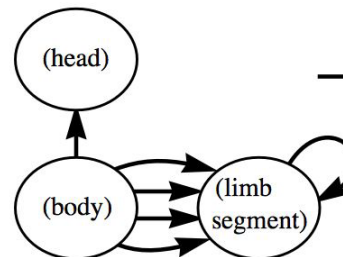
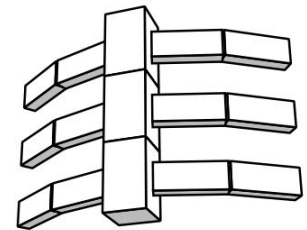
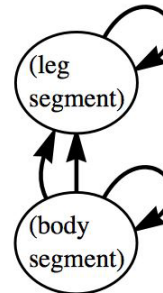
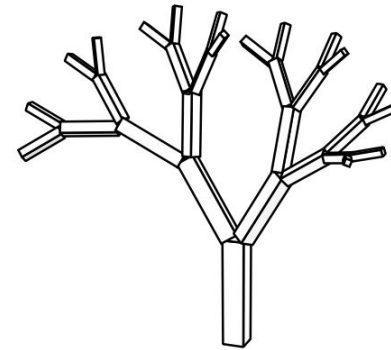
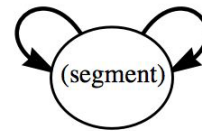
*development*



*“embodied  
agent”  
(phenotype)*

*(recursive encoding)*

*connection  
to neural  
network  
(co-evolved  
with  
morphology)*



**Parameters:  
Beijing?**

# New version: the „Golem“ project

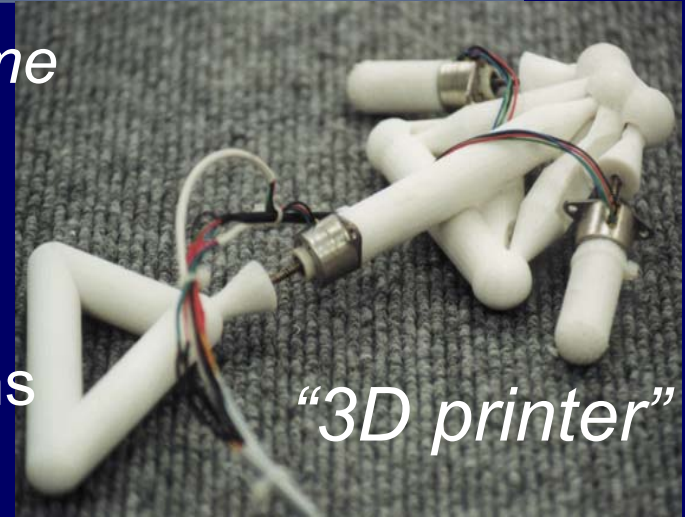
## Parameterization of morphology

(Hod Lipson and Jordan Pollack)

### *Representation of morphology in genome*

- robot: bars, actuators, neurons
- bar: length, diameter, stiffness, joint-type
- neurons: threshold, synaptic strengths
- actuator: type, range

*(recursive encoding)*



*limitations:  
Munich?*

# New version: the „Golem“ project

## Parameterization of morphology

(Hod Lipson and Jordan Pollack)

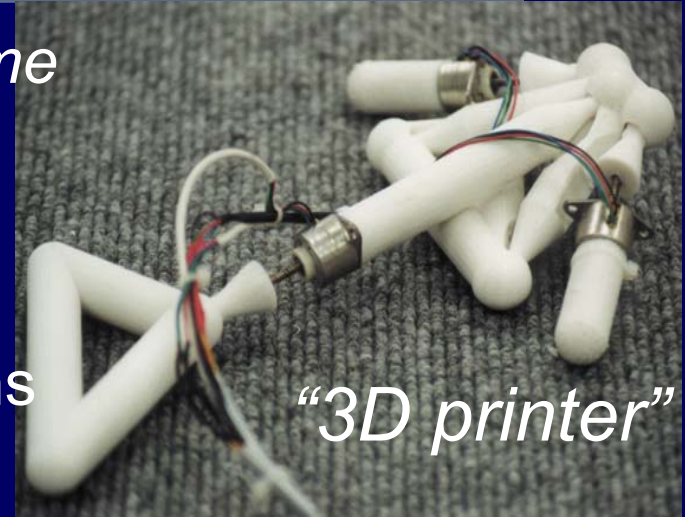
### *Representation of morphology in genome*

- robot: bars, actuators, neurons
- bar: length, diameter, stiffness, joint-type
- neurons: threshold, synaptic strengths
- actuator: type, range

*(recursive encoding)*

### *Implications*

- strong designer bias
- complex structures (like muscles) not possible

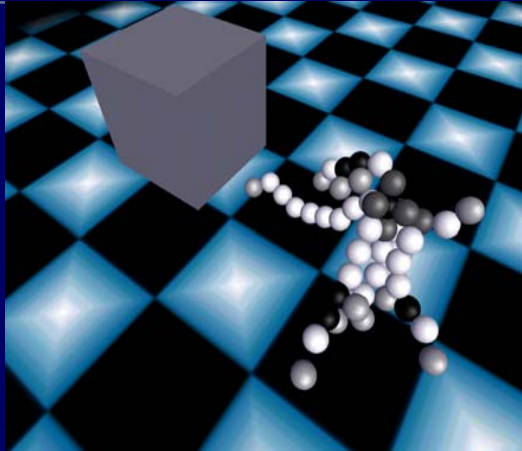


# Genetic Regulatory Networks

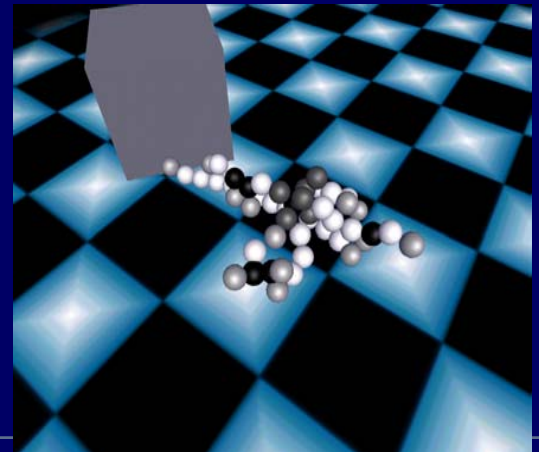
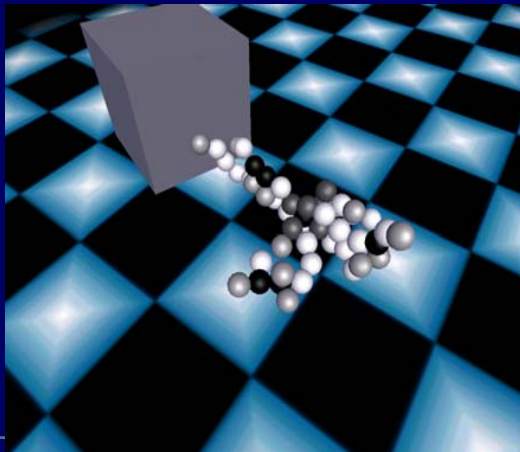
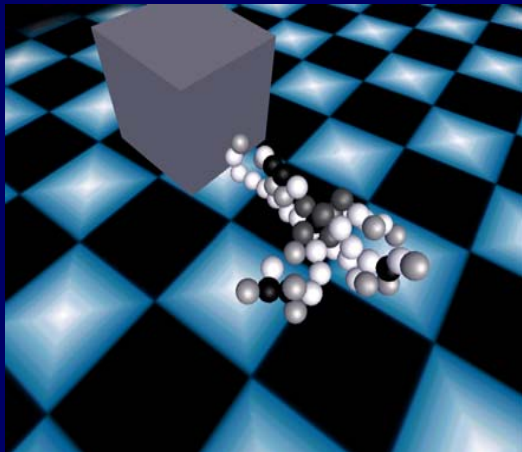
## Josh Bongard's "Block Pushers"

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# Evolution of a “Block Pusher”

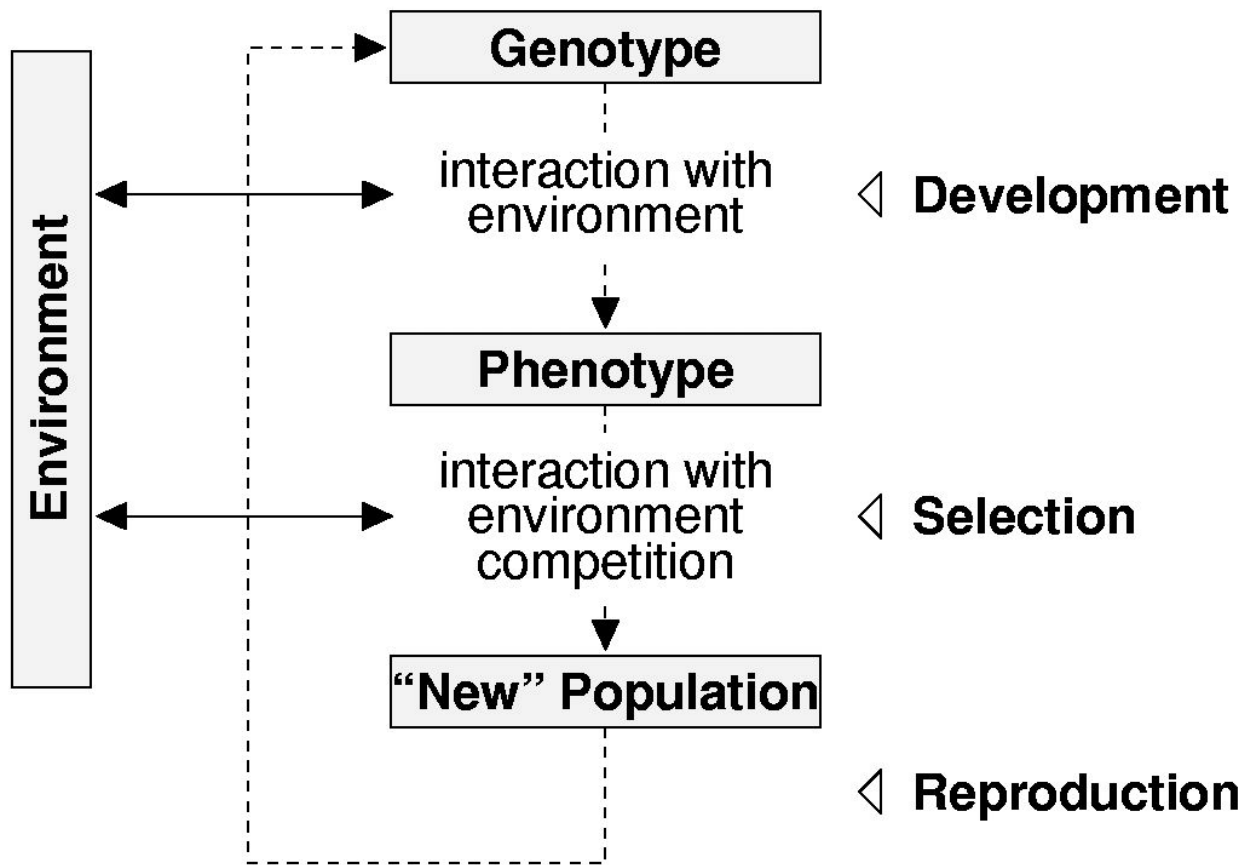


- morphogenesis (genetic regulatory networks) embedded into evolutionary algorithm
- testing of phenotype in physically realistic simulation



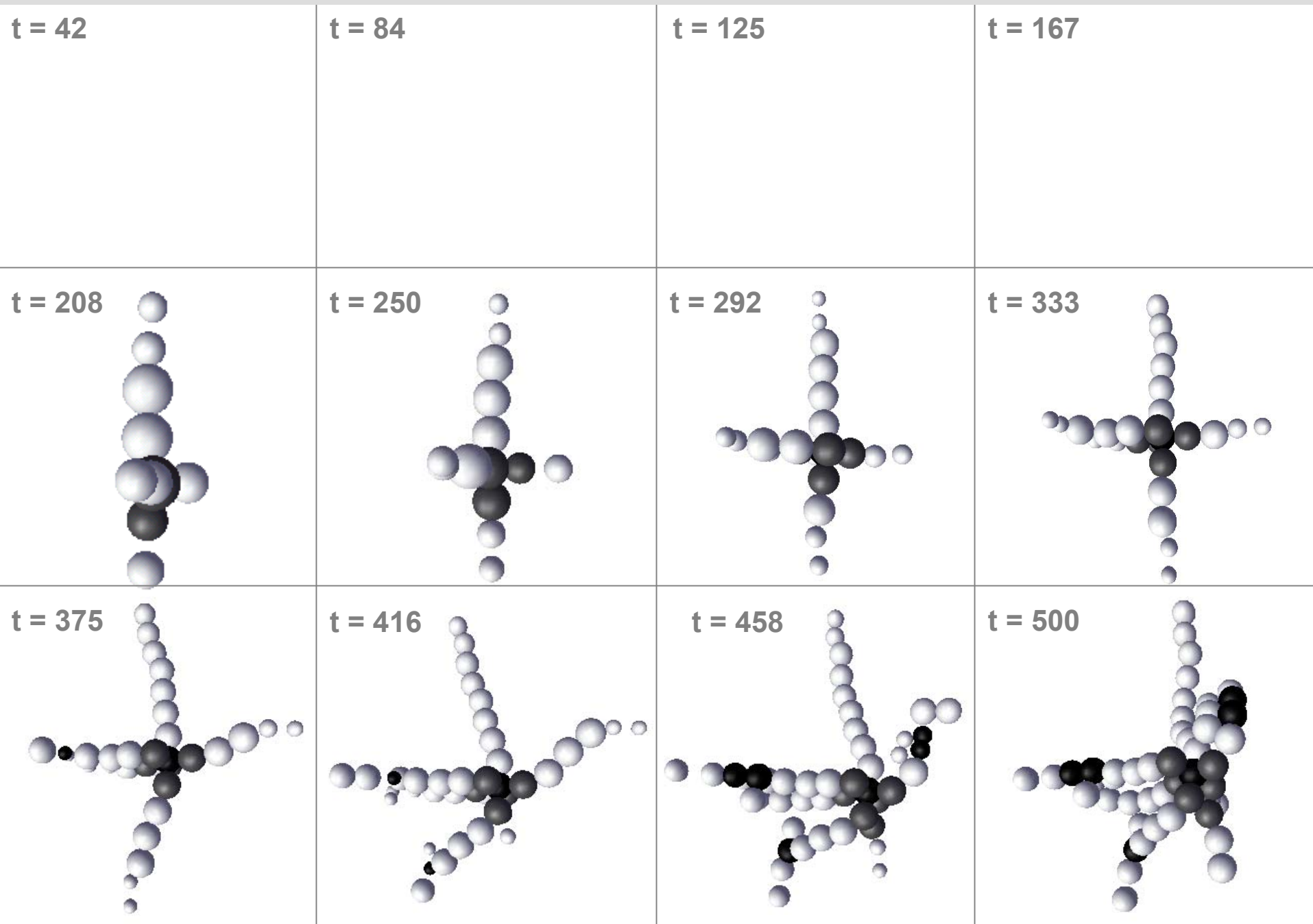
Design and programming: Josh Bongard

# “Grand” evolutionary scheme



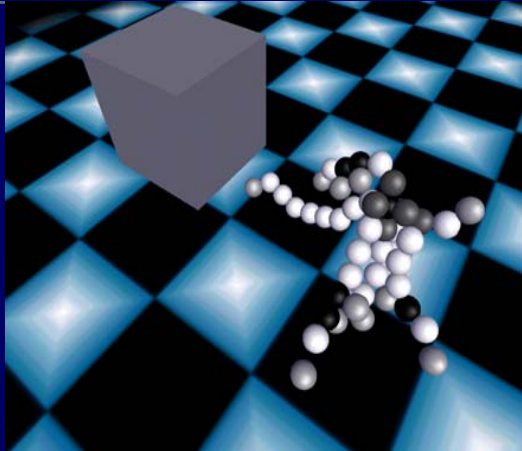
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# The Growth Phase

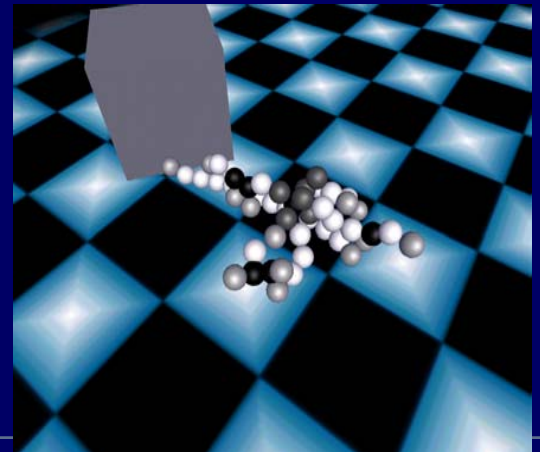
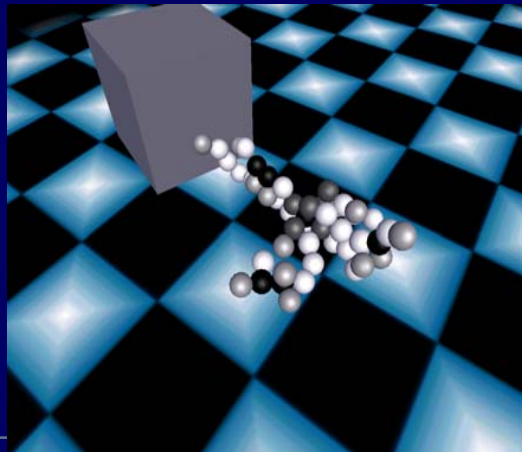
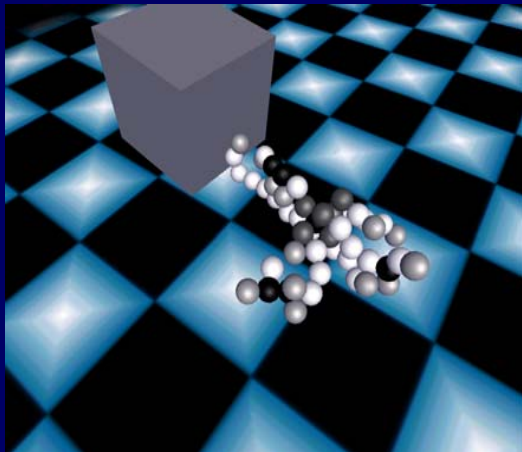


# Evolution of a “Block Pusher” **Video**

(“Artificial Ontogeny”)  
*Evolution of the “block pusher”*



- morphogenesis (genetic regulatory networks) embedded into evolutionary algorithm
- testing of phenotype in physically realistic simulation



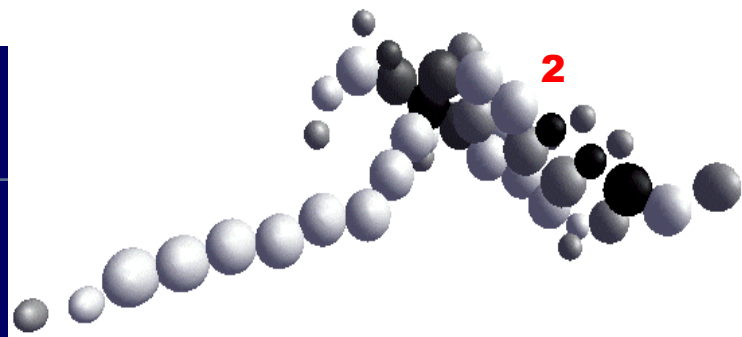
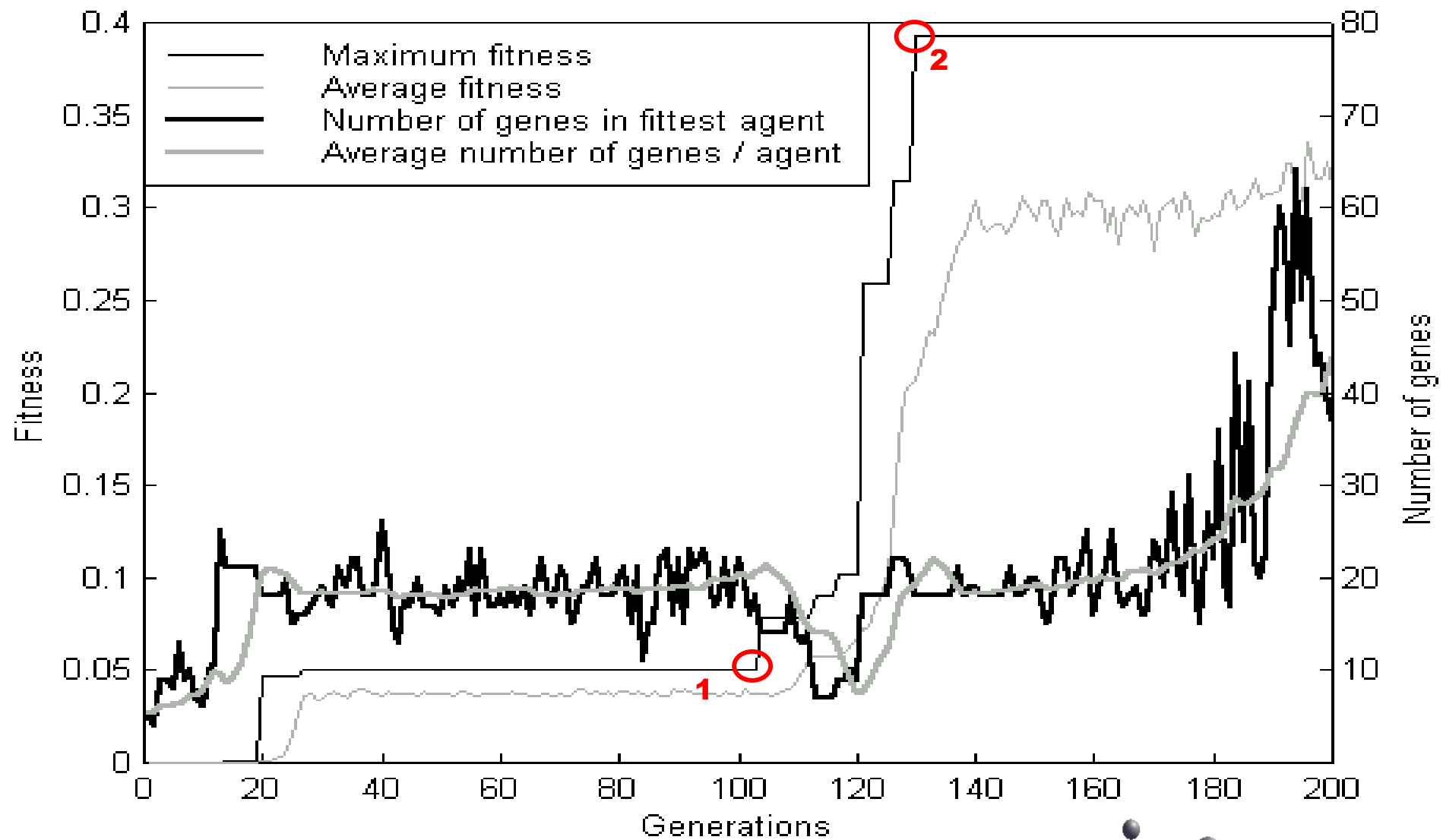
Design and programming: Josh Bongard

# Observations

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- size of the organisms
- no direct correlation between length of genome of fitness of the phenotype (not visible from behavior)
- means of locomotion: no global neuronal coordination
- specialization of the cells
- modularity of the phenotype (“Block Pusher”)

→ morphology (sensors, actuators, body, limbs) and neural system through evolution



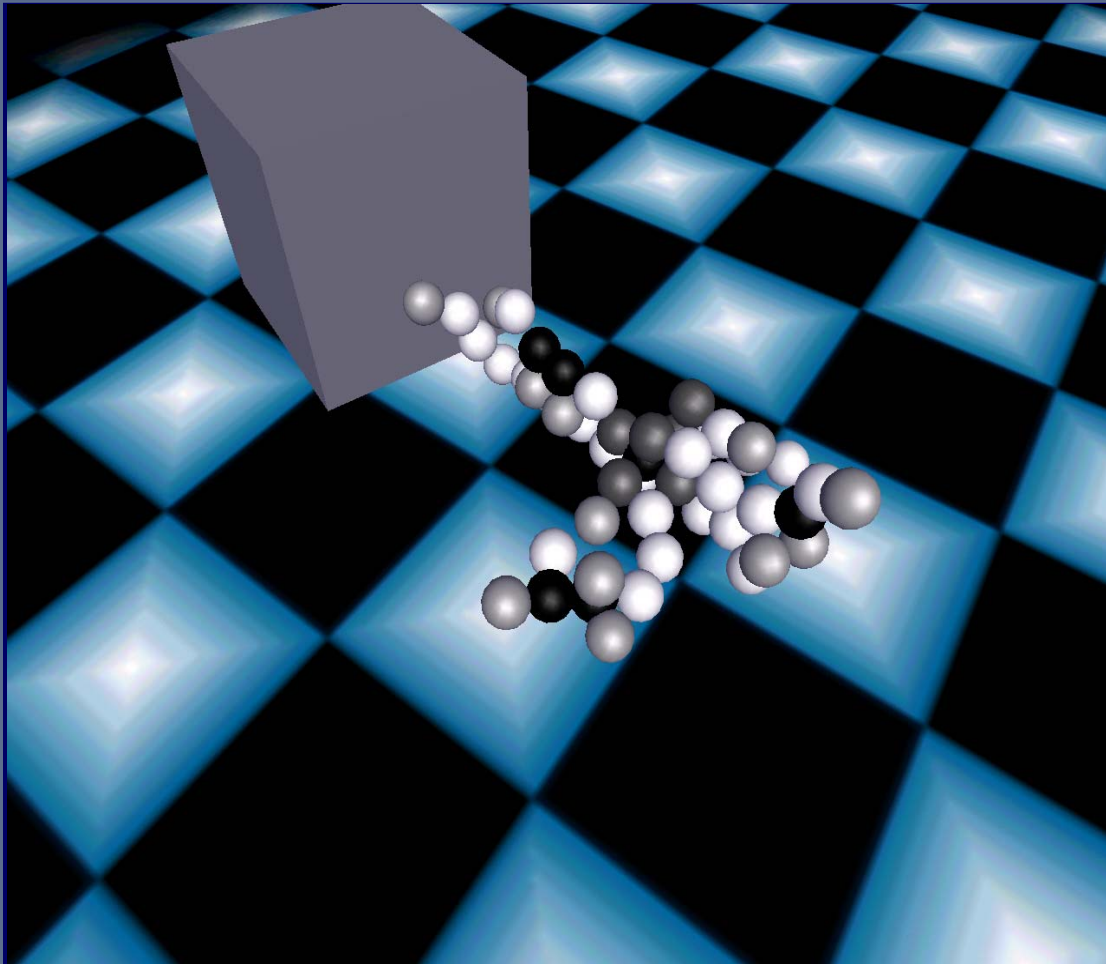
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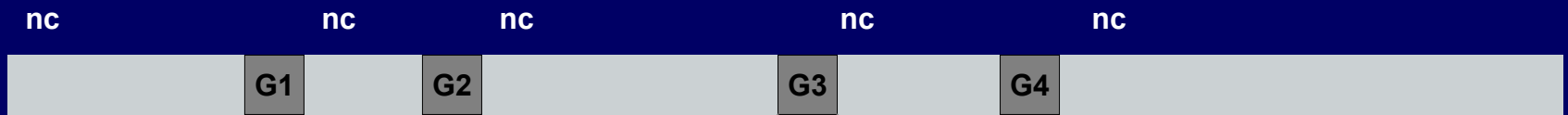
→ morphology (sensors, actuators, body, limbs) and neural system through evolution

# Evolution of a “Block Pusher”



- specialization of cells  
(different coloring)
- modularity  
(groups of cells)

# Ontogenetic growth – genetic regulatory network



TFs: transcription factors

nc	nc	Pr	P1	P2	P3	P4	P5	nc	nc
0.14	0.31	0.03	0.81	0.08	0.03	0.23	0.74	0.24	0.39

P1	P2	P3	P4	P5
TF37	TF2	0.03	0.23	0.74

# Parameters of gene

---

- Nc: non-coding region
- Pr: start of promoter region
- P1: which regulatory TF regulates its expression [0,19]
- P2: which TF this gene emits of during expression [0,41]
- P3: how much of the gene's TF is emitted at each time step
- P4, P5: lower and upper bounds of concentration range for which gene is expressed

when expressed, gene emits one of 42 TFs:

- 20 regulatory, 22 structural (morphological and neuronal growth)

# Growth process (examples)

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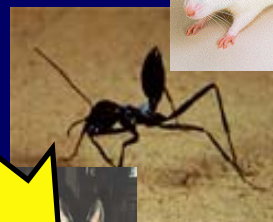
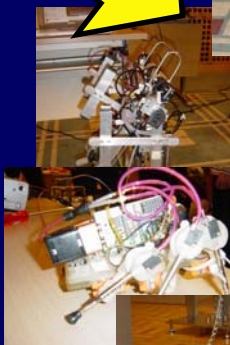
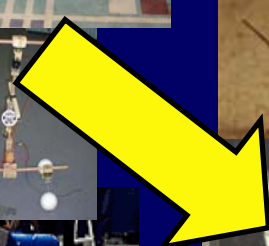
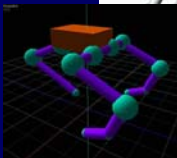
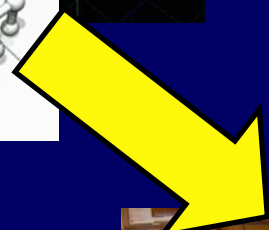
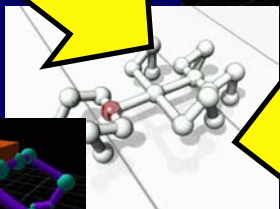
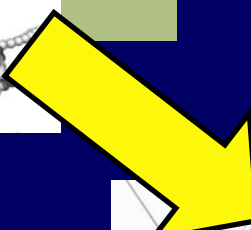
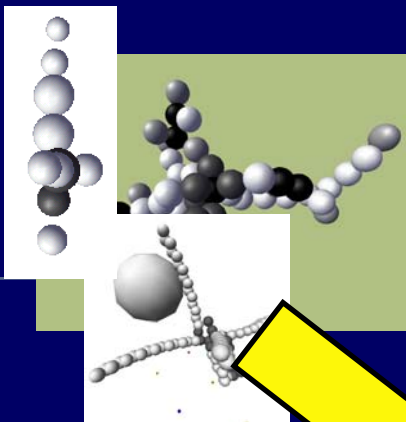
- TF0: splitting
- TF1, TF2: attachment of cell with angle
- TF3: joint type
- ...
- TF6: create neuron
- TF7, TF8: position of neuron in cell
- TF7: delete neuron
- TF8: create synapse
- TF9: delete synapse
- TF10: split synapse into two branches
- ...
- TF40: produced by touch
- TF41: produced by torque on hinge joint

# Fully automated design tool?

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- artificial evolution with morphogenesis
- how far can we go?

Where will we go???



???



# Automated Design

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- Warsaw:  
Special Assignment: “Artificial Evolution as a tool for Automated Design”  
(5 min presentation)

*switch to Warsaw*

# Limitations of the model

---

# Limitations of the model

---

- fitness function rather than survival  
--> survival as the only criterion for selection (e.g. Joeffrey Ventrella)
- simulation rather than real world  
--> “connect” to real world (e.g. Adrian Thompson)
- no interaction with the environment during ontogenetic development  
--> developmental plasticity (e.g. Josh Bongard)

# This concludes chapter 8

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- please read complete chapter (including artificial life part)

# Design principles for “...” systems



# The “grand scheme”

---

# Artificial Intelligence

goals

not only “life as it is” but “life as it could be”

understanding  
biological  
systems

principles of  
intelligent  
systems

useful  
artifacts  
applications



*abstract  
theory*



# General idea

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“bottom-up”: many examples --> extract principles

- *“Swiss robots”* --> principle of “cheap design”
- *“Fungus Eaters”* --> complete agent principle
- *Braitenberg vehicles* --> principle of “cheap design”
- *Braitenberg 1 with large brain* --> principle of “ecological balance”
- *DAC* (today - see later) --> “redundancy principle”
- *Subsumption architecture* (today - see later)  
--> principle of “parallel loosely coupled processes
- *Artificial evolution and morphogenesis*  
--> time perspectives; emergence

# Time scales for understanding and design

---

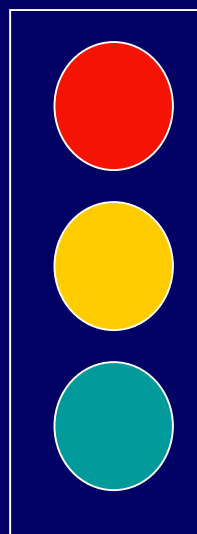
state-oriented	--	the “here and now”
learning and development	--	the ontogenetic perspective
evolutionary	--	the phylogenetic perspective

# Time frames illustration: Traffic lights

## Why stop at traffic light?

### SHORT TERM

specific visual stimulus,  
the red light → apply  
brakes



### LONG TERM (PHYLOGENETIC)

historical process whereby  
traffic lights came to be used

### LEARNING AND DEVELOPMENT (ONTOGENETIC)

rule learned from school,  
TV, experience

### FUNCTIONAL EXPLANATION

drivers who do not stop  
→ reduced fitness

# Time scales for understanding and design

---

state-oriented -- the “here and now”

learning and development -- the ontogenetic perspective

evolutionary -- the phylogenetic perspective

*emergence*

---

# Time scales for understanding and design

---

state-oriented -- the “here and now”  
*“hand design”*

learning and development -- the ontogenetic perspective  
*initial conditions*

*learning/dev. procs.*  
evolutionary -- the phylogenetic perspective  
*evolutionary algs.*  
*morphogenesis*

---

*comprehensive explanation of behavior: all three required*

# Time scales for understanding and design

---

state-oriented <i>“hand design”</i>	--	the “here and now”
learning and development <i>initial conditions</i> <i>learning/dev. procs.</i>	--	the ontogenetic perspective
evolutionary <i>evolutionary algs.</i> <i>morphogenesis</i>	--	the phylogenetic perspective

---

*for engineering: level of designer commitments*

# Design principles of intelligent systems

## Overview

---

### *Design procedure / „meta principles“*

- synthetic methodology
- time perspectives
- emergence
- diversity/compliance
- frame-of-reference

### *Agent design*

- three constituents
- complete agent principle
- „cheap design“
- redundancy principle
- „ecological balance“
- parallel, loosely coupled processes
- sensory-motor coordination
- value principle

# Case study: Walking

---

illustrating

- principle of “cheap design”
- principle of “ecological balance”

## Goal: natural walking

*Miriam*



## “Passive Dynamic Walker” – the brainless robot

*SCollinsWalker*

*“walking without control”*

Design and construction:  
Ruina/Wisse/Collins, Cornell University



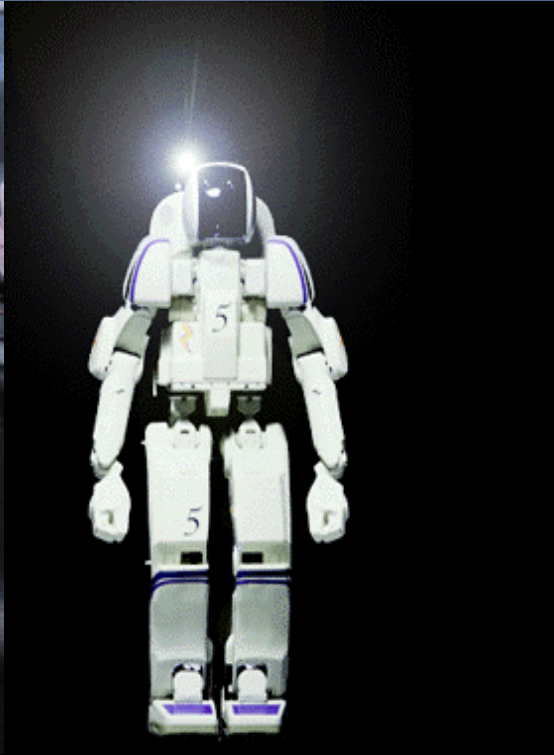
Morphology:

- wide feet
- elastic heels
- counterswing of the arms
- surface of feet

dynamically stable  
statically unstable

## Asimo (Honda) and H-7 (Univ. of Tokyo)

HONDA Asimo



Asimo



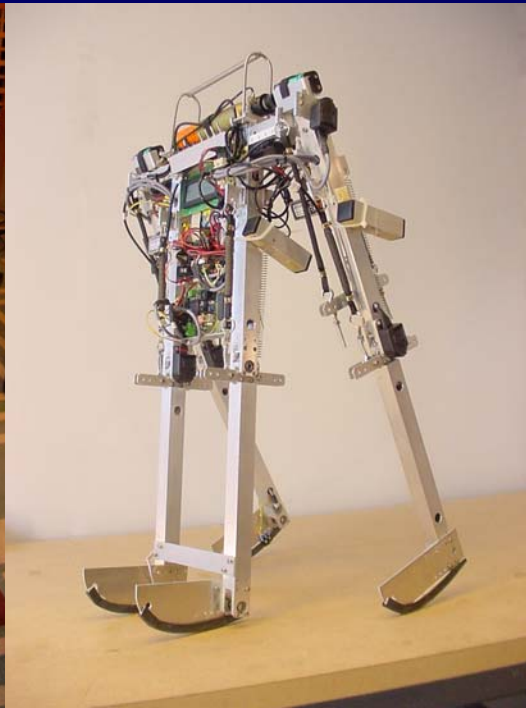
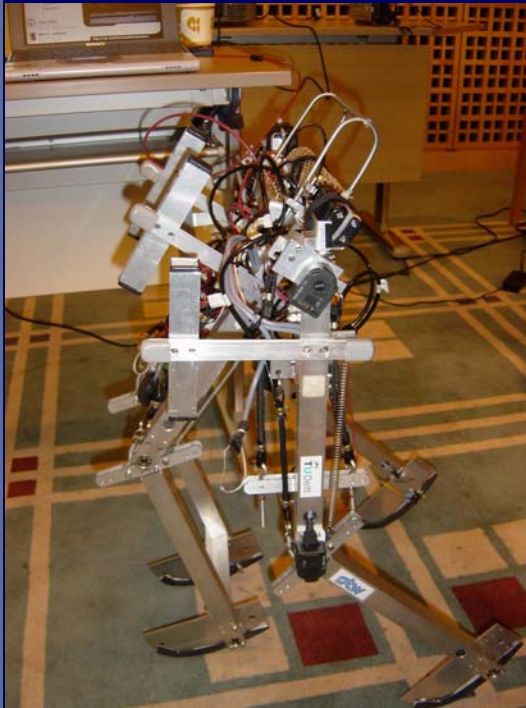
H-7

design and construction  
S. Kagami, Univ. of Tokyo



# “Almost Passive Dynamic Walker” – MIKE

Design and construction: Martijn Wisse  
Delft University, The Netherlands



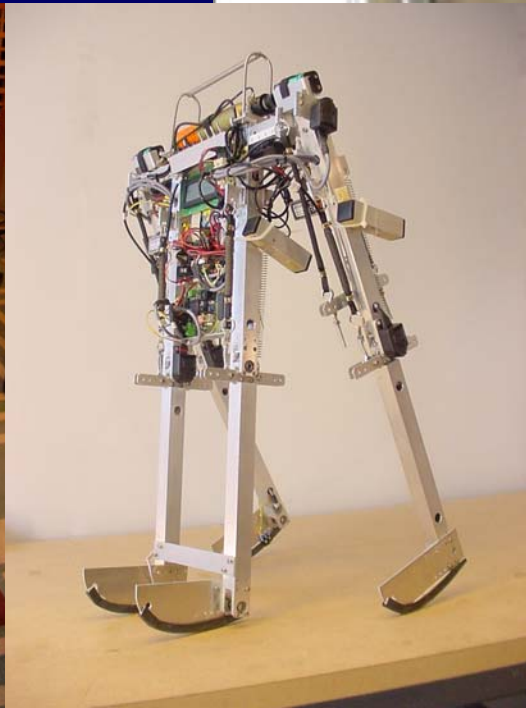
Morphology  
Materials  
pneumatic actuators  
(artificial muscles)  
minimal actuation  
passive dynamics

*walking almmost without control*

## “Almost Passive Dynamic Walker” – MIKE

Mike

Design and construction:  
Martijn Wisse, Delft University  
The Netherlands



Morphology  
Materials  
pneumatic actuators  
(artificial muscles)  
minimal actuation  
passive dynamics

*walking almost without control*

# Conclusions

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- appropriate embodiment („ecological balance“)
  - morphology
  - materials
  - exploitation of dynamics in interaction with environment
- minimal effort for control
- energy-efficient walking
- natural walking

# Felix, Regula and Exuperantius

the three saints of the city of Zürich



Grossmünster



*legend??*

→ *“passive dynamic walkers”*

# “Cheap design” and “ecological balance”

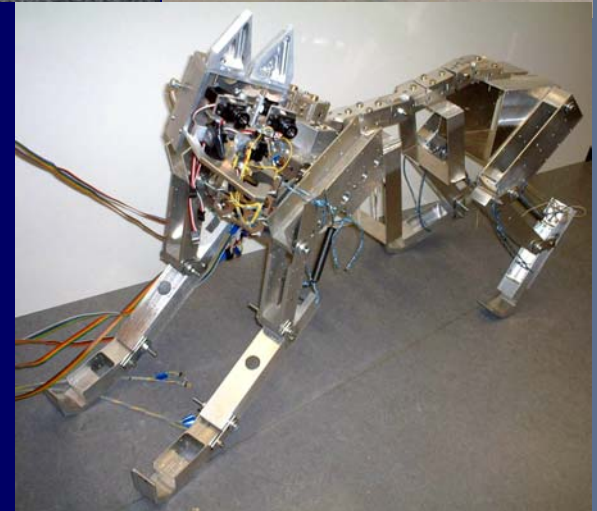
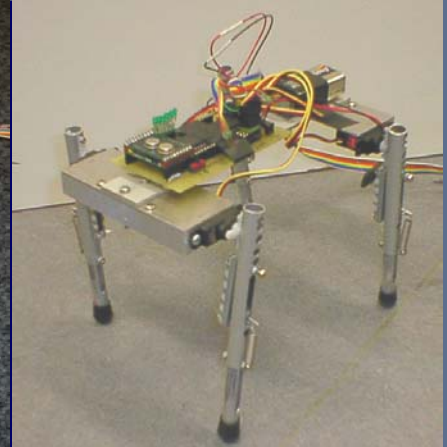
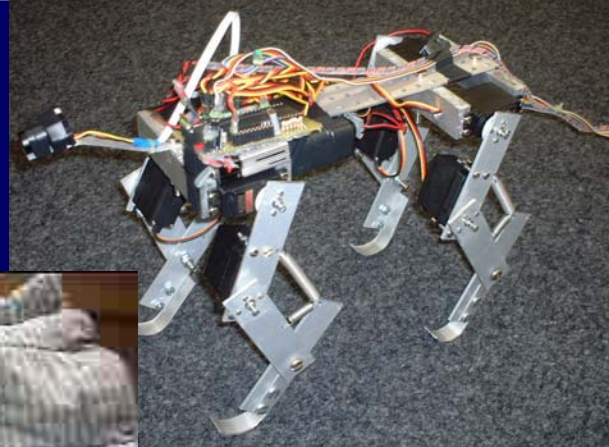
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another illustration: The quadruped “puppy”

## The quadruped “puppy”

*puppy*

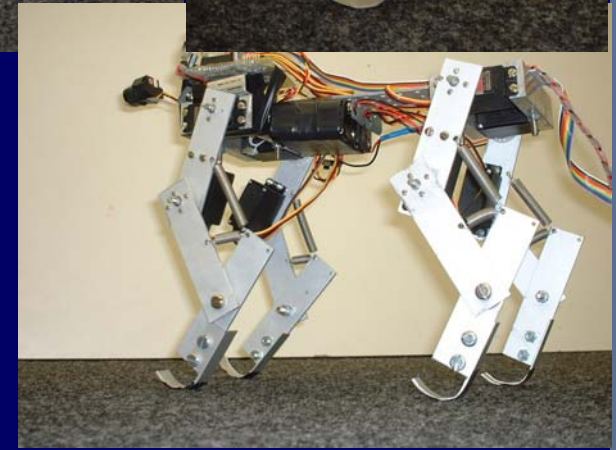
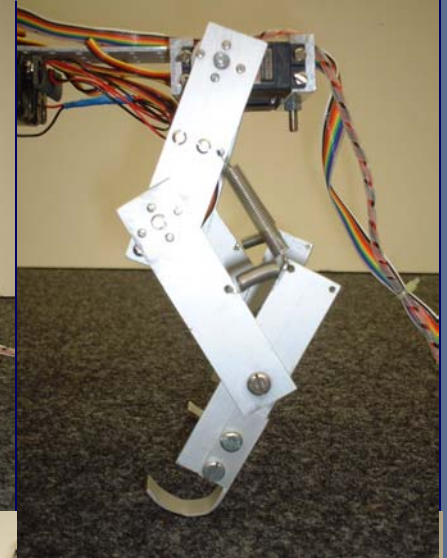
rapid locomotion  
in biological systems



Design and construction:  
Fumiya Iida

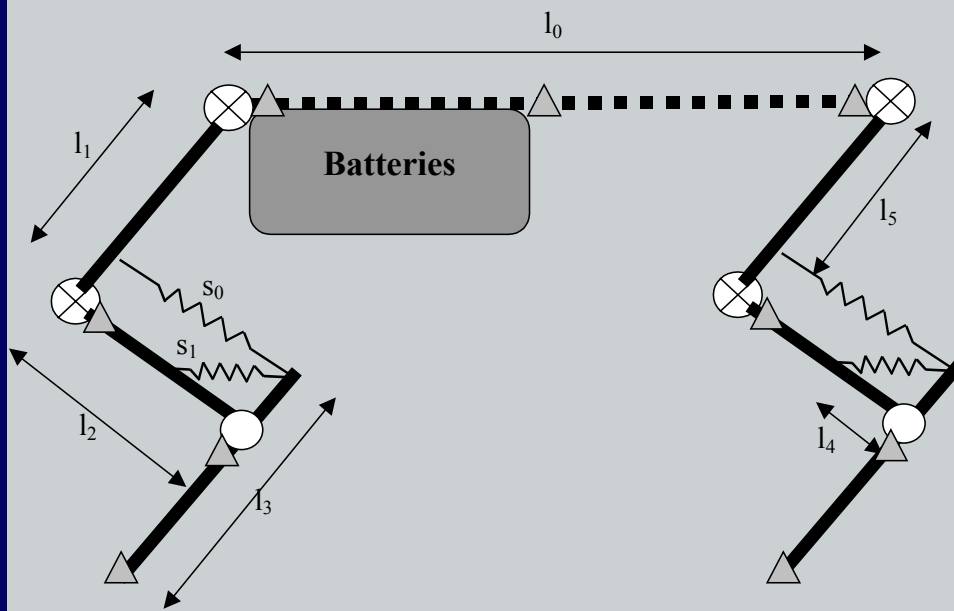
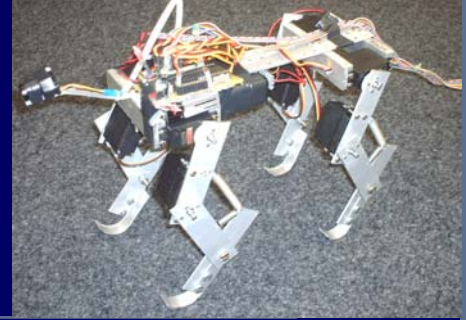
## The quadruped “puppy” *puppy, slow motion*

slow motion

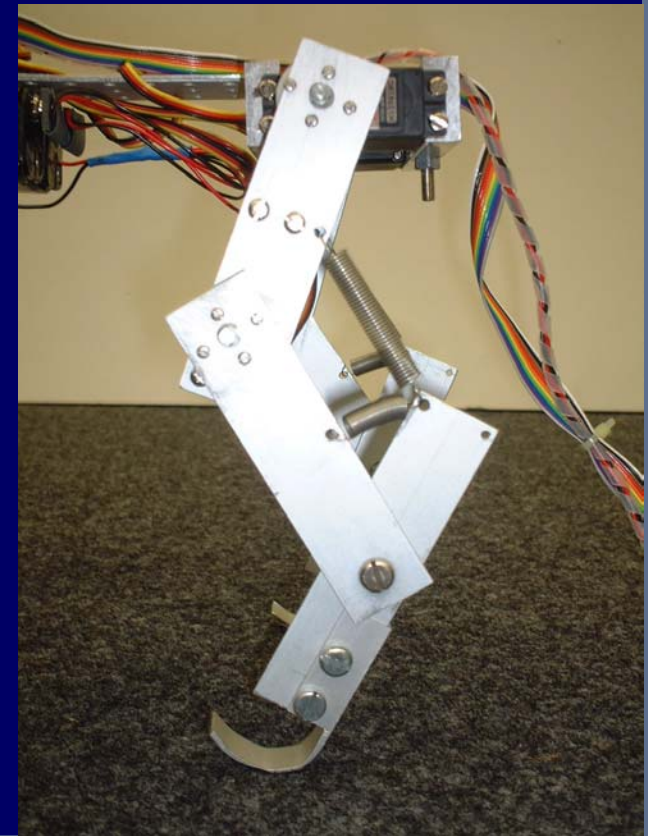


Design and construction:  
Fumiya Iida

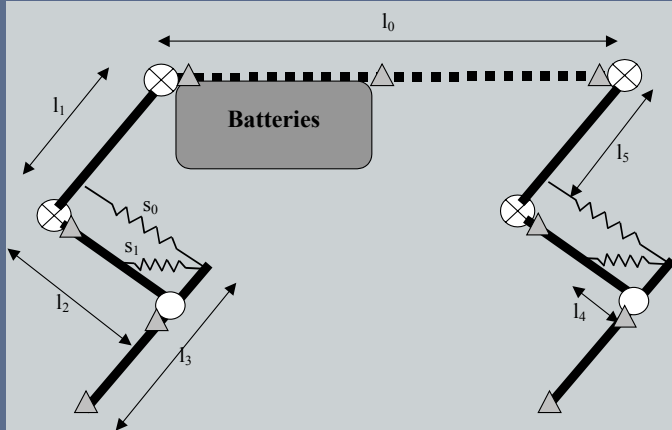
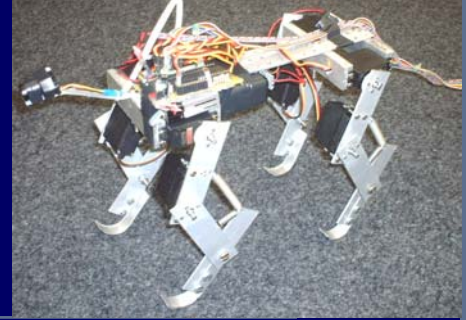
# The quadruped “puppy”



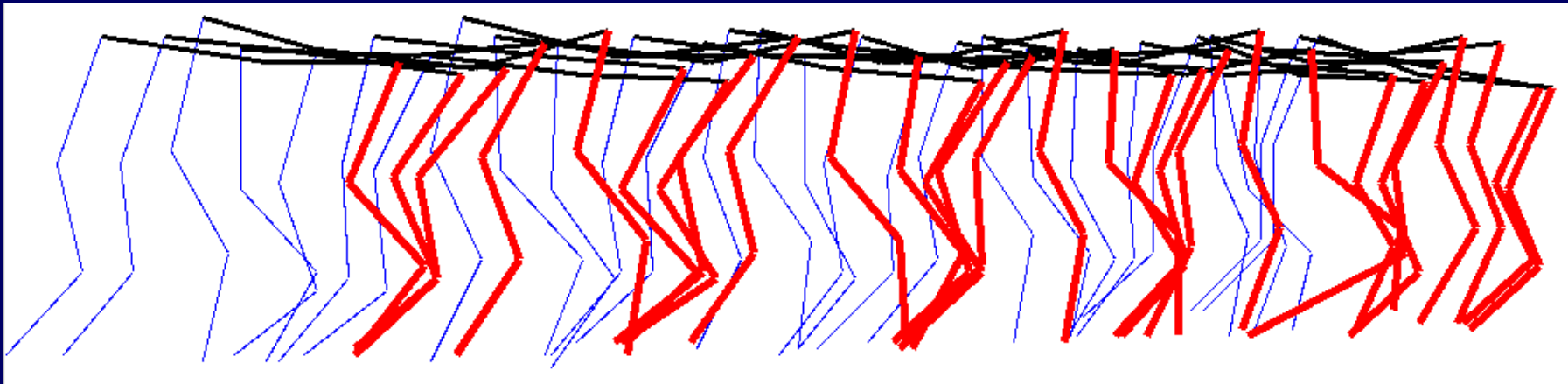
- circles: passive joints
- circles with cross: joints with servo-motors
- fat lines: solid limbs
- dashed line: elastic plate
- triangles: positions of LEDs for visual tracking



# The quadruped "puppy"



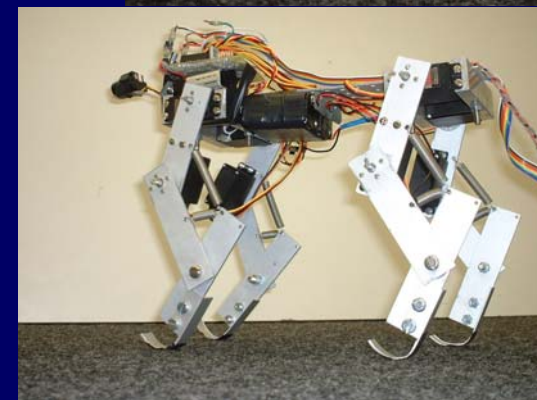
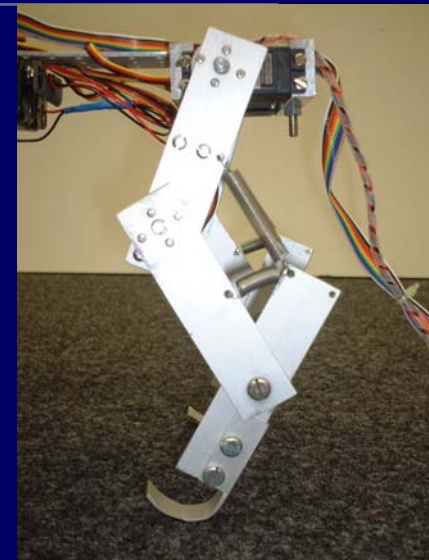
*Analyzing the behavior*



red=hind legs, frame rate 25 frames per second

# The quadruped “puppy”: summary

- simple control (!)
  - springlike materials
  - flexible spine
  - exploitation of dynamics of actuators and of interaction with environment
  - self-stabilization
- “cheap design” and “ecological balance”***



# The principle of “cheap design”

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*intelligent agents: “cheap”*

- exploitation of ecological niche
- parsimonious (Occam’s razor) (but see “redundancy principle”)
- exploitation of specific physical properties of interaction with real world

# Principle of “ecological balance”

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*balance / task distribution between*

- morphology
- neuronal processing (nervous system)
- materials
- environment

*balance in complexity*

- given task environment
- match in complexity of sensory, motor, and neural system

# Assignments

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- Read chapters 8 and 10 of “Understanding Intelligence”
- Task sheet 5
- “Global Webots Communication Workshop”
- Munich:  
Special Assignment: “Theory of intelligence: What should it look like?”

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Merry Christmas and a  
Happy New Year

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Thank you for your kind attention!

CU all next year  
13 January 2004 in the

**GLOBAL VIRTUAL LECTURE  
HALL**